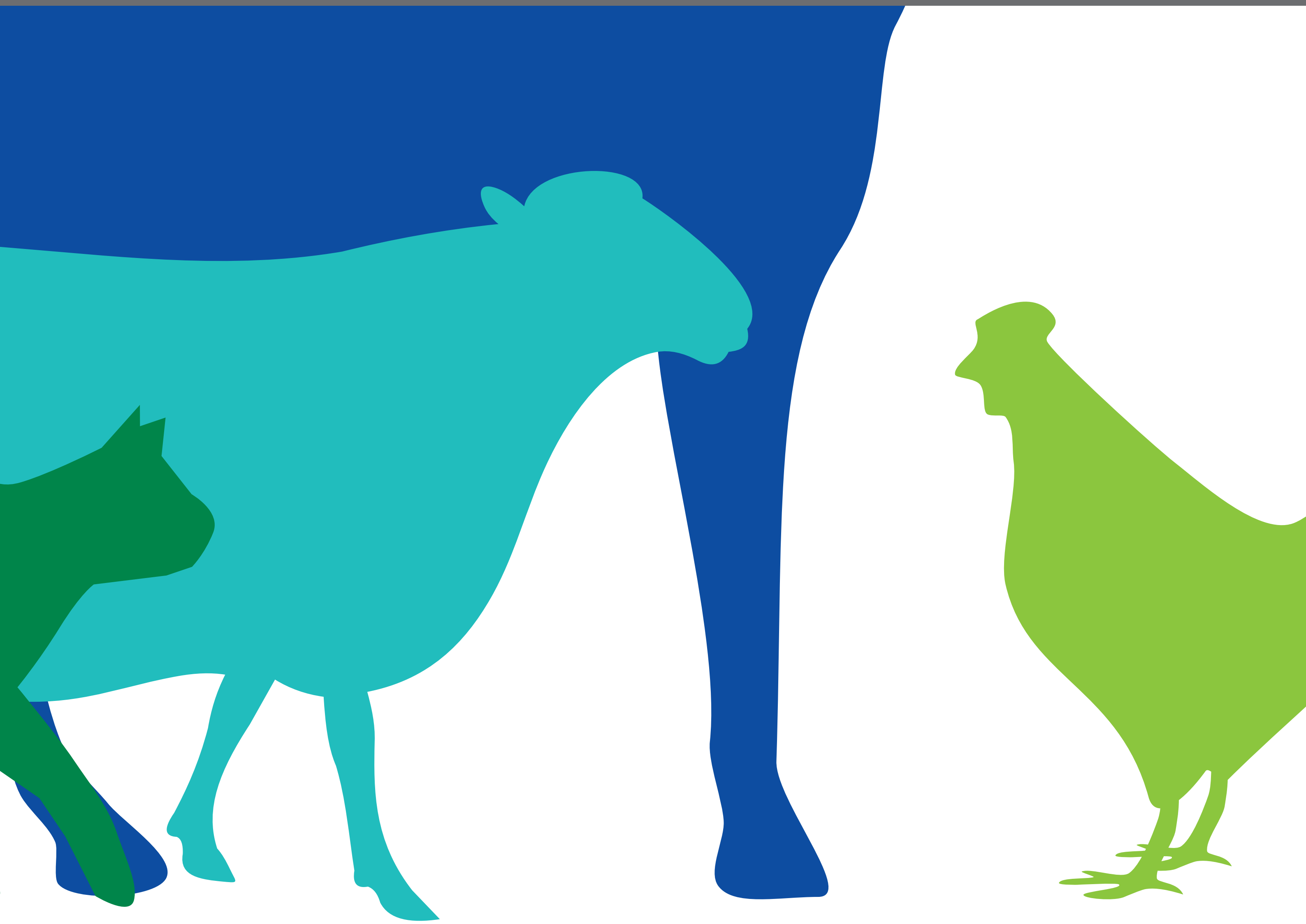
AFRICAN SWINE FEVER IN SMALLHOLDER AND TRADITIONAL PIG FARMING SYSTEMS: RESEARCH, CHALLENGES AND SOLUTIONS

EDITED BY: Mary-Louise Penrith, Robyn Gwen Alders, Erika Chenais, Klaus Depner, Michel Dione and Ferran Jori

PUBLISHED IN: Frontiers in Veterinary Science



frontiers Research Topics

Frontiers eBook Copyright Statement

The copyright in the text of individual articles in this eBook is the property of their respective authors or their respective institutions or funders. The copyright in graphics and images within each article may be subject to copyright of other parties. In both cases this is subject to a license granted to Frontiers.

The compilation of articles constituting this eBook is the property of Frontiers.

Each article within this eBook, and the eBook itself, are published under the most recent version of the Creative Commons CC-BY licence. The version current at the date of publication of this eBook is CC-BY 4.0. If the CC-BY licence is updated, the licence granted by Frontiers is automatically updated to the new version.

When exercising any right under the CC-BY licence, Frontiers must be attributed as the original publisher of the article or eBook, as applicable.

Authors have the responsibility of ensuring that any graphics or other materials which are the property of others may be included in the CC-BY licence, but this should be checked before relying on the CC-BY licence to reproduce those materials. Any copyright notices relating to those materials must be complied with.

Copyright and source acknowledgement notices may not be removed and must be displayed in any copy, derivative work or partial copy which includes the elements in question.

All copyright, and all rights therein, are protected by national and international copyright laws. The above represents a summary only. For further information please read Frontiers' Conditions for Website Use and Copyright Statement, and the applicable CC-BY licence.

ISSN 1664-8714
ISBN 978-2-88976-180-7
DOI 10.3389/978-2-88976-180-7

About Frontiers

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

Frontiers Journal Series

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

Dedication to Quality

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

What are Frontiers Research Topics?

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

AFRICAN SWINE FEVER IN SMALLHOLDER AND TRADITIONAL PIG FARMING SYSTEMS: RESEARCH, CHALLENGES AND SOLUTIONS

Topic Editors:
Mary-Louise Penrith, University of Pretoria, South Africa
Robyn Gwen Alders, Chatham House, United Kingdom
Erika Chenais, National Veterinary Institute, Sweden
Klaus Depner, Friedrich-Loeffler-Institute, Germany
Michel Dione, International Livestock Research Institute (ILRI), Kenya
Ferran Jori, UMR ASTRE - CIRAD, France

Citation: Penrith, M.-L., Alders, R. G., Chenais, E., Depner, K., Dione, M., Jori, F., eds. (2022). African Swine Fever in Smallholder and Traditional Pig Farming Systems: Research, Challenges and Solutions. Lausanne: Frontiers Media SA. doi: 10.3389/978-2-88976-180-7

Table of Contents

frontiers | Frontiers in Veterinary Science

EDITORIAL
published: 26 April 2022
doi: 10.3389/fvets.2022.878928

Editorial: African Swine Fever in Smallholder and Traditional Pig Farming Systems: Research, Challenges and Solutions

Mary-Louise Penrith[1]*, *Klaus Depner*[2], *Ferran Jori*[3], *Michel Dione*[4], *Robyn Alders*[5,6] and *Erika Chenais*[7]

[1] Department of Veterinary Tropical Diseases, Faculty of Veterinary Science, University of Pretoria, Pretoria, South Africa, [2] Institut für Internationale Tiergesundheit/One Health, Friedrich-Loeffler-Institute, Greifswald, Germany, [3] UMR ASTRE (Animals, Health, Territories, Risk and Ecosystems), CIRAD-INRAE, Montpellier, France, [4] Animal and Human Health Program, International Livestock Research Institute, Dakar, Senegal, [5] Development Policy Centre, Australian National University, Canberra, ACT, Australia, [6] Kyeema Foundation, Brisbane, QLD, Australia, [7] Department of Disease Control and Epidemiology, National Veterinary Institute, Uppsala, Sweden

Keywords: African swine fever, control and prevention, smallholder pig farmers, socioeconomic impacts, participatory approaches

OPEN ACCESS

Edited by:
Salome Dürr,
University of Bern, Switzerland

Reviewed by:
Terence Odoch,
Makerere University, Uganda

***Correspondence:**
Mary-Louise Penrith
marylouise_penrith@yahoo.com

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

Received: *18 February 2022*
Accepted: *01 April 2022*
Published: *26 April 2022*

Citation:
Penrith M-L, Depner K, Jori F, Dione M, Alders R and Chenais E (2022) Editorial: African Swine Fever in Smallholder and Traditional Pig Farming Systems: Research, Challenges and Solutions. Front. Vet. Sci. 9:878928. doi: 10.3389/fvets.2022.878928

Editorial on the Research Topic

African Swine Fever in Smallholder and Traditional Pig Farming Systems: Research, Challenges and Solutions

African swine fever (ASF) is a devastating disease of pigs that originated in south-eastern Africa in a sylvatic cycle involving warthogs and soft ticks of the *Ornithodoros moubata* complex. The disease is now global with presence in five continents (1–3). While it is greatly feared throughout all parts of the pig industry worldwide, its effects in the smallholder and traditional pig farming sectors that predominate in most low-income countries and are also present in many higher income countries are often underestimated. Smallholder pig farming is important for many reasons, providing crucial household income, improving nutrition and food security by supplying an affordable source of high quality protein and bioavailable micronutrients as well as fulfilling social and cultural obligations that keep ancient traditions alive and improve social coherence and sustainability (4, 5). Pig production units categorized as "backyard" and "village" are over-represented in reports of ASF outbreaks to the World Organization for Animal Health (OIE) from low- and middle-income countries, and they may be seen as a threat to the commercial pig industry and a hindrance to eradication of ASF. However, recognizing the importance of pigs to numerous smallholders and their potential contribution to poverty alleviation, preventing ASF in smallholder pigs has become a focus of attention and research.

Early detection and rapid reaction are important for efficient control of ASF, but are difficult to achieve in the smallholder sector as it involves large numbers of pig owners in rural areas with inadequate infrastructure and animal health service provision. Prevention of ASF outbreaks by improving biosecurity in production systems and the value chains that serve them is key to limit losses and can only be achieved by working with the pig owners to decide what is feasible for them, using participatory methods. Much has been done to create awareness of ASF and how to prevent it in the absence of an effective vaccine, but many of the recommendations are not feasible for people with limited resources, including inadequate access to finance (6).

This Research Topic is aimed at collecting articles that will add to our knowledge of the traditional and smallholder pig sectors, the impacts of ASF and challenges faced in these sectors, and the approaches that are being used to support feasible and effective prevention and control.

In this special Research Topic there are 12 articles addressing these aspects in seven countries across three continents. Seven articles focus on management of ASF, three on socio-economic impact, one on rapid field diagnosis and one on policy and legislation. The articles are briefly summarized according to those categories.

In the article by Mutua and Dione the epidemiological role of factors such as the context of pig value chains and human risk behaviors is reviewed with a focus on smallholder pig systems in Africa. In this regard farm level biosecurity is particularly emphasized, and factors influencing its adoption are highlighted in the article. Priority areas to consider while designing interventions to improve pig productivity are identified to be socio-cultural factors, weaknesses at the disease control policy level as well as gender and other broader equity aspects. Aliro et al. identify challenges for implementing biosecurity in smallholder pig value chains in spite of the actors understanding and accepting its importance, and propose addressing the constraints through participatory development of socially and culturally appropriate biosecurity measures.

The implementation of improved biosecurity measures is particularly relevant in areas combining a common and abundant presence of wild pigs with extensive and other outdoor farming systems in all different regions of the world, including smallholder or free-ranging pig systems in Africa (Payne et al.) or traditional pig farming systems in the Mediterranean (Gisclard et al.; Rolesu et al.) and North Macedonia (O'Hara et al.). In all cases, regardless of the geographic origin and diversity of cultural contexts, the measures required to reach a higher level of biosecurity should be flexible, adapted to the local socio-economic and cultural context and incentivised by improved trade and higher production gains.

Long-distance spread of ASF virus remains an important unsolved problem, mainly due to anthropogenic factors that can hardly be controlled. In the Samara oblast of Russia, Glazunova et al. demonstrate that outbreaks reported in backyard farms with low biosecurity were mainly related to the transport and trade of pigs and pork products from ASF-affected regions.

All three ASF impact studies in this issue relate to different parts of Asia. The study in Vietnam (Nguyen-Thi et al.) focuses on the economic effect of the ASF outbreaks and control measures across the different pig sectors, indicating that ASF might change the structure of the pig sector to a larger modern sector but that smallholder pig farmers still need to be supported. The studies in the Philippines (Cooper et al.) and Timor-Leste (Berends et al.) place a strong emphasis on the social impacts as well as economic effects on the large backyard pig farming sectors in both countries and propose participatory ASF management interventions that could mitigate the identified impacts.

Although there are very good and reliable laboratory tests for the detection of ASF (e.g., qPCR diagnostic tests), laboratory diagnosis remains a bottleneck in countries with limited laboratory capacity and financial resources. Cost-effective and alternative methods suitable for field use are therefore desirable, especially for areas with suboptimal laboratory infrastructure. The loop-mediated isothermal amplification test (LAMP) has been shown in Timor-Leste to be a robust, highly specific and sensitive diagnostic test for ASF, suitable for use in the field and in areas with limited laboratory capacity (Phillips et al.).

The article by Busch et al. argues that in order to improve ASF control, a disease-specific legal framework based on the latest scientific evidence is needed. It compares the legal basis for ASF control in a number of pig-producing regions globally, considering diverse production systems while considering current scientific evidence in relation to ASF spread and control. It is specifically emphasized that blanket policies, which do not take into account disease-relevant characteristics of a biological agent or the specifics under which the host species are kept, can hamper disease control efforts and even be counter-productive.

In summary, the results of these studies provide new and relevant insights into the challenges facing prevention and control of ASF in an array of smallholder pig farming settings, with and without wildlife involvement, and its impacts on the farmers and pig value chain actors. Based on their findings, the researchers offer constructive proposals for more participatory, inclusive and context-adapted approaches to prevention and control of ASF.

AUTHOR CONTRIBUTIONS

M-LP wrote the introduction and conclusion. All authors contributed to the central part relating to the individual articles and reviewed and approved the submitted version.

REFERENCES

1. Penrith M-L. Current status of African swine fever. *CABI Agric Biosci.* (2020) 1:11. doi: 10.1186/s43170-020-00011-w
2. Food and Agriculture Organization of the United Nations. *Update on the ASF Situation in Asia and the Pacific*. (2022). Available online at https://www.fao.org/ag/againfo/programmes/en/empres/ASF/situation_update.html (accessed February 6, 2022).
3. Food and Agriculture Organization of the United Nations. *African Swine Fever. FAO Regional Office for Latin America and the Caribbean*. Available online at: https://www.fao.org/americas/priorities/african-swine-fever/en/ (accessed February 6, 2022).
4. Chenais E, Boqvist S, Emanuelson U, von Brömssen C, Ouma E, Aliro T, et al. Quantitative assessment of the social and economic impact of African swine fever outbreaks in northern Uganda. *Prev Vet Med.* (2017) 144:134–48. doi: 10.1016/j.prevetmed.2017.06.002

5. Dione MM, Akol J, Roesel K, Kungu J, Ouma EA, Wieland B, et al. Risk factors for African swine fever in smallholder pig production systems in Uganda. *Transbound Emerg Dis.* (2017) 64:872–82. doi: 10.1111/tbed.12542
6. Penrith M-L, Bastos A, Chenais, E. With or without a vaccine—complementary and alternative approaches to managing African swine fever in resource-constrained smallholder settings. *Vaccines.* (2021) 9:116. doi: 10.3390/vaccines9020116

Conflict of Interest: RA was employed by Kyeema Foundation.

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

The handling editor declared a past collaboration with the FJ.

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

Copyright © 2022 Penrith, Depner, Jori, Dione, Alders and Chenais. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.

frontiers in Veterinary Science

REVIEW
published: 24 March 2021
doi: 10.3389/fvets.2021.637487

Evidence-Based African Swine Fever Policies: Do We Address Virus and Host Adequately?

Frank Busch[1†], Céline Haumont[2†], Mary-Louise Penrith[3], Alberto Laddomada[4], Klaas Dietze[1], Anja Globig[1], Vittorio Guberti[5], Laura Zani[1] and Klaus Depner[1]*

[1] Institute of International Animal Health/One Health, Friedrich-Loeffler-Institute, Greifswald, Germany, [2] National College of Veterinary Medicine, Food Science and Engineering, Oniris, Nantes, France, [3] Department of Veterinary Tropical Diseases, Faculty of Veterinary Science, University of Pretoria, Pretoria, South Africa, [4] Consultant, Cagliari, Italy, [5] Istituto Superiore per la Protezione e la Ricerca Ambientale, Epidemiology and Ecology Unit, Ozzano Emilia, Italy

OPEN ACCESS

Edited by:
Barbara Wieland,
International Livestock Research Institute, Ethiopia

Reviewed by:
Anette Ella Boklund,
University of Copenhagen, Denmark
James A. Roth,
Iowa State University, United States
Karl Ståhl,
National Veterinary Institute, Sweden

***Correspondence:**
Frank Busch
frank.busch@fli.de

† These authors have contributed equally to this work

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

Received: 03 December 2020
Accepted: 18 February 2021
Published: 24 March 2021

Citation:
Busch F, Haumont C, Penrith ML, Laddomada A, Dietze K, Globig A, Guberti V, Zani L and Depner K (2021) Evidence-based African Swine Fever Policies: Do We Address Virus and Host Adequately? Front. Vet. Sci. 8:637487. doi: 10.3389/fvets.2021.637487

African swine fever (ASF) is one of the most threatening diseases for the pig farming sector worldwide. Prevention, control and eradication remain a challenge, especially in the absence of an effective vaccine or cure and despite the relatively low contagiousness of this pathogen in contrast to Classical Swine Fever or Foot and Mouth disease, for example. Usually lethal in pigs and wild boar, this viral transboundary animal disease has the potential to significantly disrupt global trade and threaten food security. This paper outlines the importance of a disease-specific legal framework, based on the latest scientific evidence in order to improve ASF control. It compares the legal basis for ASF control in a number of pig-producing regions globally, considering diverse production systems, taking into account current scientific evidence in relation to ASF spread and control. We argue that blanket policies that do not take into account disease-relevant characteristics of a biological agent, nor the specifics under which the host species are kept, can hamper disease control efforts and may prove disproportionate.

Keywords: African swine fever, ASF policies, ASF surveillance, disease control, legislation, backyard farm, transboundary animal disease, contagiousness

INTRODUCTION

Like other transboundary animal diseases (TADs), African swine fever (ASF) can impact economies in affected countries significantly due to losses in trade, pig production and associated food security threats (1, 2). Whilst ASF virus (ASFV) continues to spread among domestic pigs (*Sus scrofa domesticus*) and wild boar (*Sus scrofa*) in large areas of Eurasia, many aspects regarding the key mechanisms that drive infection transmission and disease persistence are yet to be fully understood (3, 4). Legal frameworks that underpin animal health interventions must take into consideration the biology of an infectious agent as well as the host species and, if domestic, the production systems, in order to develop appropriate and targeted strategies to combat the disease.

Whilst it is commonly accepted that ASF disease control in wild boar warrants a tailored approach, no special dispensation exists for domestic pigs, despite the fact that differences in the epidemiology of ASF have been observed in the various production systems: e.g., commercial industrial farming vs. traditional pig farming systems with backyard and smallholders or even free-ranging, feral pigs (5–7).

Where evidence emerges, based on scientific studies and/or well-documented field observations, that aspects of current strategies could be improved, efforts must be made to amend the relevant animal health legislation accordingly in order to ensure a progressive and measured disease control approach.

The aim of this paper is (i) to compare ASF-related legislation and the prescribed disease control and eradication measures for domestic pigs from countries spanning five continents (Africa, Asia, Europe, America, Oceania) and covering over 75% of the global pig population, and (ii) to analyze their applicability, taking into account our current understanding of the disease, drawing from global ASF experiences.

The authors are discussing disease control policies in relation to highly virulent ASF strains as the genotype II virus that is currently circulating in Eurasia.

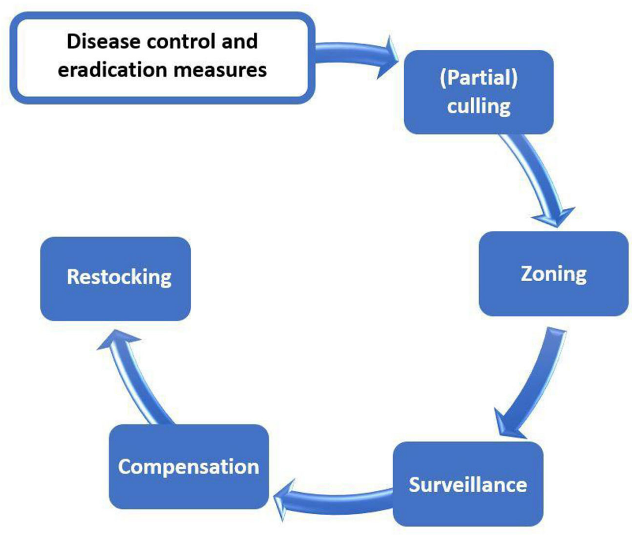


FIGURE 1 | Schematic view of ASF control and eradication measures across the globe.

DISEASE CONTROL AND ERADICATION MEASURES OF ASF ACROSS THE GLOBE

The control of ASF in domestic pigs follows the general concepts recommended for controlling transboundary animal diseases: As soon as the presence of the disease is suspected, a number of specific diagnostic actions must follow in order to confirm or exclude the presence of disease. Once ASF is confirmed, the infected holding must be isolated and depopulated, partially or entirely, although this is not always possible due to socio-economic constraints, for example. Further spread must be prevented through immediate cessation of animal movements (standstill), the tracing of contact holdings and potentially contaminated products, and through the establishment of surveillance and protection zones around the index case. The aim of these activities is to eradicate the disease within the affected area, prevent the spread outside of it and at the same time allow trade and movements of animals and animal products outside the restricted areas in order to minimize disruption to the pig value chain (**Figure 1**).

European legislation aims to harmonize measures for Member States regarding disease control and eradication and the measures therein (**Figure 1**) are very prescriptive. The measures laid down in the current European Union (EU) legislation represent the minimum set of measures that must be implemented.

Outside of the EU, ASF-related legislation seems less prescriptive. In the case of the United States of America (USA), instructions are limited and guidance is provided based on a number of disease scenarios and on a case-by-case basis. The relevant documents advise that it is more effective to share distinct, concise, flexible policy guidance, as an outbreak unfolds, in order to adapt it rapidly to a specific situation. Therefore, measures and protocols differ between USA-States (8). The United States Department of Agriculture (USDA) stresses the use of strategies that (a) detect, control, and contain the disease in animals as quickly as possible, (b) eradicate the disease using strategies that seek to stabilize animal agriculture, the food supply, the economy, and to protect public health and the environment and (c) provide science- and risk-based approaches and systems to facilitate continuity of business for non-infected animals and non-contaminated animal products (8). In contrast to the 2013 USDA ASF response plan, the updated response plan (2020) has further developed different components of control and eradication (including feral pig management, culling guidelines and others) resulting in a more comprehensive guidance aiming to harmonize procedures between USA-States. For example, well-defined radii for zoning are now provided, which constitutes a common and solid reference to rely on before adjusting them to the epidemiological situation of a given outbreak (8).

Australian ASF-legislation focuses particularly on reassessments of decisions taken following unfolding epidemiological events. The legislation envisages the possibility of a transition to a long-term control policy if eradication is deemed to be impossible (9).

Chinese and Russian ASF legislation employ stamping out policies without exceptions; case- by-case approaches are not permissible (10, 11).

Vietnamese ASF-legislation appears to provide some flexibility, stating that "provinces and cities develop plans for pig production areas appropriate to local practical conditions" (12). It also expresses the need to cooperate with international, intergovernmental and non-governmental organizations and mentions, besides others, the Food and Agriculture Organization (FAO), the World Organization for Animal Health (OIE), and the Association of Southeast Asian Nations (ASEAN); it suggests to seek out cooperation with neighboring countries, in particular China, as the geographically closest ASF-infected country, in order to obtain regional information and benefit from technical and financial assistance (12).

Although total eradication of ASF is not possible in South Africa due to natural vectors and hosts, the disease can be successfully controlled and eradicated in domestic pig production systems if contact with the virus is eliminated (13–15). The strategy is that of long-term control with an emphasis on prevention. Three types of pig farms are permitted in the ASF controlled areas where the disease is endemic in the warthog-tick sylvatic cycle, namely compartments, accredited and listed piggeries as defined by law (13). Compartments comply with international standards provided in Chapters 4.4 and 4.5 of the Terrestrial Animal Health Code of the OIE and South African legislation for pig compartments (16). Compartments have the highest level of biosecurity and may supply the export market regardless of the status of the area where they are situated (17). Accredited farms are registered farms that comply with biosecurity standards laid down in the abovementioned legislation for control of ASF and may supply pigs for slaughter outside the control area but only to non-export abattoirs. Listed farms are those that are registered and maintain basic biosecurity measures but may only supply pigs for slaughter to abattoirs within the control area (13). The South African legislation allows for flexibility since action plans for investigation and control must be developed by the respective farmer/owner of the pig herd in consultation with the local State Veterinarian (13). The strategy cited is an initiative to improve this situation.

Summarizing coordinated efforts across the African continent, however, the FAO, the African Union—Interafrican Bureau for Animal Resources (AU-IBAR) and the International Livestock Research Institute (ILRI) observe that "there is lack of intra-regional cooperation toward the control of the disease in Africa" (18).

The variations in the disease control and eradication measures of the countries and regions included in this paper are summarized in **Tables 1A**, **B**.

LEGISLATION AND CONTAGIOUSNESS

When ASF-legislation was formulated for the EU, ASF was defined to be a highly contagious disease and such references still prevail (19). However, analyses of domestic pig outbreaks in the current epizootic in Europe, as well as in experimental studies, revealed that the contagiousness of ASF is comparatively low and that under field conditions ASFV transmission between animals is considered to be slow (20, 21).

Therefore, ASF ought not be considered to be a highly contagious disease (21) and consequently, ASF control and eradication measures warrant a different approach to that of highly contagious diseases such as Foot and Mouth disease (FMD) or Classical Swine Fever (CSF) (**Figure 2**).

Nonetheless, many legislations worldwide have classified ASF as a highly contagious disease, as is the case in the Russian Federation (10), the Socialist Republic of Vietnam (12), the Commonwealth of Australia (9) and Canada (23), from the set of analyzed countries.

In the EU, legislation for CSF (a highly contagious disease) was employed as a template for ASF legislation: the CSF Directive (24) was used as a model for drafting the ASF Directive (25), following the same control and eradication measures for CSF.

If ASF is detected early and control measures are implemented without delay, the contagiousness has been demonstrated to be low (20). Virus spread within a farm as well as within a habitat is considered to be slow (7). The disease merely appears to be highly contagious in an environment where pigs are kept closely together and maintain frequent contact with other pigs within the pen.

During an outbreak investigation in 2017 on a large commercial pig farm (5,000 pigs) in Latvia, no deviation from the expected farm mortality rate was recorded during the first weeks of infection. More than 1 month passed before suspicion of ASF arose (26). This example demonstrates that under certain circumstances, i.e., in very large farms, early detection, within the first 2 weeks after virus introduction, can only be achieved through the regularly testing of sick and deceased animals (27). The presumptions made may slow down control and eradication and may even lead to further spread of the disease when a higher initial mortality rate is expected ("highly contagious disease"). Therefore, a surveillance scheme based on weekly sampling of deceased post-weaning pigs has been suggested as an early detection measure for ASF (28), particularly in holdings under risk of ASF incursions, e.g., where the virus is circulating in wild boar populations. In the current legislation of many countries, the characteristics of the disease such as low contagiousness/mortality and high case-fatality are not taken into account. Not specifying these characteristics may lead to the assumption that all disease scenarios are equal in this regard.

STAMPING OUT MEASURES

According to the current EU legislation (25), Member States shall ensure that in cases where ASF is officially confirmed in a holding, all pigs are to be killed without delay. However, exemptions to cull the entire farm can be made (25), based on a risk assessment and under a number of conditions that for the most part cannot be met in practice. The approach is similar in the USA (8).

The Republic of South Africa allows specific quarantine measures and not all animals must be culled within a holding (13). The Socialist Republic of Vietnam allows the slaughter of pigs for human consumption if these test negative for ASFV (12). Similarly, pre-emptive slaughter of healthy-looking pigs (often without testing) in an affected herd or area is practiced in a number of African countries where no compensation can be paid for culling and herd reduction is a preventive measure (14).

ZONING

Recent events have highlighted that international trade can be significantly interrupted when ASF is detected even in just one region of a country, despite the fact that the principle of zoning

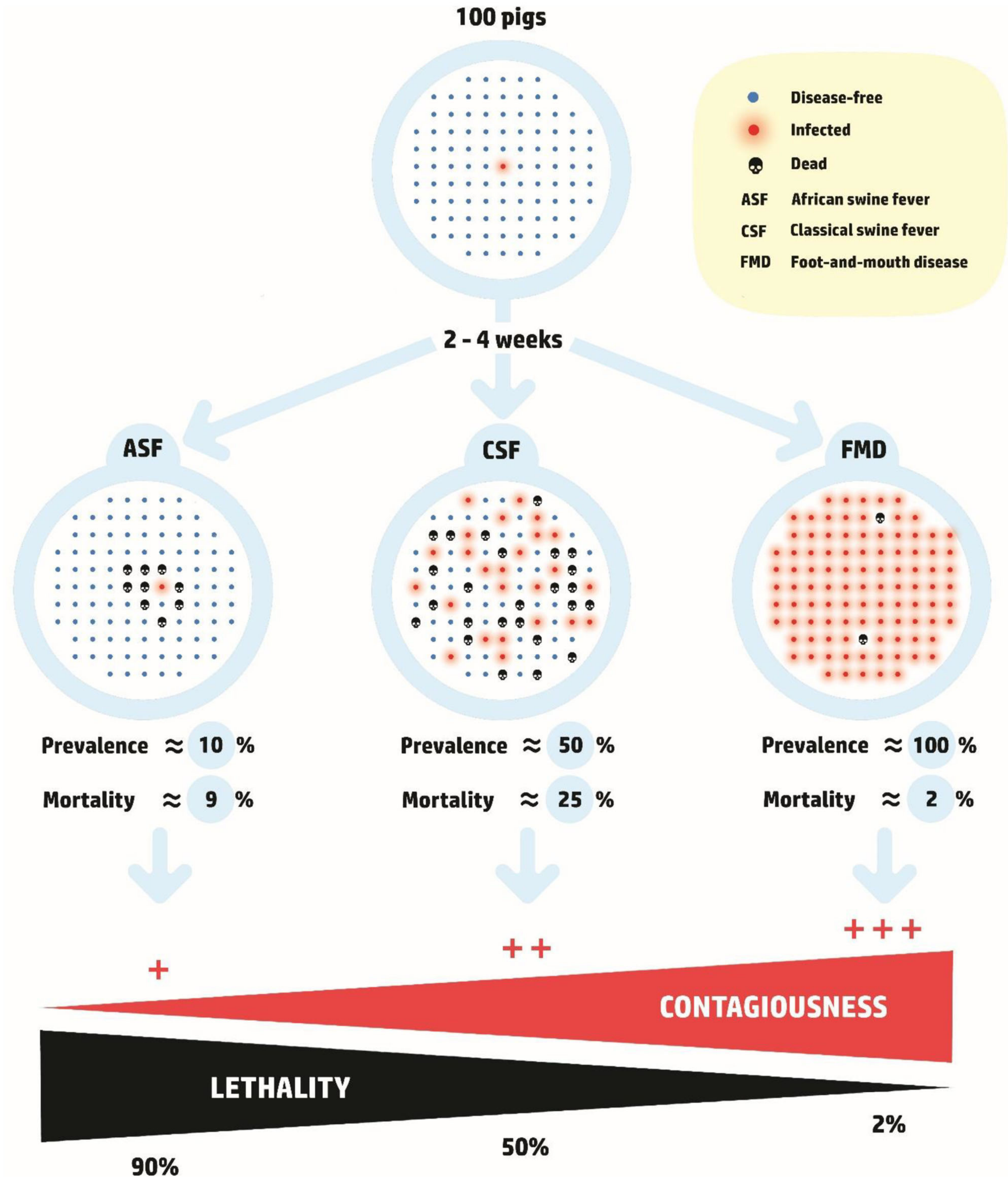


FIGURE 2 | Hypothetical disease scenario of three major pig diseases over a period of 2–4 weeks (22), highlighting the differences between Foot and Mouth Disease (FMD), Classical Swine Fever (CSF) and African Swine Fever (ASF). In comparison to FMD and CSF, contagiousness and mortality of ASF during the initial phase of an incursion is low to moderate while the case fatality rate is above 90%.

TABLE 1 | A selection of disease control and eradication measures in the international context.

Measures	EU	USA	South Africa	Russia	Australia
A					
Stamping out	Mandatory All pigs in the infected holding	Mandatory All pigs in the infected holding	No Quarantine preferred	Mandatory All pigs in the 1st zone	Mandatory All pigs in the infected and highly suspected holdings
Zoning	Yes 3 km 10 km	Yes 3 km 2 km buffer zone 10 km	No but permanent "controlled areas" for endemic ones	Yes 5–20 km 100–150 km	Yes 3 km 10 km
Standstill of animal movements	Yes In restricted zones	Yes	Yes In the infected property	Yes	Yes In restricted zones
Surveillance	Active and passive	Active and passive	Yes if resources (active, passive)	Yes Type (active or passive) unclear	Active and passive
Compensation	Up to 100%	50% of market value	No	Not specified	50% government 50% industry
Lifting of restrictions	Min. 30 days after C and D	Min. 30 days after C and D	3 months after the last case	6 months after end of quarantine	Min. 30 days after C and D
Restocking	Min. 40 days after C and D	Variable	Not specified	One year after end of quarantine	Min. 6 weeks after C and D
Sentinel animals	Variable	Variable	Variable	No	Yes
Frequency of legislation's review	No mention Last update in 2002	"As needed" Last update in 2020	No mention Last update in 2018	No mention Last update in 1980	"As needed" Last update in 2016

Measures	Canada	China	Vietnam	Japan
B				
Stamping out	Mandatory All pigs on any site where testing indicates ASF-presence	Mandatory All pigs in the infected holding	Variable Only pigs with (+) test results	Mandatory All pigs in the infected holding
Zoning	Yes 1st zone: no radius specified 2nd zone: 10 km	Yes 3 km 10 km 50 km if wild boar activity	Yes 3 km 10 km	Yes 3 km 10 km
Standstill of animal movements	Yes	Yes	Variable Not for pigs tested (-)	Yes
Surveillance	Passive	Active and passive	Active	Yes Type (active or passive) not specified
Compensation	Yes Up to 5,000 Can.$/culled pig	Variable *Pro rata* basis	38,000 VND/kg pig (1,49€/kg)	100%
Lifting of restrictions	3 months after C and D	21 days after C and D	2 months after C and D	22 days after C and D
Restocking	If sentinel pigs are (-) after 2 months	If sentinel pigs are (-) after 45 days Or if environment is (-) after 5 months empty	30 days after the last case	Min. 6 weeks after C and D
Sentinel animals	Yes	Optional	Yes	Yes
Frequency of legislation's review	"As needed" Last update in 2019	No mention Last update in 2020	"As needed" Last update in 2020	Every 3 years Last update in 2019

C, Cleaning; D, Disinfection.

is consistently applied, at least in the EU. However, since this concept is not always recognized by all trade partners, the entire pig sector of the country in question suffers the consequences of a ban on trade although only a few cases in a restricted area have been detected, even when they refer only to wild boar or non-commercial backyard pigs. Depending on the production system, economic consequences differ (29): zoning (the free area is defined by geography) may be the most cost-effective approach for small production systems, whereas compartmentalization (the free area is defined by husbandry practices related to biosecurity) may be the preferred approach for large commercial farms, due to the extensive areas covered (29).

Protection and surveillance zones in the EU need to measure a minimum of 3 km and 10 km respectively. The USA prescribes the same, including a buffer zone of 2 km between the two (8). In the Republic of South Africa "controlled areas" were established in 1935 in places where the sylvatic cycle is endemic (13). The Russian Federation establishes two distinct "threat zones," the "first-threat" zone measuring a minimum of five to 20 km, the "second-threat" zone has a radius of 100–150 km (10). In the ASF-free Commonwealth of Australia, a 3 km "restricted area" will be established and the responsible authorities have flexibility regarding the control area which usually measures 10 km (9). China sets a 3 km radius in "infected areas" whereas the "threatened area" of 10 km will be extended to 50 km in areas of known wild boar activity. In all cases, a full epidemiological assessment must be conducted in order to estimate the extent of the outbreak (11).

SURVEILLANCE

Surveillance activities in domestic pig populations are embedded within the various pieces of legislation relating to ASF. Variations exist regarding the locality of the surveillance measures applied and regarding the protocols and methods used for sampling and testing. For example, Canada pursues surveillance within and outside designated high-risk areas whilst Vietnam focuses its surveillance activities in its high-risk areas only (12, 23). EU legislation requires a minimum number of samples to be tested in the absence of clinical signs to detect 10% sero-prevalence with 95% confidence in infected areas (28, 30), whilst in the USA and Australia, the pattern and timing of testing may be determined according to the local disease situation and its specific circumstances (8, 9). In South Africa, apart from passive surveillance to identify outbreaks, active surveillance is based on monitoring of *Ornithodoros moubata* complex ticks from warthog burrows at the borders of the controlled area (31). Serological surveys are carried out in areas outside the controlled area after outbreaks to confirm absence of viral circulation (15).

In the European setting, disease surveillance in wild boar is carried out either by testing of all wild boar found sick or dead (passive surveillance is mainly aimed at the early detection of the virus in free at-risk areas), or by the testing of all hunted wild boar in an infected area, together with the testing of each dead animal (active plus passive surveillance). When virus prevalence and wild boar densities are low toward the end of disease eradication, the question whether active or passive surveillance is more efficient in detecting the virus is still open (32). EU legislation pursues both active and passive surveillance, whilst Canada's legislation predominantly focuses on passive surveillance as part of its control strategies in feral pigs (23).

COMPENSATION

Fair and timely compensation schemes ensure business viability and compliance with veterinary authorities. Farmers in the EU will receive compensation and the compensation modalities are organized in each Member State individually. The EU as the regional body provides the overall disease control framework and also contributes to compensation (33). In the USA and Australia (both currently ASF-free countries), only partial compensation is afforded with a cost-shared model operating between industry and government for the latter (8, 9). In China, compensation measures have become increasingly complex since 2018 when compensation for compulsory culling for ASF may have been at its highest. In February 2020, the Ministry of Agriculture and Rural Affairs of China (MARA) released the 2020 edition of the "ASF Epidemic Emergency Implementation Plan" in which it changed compensation measures depending on a number of factors, including cost-sharing arrangements between holdings where the outbreak occurred and the place of animal origin (11). Compensation for animals culled during outbreaks of controlled animal diseases was stipulated in earlier legislation in South Africa, but this has been rescinded for ASF (13). During outbreaks outside the control area, support was made available to subsistence farmers by industry and the Department of Social Development (15).

RESTOCKING

In the EU, restocking procedures are complex and restocking *per se* can only be permitted after a minimum of 40 days after cleaning and disinfection has been completed (25). In the USA, the local authorities can decide on restocking procedures depending on circumstances (8). Whilst in the Republic of South Africa no specific restocking procedures are laid down (13), in the Russian Federation, restocking can be undertaken within the "first-threat zone" only 1 year after quarantine removal (10). The legislation in China allows for restocking after a period of 5 months in addition to ASF-negative environmental samples; it also allows for restocking to take place 45 days after the introduction of sentinel pigs if these show no clinical abnormalities and produce negative test results (11).

The use of sentinel pigs as part of the restocking procedure varies. Sentinels are recommended to be used in the USA, South Africa, Canada only for outbreaks linked to ticks. The EU, Australia, Vietnam and Japan employ sentinel pigs regardless of ticks. Russia does not employ a sentinel system; the use of sentinel pigs in China is optional (8–10, 12, 13, 23, 25, 34). Sentinel pigs were used in several countries in West Africa before restocking (35), and served as core breeding stock in farms that did not receive compensation.

DISCUSSION

EU-legislation on ASF is about to change: from 21 April 2021, the so-called "Animal Health Law" will apply together with new regulations on disease listing, eradication programs, surveillance, prevention and control (36). Under the new legislation, ASF will be listed as a "Category A" disease and will continue to be subjected to rigorous prevention and control measures aimed at its eradication. However, compared to the current legal framework, there will be increased opportunities for each EU Member State to tailor ASF control measures, taking into account the local disease picture. Given the occurrence and persistence of ASF in several EU Member States, the Commission envisages safe trade and the smooth functioning of the EU single market through the implementation of the OIE-recognized principle of "zoning" *via* a new, specific Implementing Regulation (36).

Under this new legal framework, there will be opportunities to implement changes that improve outcomes and address specific problems posed by ASF in the EU. For instance, the most at-risk holdings vary according to the country, such as Estonia where commercial herds have been estimated to be more at risk than backyard farms (37), whereas the contrary has been reported from the Russian Federation (38).

African swine fever control measures in the EU largely follow the CSF control measures, based on the erroneous assumption that ASF is a highly contagious disease with a high mortality, affecting large numbers of pigs within a short time in an epidemiological unit, spreading readily from pig to pig and from farm to farm. However, analyses of domestic pig outbreaks in the current epizootic, as well as in experimental studies, revealed that the contagiousness is rather low and that under field conditions ASF virus transmission between animals can be slow (20). The principle aim is to eradicate the virus within affected zones and allow for the trade of animals and animal products outside the restricted areas in order not to disrupt commerce.

Japan and the USA do not define ASF to be a highly contagious disease (8, 34) and relevant legislation characterizes ASF as "a typical example of a transboundary animal disease" defined by international organizations such as the FAO as "a disease that spreads across national borders and is of importance to the economy, trade, and food security of the outbreak country and requires multilateral cooperation to prevent its epidemic" (34). South African legislation does not mention contagiousness, only describing the different transmission routes (13).

Anthropogenic activities have been identified as the main drivers for disease transmission in the domestic pig cycle and are responsible for long-distance jumps of disease in wild boar (20, 21), as opposed to animal-to-animal transmission, which has also been recently described for domestic pigs in South Africa (14).

The sound implementation of any early detection surveillance scheme will enable the detection of potentially infected holdings in the early stages of disease progression with only few virus-positive animals present. While early detection and removal of infected animals is crucial to eliminate or reduce the risk of virus transmission, on-farm depopulation or preventive culling often lead to highly emotional and difficult situations where farmers refuse to accept depopulation measures when they do not see the justification for drastic measures.

Environmental complications arise when a high number of carcasses are disposed of *via* incineration or burial. The benefits of effective disease control must be balanced against costs and ethical consideration of the control measures applied. Excessive culling raises ethical issues when more pigs are culled than deemed necessary to prevent disease spread. In the Netherlands in 1997, ∼11 million pigs were culled to combat CSF whereas <1 million were actually infected (39).

Nevertheless, the stamping-out policy seems entirely justified where it leads to rapid disease eradication and a return to normal trade, i.e., where intensive, trade-oriented pig farming is an important economic activity. Conversely, it seems questionable under other contexts, where this policy does not effect clear advantages, either in epidemiological or in economic and social terms and is at odds with safeguarding animal welfare. This is the case when ASF cannot be swiftly eradicated due to biological reservoirs other than domestic pigs and where backyard/non-commercial pig farming prevails. Under these circumstances, alternatives to a stamping out policy should be explored and reflected in legislation.

If good on-farm surveillance can be established *via* the use of modern diagnostic techniques (e.g., sensitive and specific pen-side tests) the number of animals destined to be destroyed on an affected farm could be reduced. Equally, targeted culling programs of infected contact animals could be employed, based on veterinary risk assessments that take into account the characteristics of the biological agent, the farming system, biosecurity and distances between animal groups (40).

Zoning is one of the early actions to be employed in case of an ASF incursion into a country. Many countries request 3 km and 10 km zones around outbreak points (e.g., EU, Australia, Japan). Those radii largely remain a proven tool for controlling and eradicating highly contagious diseases such as CSF, although in very densely populated areas preventive culling may need to be applied as an additional measure. Relying on the epidemiological results enables the local authorities to choose radii that are scaled to the threat. In the case of ASF control and prevention, efficient epidemiological tracing of potentially infected farms may replace the zoning strategy, avoiding the implementation of zones over 3 km radius. On the other hand, larger zones may be chosen for ongoing infections in wild boar populations. The proximity of wild boar to both backyard and commercial farms is a risk factor in the emergence of ASF outbreaks in domestic pigs, which is even more impactful when the level of biosecurity is low or when wild boar abundance is comparatively significant (41). According to the local context, the increase in ASF cases in wild boar can even be the main risk factor leading to outbreaks in pig farms (37).

Ideally, tracing activity and compartmentalization should supplement any zoning strategy. The concept of compartment widens the geographical approach of zoning by going beyond the "risk borderline." It incorporates all epidemiological elements that allow to define more appropriately an effective boundary and should ideally be defined before an outbreak occurs (42). However, to maintain international pork trade for countries facing cases of ASF in wild boar or domestic pigs, a binding international agreement is required on how the safety of pork products can be guaranteed (43).

As zoning may restrict animal movements and trade potentially more than necessary regarding high-biosecurity holdings, implementing compartmentalization for eligible pig units could be viewed as a compromise between business disruption and disease control. An issue that is still discussed by the EU working group on zoning and compartmentalization is the possible scenario of a compartment being located close to a disease outbreak, for example in the surveillance or protection zone. This scenario has not yet been sufficiently considered at an international level (44). Until a derogation is issued, intra-community transport in relation to the compartment will not be permitted under existing EU legislation. An early and short standstill would apply, in order to ensure that the compartment's integrity is maintained. The EU working group is currently developing procedures to improve the management of this scheme (44).

If, for example, only backyard farms are affected, the size of restricted zones could be rapidly reduced (or derogations could be made to allow animal movements) once it has been established that commercial farms within the zones are not involved; the impact on trade would be reduced. In the current situation, commercial enterprises are keen to see that outbreaks in backyard farms are dealt with rigorously and without delay in order to avoid long lasting restrictions themselves.

The ideal radius could be determined based on local farm density and the levels of biosecurity. Infection probabilities of neighboring premises can be ascertained for the main TADs and could be readily applied if the geographical location of each farm was established; in this case, the radius would be defined according to the local conditions under a specific strategy set at national/international level; without it, the 3 km radius remains an accepted simplification.

Economic consequences differ according to the production system. It has been estimated that zoning (the free area is defined by geography) would be the most cost-effective approach for small production systems, whereas compartmentalization (the free area is defined by husbandry practices related to biosecurity) would be better for large commercial farms, due to the extensive areas covered (29). The latter study focused mainly on live pig trade though, whereas the movements of live pigs is not the only transmission route for ASF.

Considering the numerous disease-specific interdependencies and the potential means of transmission (e.g., fomites), many ASF action plans have been tested throughout the world in the last decades. A study from 2016 (45) compared twenty surveillance strategies regarding ASF mitigation. The study highlighted the importance of disease-specific intervention strategies that need to be effective and practical. It concluded that the best surveillance strategies include pig mortality assessments at farm-level [defined as the use of observable mortality-related data before confirmed diagnoses are made (46)] and carcass assessment in relation to wild boar.

The contribution of wild boar regarding disease spread is widely accepted and acknowledged in various pieces of legislation worldwide. "Wild boar are a significant risk factor for disease transmission in general [...]. The presence of wild pigs is the most predictive risk estimate of disease spread" (23). In wild boar populations, ASFV can survive in the local population with a low prevalence below 5% and a transmission speed of 2–5 km/month (20). The low contagiousness of the virus is compensated for by its high tenacity (i.e., pork products, environment, etc.). Carcasses of ASF deceased wild boar allow the virus to persist for months or even years in a given area. It is estimated that the persistence of the virus in carcasses, and its spread through carcasses, is more important than direct contact with live infectious animals (23) when at low population density.

The main strategic aims of surveillance in domestic pigs are the early detection of potentially infected holdings and proof of freedom from the disease in a region/country after a disease event in order to lift restrictions. Surveillance is compulsory within protection and surveillance zones around outbreak holdings as well as in holdings located in areas that are under restrictions due to the presence of ASF in wild boar.

Nowadays, effective surveillance is mainly based on passive surveillance, targeting sick and deceased animals that are to be tested for the presence of ASF virus. The passive surveillance approach is based on the fact that ASF case fatality is often very high (>90%), signifying that almost all animals that pick up infection will become sick and die. The low contagiousness of ASF results in only few animals affected at the beginning of an infection in a given holding (21). Seropositive animals can be identified only during an advanced stage of an epidemic (28). As there is a very short time from infection to death [3–10 days (20)] and as the case-fatality rate is close to 100%, surviving, and thus ASF-seropositive animals, can hardly be found. Therefore, active surveillance based on random serological testing is no longer recommended in regards to the early detection of ASF. The EU diagnostic manual for ASF (which took into account the experience in the Iberian Peninsula and in Sardinia, where seropositive animals were very common) (30) still prescribes random blood sampling to determine antibody-positive domestic pigs. However, as shown in a recent EFSA report (28), serological surveillance would still not lead to early detection of disease.

ASF- legislation from Japan summarizes as follows: "African swine fever has a short course from infection to death, and most cases do not show elevated antibody titers, making serologic tests less useful as a diagnosis. For rapid diagnosis, genetic testing such as conventional PCR, which specifically detects the ASFV gene, is the most effective" (34). In terms of surveillance, the lengthy persistence of antibodies means that these can be found long after any viable virus has disappeared. In the absence of recent outbreaks, detected antibodies must not be understood to be a proof of "silent circulation" of the virus, although antibodies can be a valuable tool in endemic areas in particular toward the end of an epidemic; screening for antibodies can be a valuable tool for lifting restrictions.

Equally, in areas which are under restriction due to ASF in wild boar, it is recommended to conduct passive surveillance in domestic pig holdings and to sample a number of specified animals in each production unit (27).

The role of pigs surviving the disease continues to be controversially discussed. However, old (47) and new (48, 49) studies could not demonstrate that animals that survive the disease play a significant role in disease spread (50). Despite this fact, EU legislation does not differentiate between exclusively seropositive and PCR positive cases. For outbreaks in domestic pig farms, this is not relevant as the entire herd is culled after confirmation of disease but for the management of ASF in wild boar this remains a major concern. In some areas that experienced ASF during the past 5–6 years, all reported cases were limited to sero-positive, healthy hunted wild boar; such areas are therefore struggling with, one could argue, unjustified consequences such as trade restrictions (51).

ASF in mainland Europe is gradually changing: while serological tests are of limited importance in areas that have been recently affected, serology becomes an important additional tool that allows us to better understand how the disease spreads, and evolves, in areas where the virus is circulating or has been circulating for a long time. In Sardinia, serology remains a very important tool (6).

Many countries include compensation in the framework of their respective disease control measures (e.g., China, Russia). Compensation schemes vary, from full compensation (e.g., Japan, EU) to partial compensation (e.g., the USA). At best, adequate compensation payments will incentivize farmers to report suspicion of disease and may generally aid in matters of compliance relating to on-farm disease interventions by the responsible authorities. At worst, with little or no compensation, suspicion of disease may not be reported to the responsible authorities and instead farmers choose to hastily slaughter or sell their sick pigs at local markets, or dispose of carcasses illegally. Such circumstances have been recognized as a major cause of disease spread (35, 52, 53).

Conversely, overcompensation may lead to a situation where a farmer who expects to receive compensation in the event of a disease outbreak has weaker incentives to avoid risk during "peace times." This issue can be prevented if payments are made on the condition that farmers adhere to specific biosecurity practices (54). As far as possible, compensation schemes should be carefully reviewed and improved where necessary. Innovative compensation schemes could potentially reduce the costs of control measures due to early mitigation of an outbreak. Replacement of (core) breeding stock in lieu of direct financial compensation could be considered, especially for small farming enterprises.

Following the lifting of restrictions, the time after which restocking can be attempted, varies considerably according to the relevant legislation across the globe. It can range from 1 month in the case of Vietnam to 1 year in the case of Russia, or even 6 years for the EU if the outbreak has been linked to ticks. It is unrealistic to assume that a farming enterprise will be able to hold out financially for years until restocking can take place, hence in practice this is neither affordable nor a realistic approach.

Regarding disease eradication measures, progressive legislation will take into account farming practices at the opposite ends of the spectrum, namely commercial farm enterprises and backyard farm systems. Biosecurity measures that warrant compliance were based on modern farm enterprises and cannot be readily transferred onto, or realized on, traditional backyard settings. Measures imposed on backyard farms that cannot be realized due to cost or the given farm infrastructure, may lead to compliance fatigue; farmers may abandon traditional farming practices altogether, potentially leading to the loss of rare breeds and the loss of cultural identities of many nations.

When dealing with small non-commercial producers the EU Directive for the control of avian influenza, for example, considers different measures to those employed on large commercial enterprises (55). Although highly pathogenic avian influenza is considered highly contagious (as opposed to ASF), there are a number of derogations for non-commercial holdings where animals are kept either as pets or for own consumption. Derogations exist also for culling, establishment of protection and surveillance zones, visits by the official veterinarian and surveillance. Such derogations aid the official veterinarian when dealing with non-commercial holdings and could be adapted to the situation of ASF in the backyard sector.

ASFV is a very complex virus and our understanding continues to evolve in parallel with its current, unprecedented spread. We are not yet in a situation to draw conclusions on a single, "worldwide valid" disease control strategy and the legislation that requires its control and eradication. Strategies based on farming systems would provide the flexibility that a global and rigid disease control strategy cannot offer.

In Sardinia, an ASF scenario emerged that largely differed from the one in mainland Europe: free ranging pigs represented the main ASF reservoir whilst infection in wild boar played merely an ancillary role (6, 56). This specific disease scenario may be in large part due to the long evolution of ASFV, over four decades, where a large proportion of affected animals (at least free-ranging pigs and wild boar) survive the disease (6). Accordingly, a disease control strategy was implemented by the local authorities in recent years that targeted illegally kept free ranging pigs (where virus prevalence was never higher than 2–3%, while sero-prevalence reached 70%). This led also to a major, rapid drop of virus circulation in wild boar and confirms that in the Sardinian scenario wild boar merely play(ed) an ancillary role in disease transmission.

CONCLUSIONS

- Based on the spirit of the new EU Animal Health Law, future legislation should take into consideration the disease-relevant characteristics of a biological agent, biology of disease and its epidemiological profile as well as specific pig husbandry traditions. Animal Health related legislation, policies and strategies should be revised in cases where gained scientific knowledge can improve disease control, leading to continued evidence-based policymaking.
- Detailed epidemiological farm investigations, combined with a surveillance scheme based on enhanced passive surveillance must be implemented. Epidemiological tracing of contact farms is of paramount importance in order to identify sources of infection as early as possible and to interrupt the spread of the disease.
- Holdings located outside a restricted area, but linked through human activity to an infected farm, can constitute a higher risk than holdings that implement good biosecurity within a protection or surveillance zone. In this context, a review of the size of restriction zones and studies that evaluate the effectiveness of a given surveillance zone (i.e., 10 km) in relation to the prevention of ASF could be of value.
- Taking into account the relatively low contagiousness of ASF and its relatively slow spread, smaller zones (<3 km) could be considered for outbreaks in domestic commercial pig holdings

whilst focusing efforts on epidemiological tracing to detect potential contact farms.
- Effective surveillance for early detection of ASF infection should focus on virus detection and differentiate between exclusively seropositive and virus positive animals especially in the wild boar context.
- Alternative culling schemes for large farms, at which only few infected animals have been detected at an early stage, should be developed. Good managerial and strict internal biosecurity measures as well as intelligent farm surveillance schemes would pave the way for reaching this goal. Early detection remains a key priority.
- When dealing with non-commercial holdings, derogations for smallholders should be considered in order not to put traditional self-sustaining agriculture at a disadvantage and to ensure survival of these traditional farming methods that express the cultural identity of many countries—and that contribute to conserving genetic resources through the keeping of rare and traditional breeds.
- Global trade could suffer fewer interruptions if legislation, in line with OIE standards, considered the zoning principle; this would not prohibit all imports from the whole of a country but only from its well-defined infected areas, in case of a localized outbreak.

AUTHOR CONTRIBUTIONS

FB and KDe conceptualized and designed the overall study. CH and FB collected and analyzed the data. FB drafted the manuscript. CH, M-LP, AL, KDi, AG, VG and LZ edited the manuscript. All authors contributed to the article and approved the submitted version.

ACKNOWLEDGMENTS

We thank Dr. Amy Snow (National Manager of the Foreign Animal Disease Section for the Canadian Food Inspection Agency), Dr. Pawin Padungtod (Senior Technical Coordinator at FAO, country office for Vietnam) and Dr. Qizu Zhao (Director of Department of Reference Substance Research, China Institute of Veterinary Drug Control) for providing legislation that supported our work. The authors would also like to thank the three reviewers that have enabled the authors to improve the manuscript through their constructive criticism.

REFERENCES

1. Olsevskis E, Guberti V, Serzants M, Westergaard J, Gallardo C, Rodze I, et al. African swine fever virus introduction into the EU in 2014: experience of latvia. *Res Vet Sci.* (2016) 105:28–30. doi: 10.1016/j.rvsc.2016.01.006
2. Vergne T, Korennoy F, Combelles L, Gogin A, Pfeiffer DU. Modelling African swine fever presence and reported abundance in the Russian Federation using national surveillance data from 2007 to 2014. *Spat Spatiotemporal Epidemiol.* (2016) 19:70–7. doi: 10.1016/j.sste.2016.06.002
3. Guinat C, Gogin A, Blome S, Keil G, Pollin R, Pfeiffer DU, et al. Transmission routes of African swine fever virus to domestic pigs: current knowledge and future research directions. *Vet Rec.* (2016) 178:262–7. doi: 10.1136/vr.103593
4. Dixon LK, Stahl K, Jori F, Vial L, Pfeiffer DU. African swine fever epidemiology and control. *Annu Rev Anim Biosci.* (2020) 8:221–46. doi: 10.1146/annurev-animal-021419-083741
5. Zani L, Dietze K, Dimova Z, Forth JH, Denev D, Depner K, et al. African swine fever in a Bulgarian backyard farm-a case report. *Vet Sci.* (2019) 6:94. doi: 10.3390/vetsci6040094
6. Franzoni G, Dei Giudici S, Loi F, Sanna D, Floris M, Fiori M, et al. African swine fever circulation among free-ranging pigs in sardinia: data from the eradication program. *Vaccines (Basel).* (2020) 8:549. doi: 10.3390/vaccines8030549
7. Lamberga K, Olševskis E, SerŽants M, Bērzinš A, Viltrop A, Depner K. African swine fever in two large commercial pig farms in LATVIA-estimation of the high risk period and virus spread within the farm. *Vet Sci.* (2020) 7:105. doi: 10.3390/vetsci7030105
8. USDA. *The Foreign Animal Disease Preparedness and Response Plan (FAD PReP)—African Swine Fever Response Plan: The Red Book*. (2020). Available online at: https://www.aphis.usda.gov/animal_health/emergency_management/downloads/asf-responseplan.pdf (accessed January 13, 2021).
9. Animal Health Australia. *Disease Strategy: African Swine Fever Version 4.1. Australian Veterinary Emergency Plan (AUSVETPLAN)*. Edition 4, National Biosecurity Committee, Canberra, ACT (2016). Available online at: https://www.animalhealthaustralia.com.au/our-publications/ausvetplan-manuals-and-documents/ (accessed April 2, 2020).
10. Ministry's General Directorate of Veterinary Medicine and Agriculture of the USSR. *Warning Instruction and Elimination of the African Swine Fever*—ИНСТРУКЦИЯО МЕРОПРИЯТИЯХ ПО ПРЕДУПРЕЖДЕНИЮ И ЛИКВИДАЦИИ АФРИКАНСКОЙ ЧУМЫ СВИНЕЙ (1980). Available online at: https://www.fsvps.gov.ru/fsvps-docs/ru/laws/rules/asf.pdf (accessed October 29, 2020).
11. Ministry of Agriculture and Rural Affairs of China. *Emergency Implementation Plan for African Swine Fever Epidemic*—农业农村部关于印发《非洲猪瘟疫情应急实施 方案（2020年版）》的通知(2020). Available online at: http://www.gov.cn/zhengce/zhengceku/2020-03/02/content_5485530.htm (accessed April 22, 2020).
12. Ministry of Agriculture and Rural Development of Vietnam. *National Plan on the Prevention and Control of African Swine Fever for the Period 2020-2025*. (2020). Available online at: https://www.mard.gov.vn/en/Pages/default.aspx (accessed May 04, 2020).
13. Department of Agriculture Forestry and Fisheries of South Africa. *Veterinary Procedural Notice for African Swine Fever Control in South Africa*. (2018). Available online at: https://www.nda.agric.za/vetweb/pamphletsandInformation/Policy/DRAFT%20African%20Swine%20Fever%20VPN%20for%20consultation%202018-05.pdf (accessed April 06, 2020).
14. Janse van Rensburg L, Penrith ML, van Heerden J, Heath L, Etter Eric MC. Investigation into eradication of African swine fever in domestic pigs from a previous outbreak (2016/17) area of South Africa. *Res Vet Sci.* (2020) 133:42–7. doi: 10.1016/j.rvsc.2020.08.013
15. Janse van Rensburg L, Van Heerden J, Penrith ML, Heath LE, Rametse T, Etter EMC. Investigation of African swine fever outbreaks in pigs outside the controlled areas of South Africa, 2012-2017. *J S Afr Vet Assoc.* (2020) 91:e1–9. doi: 10.4102/jsava.v91i0.1997
16. Department of Agriculture Forestry and Fisheries of South Africa. *Standards for the Registration of a Veterinary Approved Pig Compartment. Veterinary Procedural Notice VPN/39/2011-01*. (2011). Available online at: https://www.nda.agric.za/vetweb/VPN%20and%20SOP/VPN-39-2011-01%20Pig%20compartments.pdf.pdf (accessed October 15, 2020).
17. Maja M, Janse van Rensburg L, Gerstenberg C. Compartmentalisation: an example of a national official insurance system. *Rev Sci Tech.* (2020) 39:213–21. doi: 10.20506/rst.39.1.3074

18. FAO, AU-IBAR, ILRI, Food and Agriculture Organization of the United Nations and African Union—Interafrican Bureau for Animal Resources and International Livestock Research Institute. *Regional Strategy for the Control of African Swine Fever in Africa*. FAO (2017). Available online at: http://www.fao.org/3/a-i6053e.pdf (accessed April 06, 2020).
19. OIE, World Organisation for Animal Health. *African Swine Fever*. (2018). Available online at: https://www.oie.int/en/animal-health-in-the-world/animal-diseases/african-swine-fever/ (accessed December 1, 20).
20. Chenais E, Depner K, Guberti V, Dietze K, Viltrop A, Ståhl K. Epidemiological considerations on African swine fever in Europe 2014-2018. *Porcine Health Management.* (2019) 5:6. doi: 10.1186/s40813-018-0109-2
21. Schulz K, Conraths FJ, Blome S, Staubach C, Sauter-Louis C. African swine fever: fast and furious or slow and steady? *Viruses*. (2019) 11:866. doi: 10.3390/v11090866
22. Depner K, Staubach C, Probst C, Globig A, Blome S, Dietze K, et al. *Die Afrikanische Schweinepest - Epidemiologische Betrachtungen Und Konsequenzen Für Die Tierseuchenbekämpfung*. (2016). Available online at: https://www.openagrar.de/receive/openagrar_mods_00019749
23. Canadian Food Inspection Agency. *African Swine Fever Hazard: Specific Plan RDIMS # 11112464*. (2018). Available online at: https://www.inspection.gc.ca/animal-health/terrestrial-animals/diseases/reportable/african-swine-fever/reducing-$\sim$risk/eng/1556035111040/1556035111309 (accessed April 13, 2020).
24. Council of the European Union. *Council Directive 2001/89/EC of 23 October 2001 on Community Measures for the Control of Classical Swine Fever. Official Journal of the European Communities, L316/5* (2001/89/EC). Available online at: https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=celex%3A32001L0089 (accessed April 13, 2020).
25. Council of the European Union. *Council Directive 2002/60/EC of 27 June 2002 Laying Down Specific Provisions for the Control of African Swine Fever and Amending Directive 92/119/EEC as Regards Teschen Disease and African Swine Fever. Official Journal of the European Communities, L192/27* (2002/60/EC). Available online at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32002L0060 (accessed April 13, 2020).
26. Lamberga K, SerŽants M, Olševskis E. African swine fever outbreak investigations in a large commercial pig farm in Latvia: a case report. *Berliner und Münchener Tierärztliche Wochenschrift.* (2018) 131. doi: 10.2376/0005-9366-18031
27. European Commission. *Working Document: Strategic Approach to the Management of African Swine Fever for the EU*. SANTE/7113/2015 Rev 12 (2020). Available online at: https://ec.europa.eu/food/sites/food/files/animals/docs/ad_control-measures_asf_wrk-doc-sante-2015-7113.pdf (accessed October 05, 2020).
28. Nielsen SS, Alvarez J, Bicout DJ, Calistri P, Depner K, Drewe JA, et al. Scientific opinion on the assessment of the control measures of the category a diseases of animal health law: African swine fever. *EFSA J.* (2021) 19:e06402. doi: 10.2903/j.efsa.2021.6402
29. Relun A, Grosbois V, Sánchez-Vizcaíno JM, Alexandrov T, Feliziani F, Waret-Szkuta A, et al. Spatial and functional organization of pig trade in different European production systems: implications for disease prevention and control. *Front Vet Sci*. (2016) 3:4. doi: 10.3389/fvets.2016.00004
30. The Commission of the European Communities. *Commission Decision of 26 May 2003 approving an African swine fever diagnostic manual (2003/422/EC). Official Journal of the European Union, L143/35* (2003/422/EC). Available online at: https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX%3A32003D0422 (accessed April 10, 20).
31. Magadla NR, Vosloo W, Heath L, Gummow B. The African swine fever control zone in South Africa and its current relevance. *Onderstepoort J Vet Res.* (2016) 83:a1034. doi: 10.4102/ojvr.v83i1.1034
32. Gervasi V, Marcon A, Bellini S, Guberti V. Evaluation of the efficiency of active and passive surveillance in the detection of African swine fever in wild boar. *Vet Sci.* (2019) 7:5. doi: 10.3390/vetsci7010005
33. Légifrance. Arrêté Du 17 Mars 2004 Fixant Diverses Mesures Financières Relatives à La Lutte Contre Les Pestes Porcines. *Journal Officiel Lois et Décrets*. (2004) 77:81.
34. Ministry of Agriculture Forestry and Fisheries of Japan. *Guidelines for Control of Specific Domestic Animal Infectious Diseases Concerning African Swine Fever—*アフリカ豚にする特定家畜染病防疫指 令和２年２月５日 林水大臣公 表(2019). Available online at: https://www.maff.go.jp/j/syouan/douei/katiku_yobo/k_bousi/attach/pdf/index-32.pdf (accessed May 04, 2020).
35. Brown VR, Bevins SN. A review of african swine fever and the potential for introduction into the United States and the possibility of subsequent establishment in feral swine and native ticks. *Front Vet Sci.* (2018) 5:11. doi: 10.3389/fvets.2018.00011
36. Council and Parliament of the European Union. *Regulation (EU) 2016/429 of the European Parliament and of the Council of 9 March 2016 on Transmissible Animal Diseases and Amending and Repealing Certain Acts in the Area of Animal Health ('Animal Health Law') Article 57. Official Journal of the European Communities, L84/1*. (2016). Available online at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.L_.2016.084.01.0001.01.ENG (accessed October 29, 2020).
37. Nurmoja I, Motus K, Kristian M, Niine T, Schulz K, Depner K, et al. Epidemiological analysis of the 2015-2017 African swine fever outbreaks in Estonia. *Prev Vet Med.* (2020) 181:104556. doi: 10.1016/j.prevetmed.2018.10.001
38. Oganesyan AS, Petrova ON, Korennoy FI, Bardina NS, Gogin AE, Dudnikov, et al. African swine fever in the Russian federation: spatio-temporal analysis and epidemiological overview. *Virus Res*. (2013) 173:204–11. doi: 10.1016/j.virusres,.2012.12.009
39. Meuwissen MP, Horst SH, Huirne RB, Dijkhuizen AA. A model to estimate the financial consequences of classical swine fever outbreaks: principles and outcomes. *Prev Vet Med.* (1999) 42:249–70. doi: 10.1016/S0167-5877(99)00079-3
40. Rubira R. Disease control options for emergency animal diseases–necessary yet sensitive elimination of disease. *Vet Ital.* (2007) 43:333–48.
41. Boklund A, Dhollander S, Chesnoiu Vasile T, Abrahantes JC, Bøtner A, Gogin A, et al. Risk factors for African swine fever incursion in Romanian domestic farms during 2019. *Sci Rep.* (2020) 10:10215. doi: 10.1038/s41598-020-66381-3
42. Scott A, Zepeda C, Garber L, Smith J, Swayne D, Rhorer A, et al. The concept of compartmentalisation. *Rev Sci Tech.* (2006) 25:873–9, 881–77, 889–5. doi: 10.20506/rst.25.3.1702
43. Roth JA. Potential to export fresh pork in the event of an African swine fever outbreak in the United States. *J Swine Health Prod*. (2020) 28:31–3.
44. Gemmeke EA, Batho H, Bonbon E, de Leeuw PW, Bruschke C. Compartmentalisation and zoning: the Dutch perspective. *Rev Sci Tech.* (2008) 27:679. doi: 10.20506/rst.27.3.1830688
45. Guinat C, Vergne T, Jurado-Diaz C, Sanchez-Vizcaino JM, Dixon L, Pfeiffer DU. Effectiveness and practicality of control strategies for African swine fever: what do we really know? *Vet Rec.* (2017) 180:97. doi: 10.1136/vr.103992
46. Hope K, Durrheim DN, d'Espaignet ET, Dalton C. Syndromic surveillance: is it a useful tool for local outbreak detection? *J Epidemiol Community Health.* (2006) 60:374–375. doi: 10.1136/jech.2005.035337
47. Hamdy FM, Dardiri AH. Clinical and immunologic responses of pigs to African swine fever virus isolated from the Western Hemisphere. *Am J Vet Res.* (1984) 45:711–4.
48. Gallardo C, Soler A, Nieto R, Sanchez MA, Martins C, Pelayo V, et al. Experimental transmission of African swine fever (ASF) low virulent isolate NH/P68 by surviving pigs. *Transbound Emerg Dis.* (2015) 62:612–22. doi: 10.1111/tbed.12431
49. Petrov A, Forth JH, Zani L, Beer M, Blome S. No evidence for long-term carrier status of pigs after African swine fever virus infection. *Transbound Emerg Dis*. (2018) 65:1318–28. doi: 10.1111/tbed.12881
50. Ståhl K, Sternberg-Lewerin S, Blome S, Viltrop A, Penrith ML, Chenais E. Lack of evidence for long term carriers of African swine fever virus—a systematic review. *Virus Res.* (2019) 272:197725. doi: 10.1016/j.virusres.2019.197725
51. Schulz K, Staubach C, Blome S, Nurmoja I, Viltrop A, Conraths FJ, et al. How to demonstrate freedom from African swine fever in wild boar-estonia as an example. *Vaccines (Basel).* (2020) 8:336. doi: 10.3390/vaccines8020336
52. Fasina FO, Shamaki D, Makinde AA, Lombin LH, Lazarus DD, Rufai SA, et al. Surveillance for African swine fever in Nigeria, 2006-2009. *Transbound Emerg Dis.* (2010) 57:244–53. doi: 10.1111/j.1865-1682.2010.01142.x

53. Lichoti JK, Davies J, Kitala PM, Githigia SM, Okoth E, Maru Y, et al. Social network analysis provides insights into African swine fever epidemiology. *Prev Vet Med.* (2016) 126:1–10. doi: 10.1016/j.prevetmed.2016.01.019
54. OECD. *Producer Incentives in Livestock Disease Management*. Paris: OECD Publishing (2017).
55. Bruschke CJ, Pittman M, Laddomada A. International regulations and standards for avian influenza, including the vaccine standards of the World Organisation for Animal Health. *Rev Sci Tech.* (2009) 28:379–89. doi: 10.20506/rst.28.1.1852
56. Loi F, Cappai S, Laddomada A, Feliziani F, Oggiano A, Franzoni G, et al. Mathematical approach to estimating the main epidemiological parameters of African swine fever in wild boar. *Vaccines (Basel).* (2020) 8:521. doi: 10.3390/vaccines8030521

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

The reviewer KS declared a past co-authorship with the authors M-LP, KD, VG to the handling editor.

Copyright © 2021 Busch, Haumont, Penrith, Laddomada, Dietze, Globig, Guberti, Zani and Depner. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.

frontiers in Veterinary Science

ORIGINAL RESEARCH
published: 21 June 2021
doi: 10.3389/fvets.2021.672048

Use of Field Based Loop Mediated Isothermal Amplification (LAMP) Technology for a Prevalence Survey and Proof of Freedom Survey for African Swine Fever in Timor-Leste in 2019

Dianne E. Phillips*[1]*, Peter T. Mee*[2]*, Stacey E. Lynch*[2]*, Felisiano da Conceição*[3]*, Joanita Bendita da Costa Jong*[3] *and Grant T. Rawlin*[2]

[1] Agriculture Victoria, Biosecurity and Agriculture Services, Bairnsdale, VIC, Australia, [2] Agriculture Victoria Research, AgriBio Centre for AgriBioscience, Bundoora, VIC, Australia, [3] Ministry of Agriculture and Fisheries, Government of Timor-Leste, Dili, Timor-Leste

OPEN ACCESS

Edited by:
Klaus Depner,
Friedrich-Loeffler-Institute, Germany

Reviewed by:
Laura Zani,
Friedrich Loeffler Institute, Germany
Caitlin Nicole Pfeiffer,
The University of Melbourne, Australia

****Correspondence:***
Grant T. Rawlin
grant.rawlin@agriculture.vic.gov.au

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

Received: *25 February 2021*
Accepted: *14 April 2021*
Published: *21 June 2021*

Citation:
Phillips DE, Mee PT, Lynch SE, da Conceição F, Bendita da Costa Jong J and Rawlin GT (2021) Use of Field Based Loop Mediated Isothermal Amplification (LAMP) Technology for a Prevalence Survey and Proof of Freedom Survey for African Swine Fever in Timor-Leste in 2019. Front. Vet. Sci. 8:672048. doi: 10.3389/fvets.2021.672048

African Swine Fever (ASF) has been spreading in numerous southeast Asian countries since a major incursion in mainland China in 2018. Timor-Leste confirmed an outbreak of ASF in September 2019 which resulted in high mortalities in affected pigs. Pigs in Timor-Leste are the second most common type of livestock kept by villagers and represent a traditionally important source of income and prestige for householders. In order to understand the extent of ASF infected villages in Timor-Leste a prevalence survey was designed and conducted in November-December 2019. Timor-Leste has limited laboratory facilities and access to qPCR diagnostic tests. Therefore, a loop mediated isothermal amplification (LAMP) assay was used to detect ASF positive blood samples collected during the prevalence survey. The LAMP assay was proven to be a robust, highly specific and sensitive laboratory test for ASF suitable for use in the field and where there are limited laboratory facilities. The results of the prevalence survey allowed the extent of the ASF incursion to be delineated and the introduction of a disease response strategy to limit the spread of ASF and assist in the recovery of the pig population in Timor-Leste.

Keywords: pigs, African swine fever, LAMP, prevalence, Timor-Leste

INTRODUCTION

African swine fever in pigs, caused by African swine fever virus (ASFV), has been spreading through countries in southeast Asia since a major incursion in mainland China in August 2018 (1). During the reporting period from late June-early July 2020 11 Asian countries reported new or ongoing ASF outbreaks to the World Organization for Animal Health, formerly the Office International des Epizooties (OIE), with losses of 16,894 pigs (2). ASFV is the only member of the genus *Asfivirus* family *Asfarviridae* and current outbreaks have resulted in high mortalities of 80–100% in affected pig herds (3). Transport of infected pigs is a common route of disease transmission. However, the virus is also able to survive for extended periods in infected carcasses, uncooked meat products and environments or equipment contaminated by infective material, resulting in disease transmission and new incursions across much greater distances, including across international boundaries (1, 3).

Pigs in Timor-Leste are the second most common type of livestock kept by villagers in Timor-Leste. Numbers per holding are typically small (usually 1–4) and most commonly < 10 animals (4, 5). They are an important source of income and prestige for villagers and are used and traded in traditional celebrations and other gatherings and exchanges (4). The species of pigs kept is typically the Timorese Warty Pig (*Sus celebensis timoriensis*) rather than the European species *Sus scrofula*. The impact of the mortalities associated with an uncontrolled ASF incursion is high in traditional villages, as there is frequently no ready source of alternative incomes and/or industry support (4, 6, 7).

Timor-Leste reported its first incursion of ASF to the OIE in late September 2019, after samples collected from sick and dead pigs around Dili were transported to the Australian Animal Health Laboratory in Geelong, Australia, where they tested positive to ASFV using real time PCR (8). The initial outbreak information consisted of reports of 100 small holder outbreaks resulting in 405 dead pigs around Dili, and unconfirmed reports of pig deaths in two other northern municipalities, Baucau and Liquicia. A survey of animal health staff in all Timor-Leste municipalities undertaken by Food and Agriculture Organization of the United Nations (FAO) during Oct and November also reported 21,155 dead pigs and 7,335 sick pigs (unpublished data).

OIE notes in its recommended measures for an ASF outbreak that control of ASF can be difficult and must be adapted to the specific epidemiological situation (3). The classic stamping out and eradication response used in countries such as Australia (9) may not be practical or implementable due to epidemiological and societal factors, logistical, technical and financial limitations. In particular, diagnostic capacity must be considered, given that several other diseases of pigs are endemic in Timor-Leste, including Classical Swine Fever, that cannot be differentiated from ASFV on clinical signs (1, 3). In this outbreak, it was unclear what proportion of the FAO survey results were attributable to ASFV. Timor-Leste has limited laboratory facilities and staff and at the time of the ASF incursion, did not include any diagnostic tests for ASF or CSF. In addition, once ASF was confirmed in the country, quarantine restrictions made it very difficult for Timor-Leste to send any more diagnostic samples to an animal health laboratory in another country such as Australia.

In order to decide on an appropriate response to the ASF outbreak, a project team from Australia worked with the Timor-Leste animal health services to deliver a number of outputs. A disease prevalence survey was designed to delineate the extent of the incursion on the mainland. Secondly, where there were areas that may have been free of disease a proof of freedom study was undertaken. Given preliminary disease reports were primarily from coastal areas on the mainland, the team hypothesized that two outlying areas may still be free of ASF: the municipality of Oecusse [embedded within West Timor, which at that point had not recorded any cases of ASF (10)] and Atauro Island some 25 km north of the mainland coastline, near Dili (see **Figure 1**). Atauro Island has fewer opportunities for disease spread, however it is serviced by a ferry and charter boats from Dili and a ferry from Oecusse. Pigs are transported on ferries in both directions. Since the ASF outbreak there had been limited reports of sudden deaths in pigs on the island and, if proven to be free of ASF, the island could serve as an important source of ASF free pigs for future breeding.

Finally, the project team sought to verify whether the use of LAMP technology would prove a suitable method of laboratory diagnosis in the ASF outbreak within Timor-Leste. After training was provided to the Timor-Leste animal health laboratory staff, samples from ASFV infected pigs to were tested using an ASFV specific, loop mediated isothermal amplification (LAMP) assay for the rapid diagnosis of ASF in the field or in basic laboratory facilities. The incorporation of a fit for purpose laboratory test, especially where multiple disease etiologies are present and indistinguishable at a clinical or gross pathology level, is also an essential step planning an emergency animal disease response (3). In countries where animal health laboratories have limited resources and skilled personnel, the use of a LAMP assay presents a viable alternative, or addition to existing recognized laboratory tests (11, 12).

MATERIALS AND METHODS

Mainland Prevalence Survey

Pigs are largely farmed in at a subsistence level in most of Timor-Leste, including rural villages and peri-urban households. Most families in a village own a few pigs and the pigs are held in small pens or tethered near village houses. Biosecurity practices are limited with regards to use of personal protective equipment for pig owners and cleaning and disinfection of equipment used to house and feed pigs. Feed sources for pigs commonly include leftover food from households and/or pigs are allowed to free range in the village where they can access food scraps and/or rubbish (4, 6). Therefore, it was considered probable that if a pig in a village became infected with ASFV it was likely that multiple pigs within the village would become infected in a short period of time and that a village with ASFV infected pigs represented a suitable unit of interest for the prevalence survey design.

Timor-Leste conducts a population and livestock census every 5 years and the results of the census from 2015 were used in planning the prevalence survey (5). Using Epitools Sample size to estimate a simple proportion (apparent prevalence) online calculator (13) and the following assumptions:

1. Assumed prevalence of ASF 0.1.
2. Desired type I error = 0.05.
3. Desired type II error = 0.05.
4. Source population 422 (all villages in Timor-Leste except Atauro Island and Oecusse).

The number of villages to be sampled was calculated to be 35 (modified hypergeometric exact calculation). Using the census village data, the sample number was proportionally distributed according to the number of villages in each municipality. Random villages were selected for sampling using a random

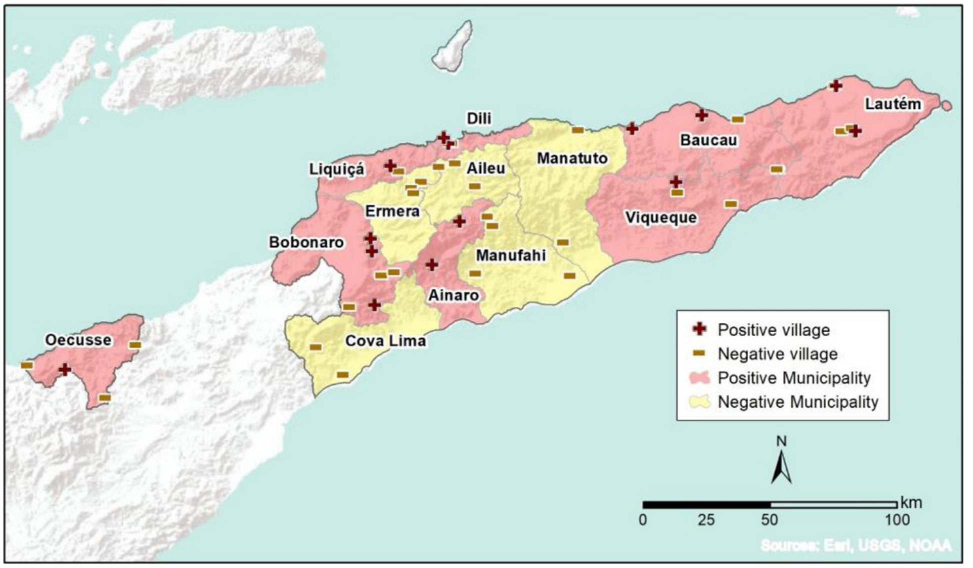


FIGURE 1 | Map of mainland prevalence survey results.

number generator across each municipal village sampling frame. If the selected village was not logistically possible to sample, the next village within a 10 km radius of the original village was selected (**Table 1**).

Epitools online calculator (14) was used to calculate the true disease prevalence at a village level. Assumptions for the calculation were the LAMP test sensitivity (Se) 0.98 and test specificity (Sp) 0.999 (15) and a confidence level of 0.95. The calculation tool recommends the use of Blaker's interval for confidence levels for general use.

Proof of Freedom Sample Design for Atauro Island

The following assumptions were used to calculate a sample size for proof of freedom from ASF on Atauro Island:

1. Population size = 5,000 (5).
2. Test Sensitivity = 0.98 (based on preliminary unpublished LAMP test data).
3. Test Specificity = 0.999 (based on preliminary unpublished LAMP test data).
4. Design prevalence to detect disease at $P = 0.1$.
5. Desired type I error = 0.05.
6. Desired type II error = 0.05.

Using Epitools 1-stage freedom analysis (16) and a modified hypergeometric calculation, the number of random samples required is 29. (If a random sample of 29 units is taken from a population of 5,000 and 0 or fewer reactors are found, the probability that the population is diseased at a prevalence of 0.1, $p = 0.05$).

Epitools online calculator for a 1-Stage Freedom Analysis was used to analyze the test results (16).

Proof of Freedom Survey for Oecusse Municipality

In the interval between planning and collection of samples (December 2019), Indonesia reported its first cases of ASF (17) and instead of conducting a proof of freedom survey for the municipality of Oecusse, it was considered to be likely to at high risk, or already have ASF infection as it is surrounded by land borders with Indonesia. This municipality was subsequently included in the mainland prevalence survey instead.

Village Sampling Visits

Within each village, three households with pigs were visited. Those with sick or recently dead pigs were targeted and up to 5 pigs per household were examined and sampled. If more than 5 pigs were present in a household, pigs were selected if there was a history of ill health, or clinical signs of poor condition, or a selection of pigs to cover ages and different pens was used. Pigs were restrained manually or using a pig snare and a cranial vena cava blood sample was collected in two plain blood tubes. Where possible, the pigs' rectal temperature was recorded and if the owner reported the pig was sick, or it had an elevated temperature, an oral and rectal swab was collected as well. For each household where pigs were sampled, the number of pigs at risk, sick pigs and dead pigs within the last month was recorded.

Analysis of the association between the presence of pyrexia (Pigs with rectal temperatures of 40.0C or higher) and a positive LAMP ASF test was conducted using a 2 × 2 risk table and Epitools online calculator incorporating a 95% confidence level and a Fisher's exact test (2-tailed) (18).

The pig samples were stored in a car fridge at 4C until they could be tested using the ASFV LAMP assay, either in the field or at the animal health laboratory in Dili. The time frame from

TABLE 1 | Timor-Leste municipalities and randomly selected villages for mainland ASFV prevalence survey.

Municipality	Number of villages in municipality	Proportional adjusted number of villages to sample	Random number selected village for sampling
Aileu	32	3	Fatisi Liquidoe Madabeno
Ainaro	21	2	Ainaro Maubisse
Baucau	60	5	Lasula Tequinomata Laisorolai Lour Betalale
Bobonaro	50	4	Bobonaro Caribau Guda Lebos
Covalima	30	2	Lactos Maudemu
Dili	26	2	Comoro Vila Verde
Ermera	52	4	Laclo Tiarlelo Talimoro Letefoho
Lautem	34	3	Euquisi Parlamento Raça
Liquicia	23	2	Leorema Metagou
Manatuto	29	2	Manehat Ma'Abat
Manufahi	29	2	Beremana Caimau
Viqueque	36	3	Ossu Afaloicai Bahatata
Total	422	35	35

pen side collection to LAMP testing varied from a few hours to 2–3 days.

Disinfection of personnel and equipment was undertaken between each village.

Preparation of Samples and the ASFV LAMP Assay

Serum was separated from blood by centrifuging for 20 min at 3,000 g. Serum was removed from the tubes and tested straight away or stored at −20°C until testing. Samples were tested for ASFV using an ASFV LAMP assay (15). Briefly, serum was diluted 1 in 10 in nuclease-free water before 2 μL of each sample was heat treated at 95°C for 2 min. LAMP reactions were setup with 15 μL of Isothermal Mastermix ISO-DR004-DT (OptiGene Ltd., Horsham UK), 2.5 μL of primer mix targeting the topoisomerase II gene (19) with a final primer concentration of F3/B3 0.2 μM, FIP/BIP 1.6 μM and loop primers at 0.8 μM and reaction made up to 25 μL with nuclease-free water. Reactions were run on a Genie III (OptiGene, Horsham, UK), instrument with run conditions of 65°C for 25 min. Each run included a synthetic positive control as well as a no template control. A sample was classified positive if the time to positivity (T_p) < 20 min and had an annealing temperature (T_a) of 87.42°C (± 0.56°C).

RESULTS

Mainland Prevalence Survey

Field teams collected 449 samples from 48 villages over a 3-month period from to late September 2019 to mid-December 2019. Of these 13 samples that were collected were not able to be tested due to issues relating to transport or storage or transcription errors in laboratory recording and were removed from the data set.

Of the remaining 436 samples, 59 samples tested positive to ASFV using LAMP and 377 samples were negative. There was ASFV detected in 16 villages within 8 municipalities. Across the remaining five municipalities ASFV was not detected in any of the 32 villages sampled. The distribution of positive and negative villages is shown in **Table 2** and the map in **Figure 1**.

Additional villages (above the number specified in the design survey) arose either through additional sampling undertaken by field staff in response to reports from local animal health staff of recent deaths or illness in village pigs or with the inclusion of ASF samples already collected in the initial months of the outbreak which were retested in using the LAMP machine and protocol and were included to improve the accuracy of the prevalence survey.

The 16 test-positive villages, adjusted for the assumed accuracy of the LAMP assay (Se = 0.98, Sp = 0.999) gave a village-level true prevalence of 16/48 = 34% (95% CI 22–48%).

Not all pig samples were accompanied by clinical records and where records were submitted, not all fields were completed. The distribution of age and gender of pigs sampled, and ASF test results are summarized in **Figures 2**, **3**.

There were 284 records which included the rectal temperature of the pig at the point of sampling. The distribution curve of body temperature recordings was approximately normal (not shown). The incidence risk ratio for a positive LAMP test given pyrexia (**Table 3**) was 5.67 (95% confidence interval 1.85–17.42, $p = 0.01$).

Atauro Island Proof of Freedom Survey

East Timor and Agriculture Victoria staff completed the collection of 33 random samples from pigs in several villages on the island from 7 to 8 November 2019 (**Figure 4**). A mixture of inland and coastal villages was sampled, and within villages, pigs to be sampled were organized by the local animal health staff with a bias toward recently sick pigs.

TABLE 2 | Results of pig samples tested for mainland prevalence survey.

Municipality	District	Village	Number of pigs tested	Number of pigs positive ASF	Village ASF status (N = negative, P = positive)
Aileu	Aileu Vila	Fatisi	7	0	N
		Madabeno	7	0	N
	Lequidoe	Liquidoe	6	0	N
Ainaro	Ainaro	Ainaro Vila	7	2	P
	Maubesi	Maubesi Vila	7	1	P
Baucau	Vemasse	Caicua	25	4	P
		Vemasse Tasi	17	7	P
	Baguia	Larisula	10	0	N
	Laga	Tequinomata	10	0	N
	Quelecai	Laisorulai	6	0	N
		Laisorulai de Baixo	4	0	N
Bobonaro	Cailaco	Meligo	10	2	P
		Goulolo	10	7	P
		Manapa	7	6	P
		Atudara	13	2	P
	Bobonaro	Bobonaro	10	0	N
		Caribau	10	0	N
	Lolotoe	Guda	7	1	P
		Lebos	10	0	N
Covalima	Tilomar	Maudemo	10	0	N
	Fohorem	Laktos	11	0	N
Dili	Dili	Beto, Becora, Bidau, Bebonuk	35	14	P
	Vera Cruz	Vila Verde	6	0	N
	Dom Alexio	Comoro	8	2	P
Ermera	Ermera	Kokoa	7	0	N
		Talimoro	12	0	N
		Eraulu	6	0	N
		Haufu	8	0	N
Lautem	Lospalos	Fuiloro	8	0	N
		Rasa	8	3	P
		Souro	8	0	N
	Moru/Parlamento	Euquisi	6	0	N
		Parlamento	6	2	P
Liquicia	Bazartete	Metagou	13	1	P
		Leorema	10	0	N
Manatuto	Manatuto	Ma'Abat	10	0	N
	Natarbora	Manehat	10	0	N
Manufahi	Faberliu	Fatucahi	9	0	N
	Same	Babulu	6	0	N
	Turiscai	Beremana	7	0	N
		Caimauc	7	0	N
Oecusse	Pante Makasar	Nipani/Sakato	5	0	N
	Passabe	Passabe	5	0	N
	Oesilo	Bobometo	8	3	P
	Citrana	Bene-Ufe/Naktuka	10	0	N
Viqueque	Watucarbau	Bahatata	6	2	P
	Watulari	Afloicai	3	0	N
	Ossu	Ossu de sima	5	0	N
Number of negative villages					32
Number of positive villages					16
Total			436	59	48

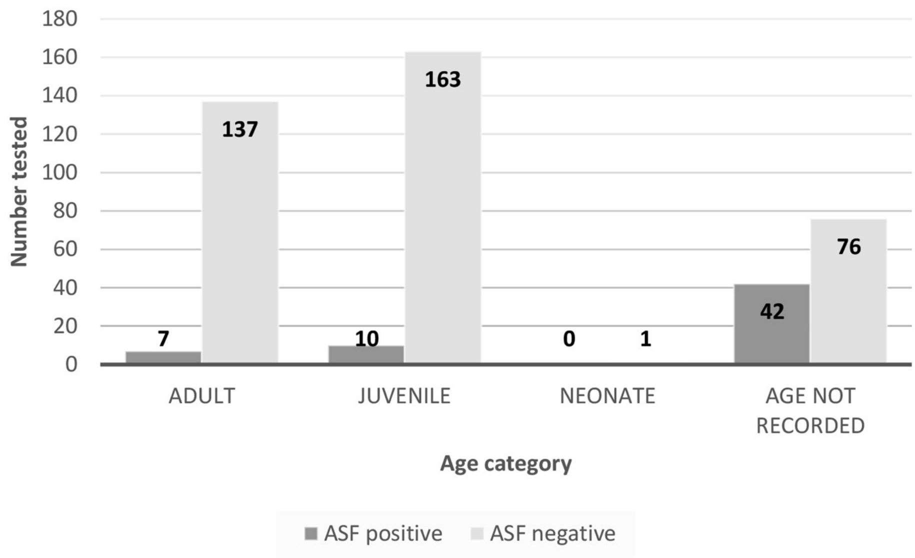


FIGURE 2 | Summary of ASF test results versus age of pigs sampled for mainland prevalence and Atauro Island survey.

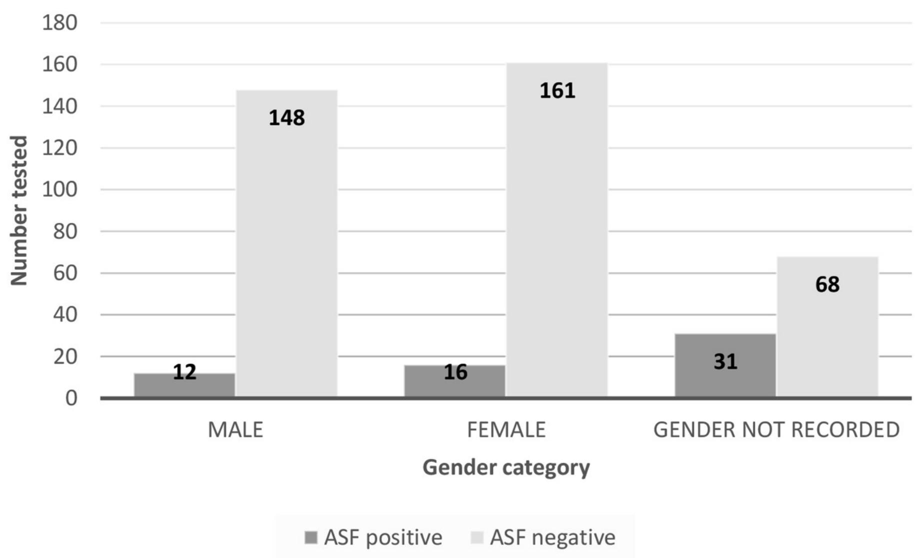


FIGURE 3 | Summary of ASF test results versus gender of pigs sampled for mainland prevalence and Atauro Island survey.

Testing of the samples using LAMP was completed on 9 November 2019 and all samples were negative. **Figure 3** shows the map of test results.

The null hypothesis set the probability of observing no reactors in a sample of 33 individuals from a population with a disease prevalence of 10% at 0.0318. The alternative hypothesis set the probability of observing at least one reactor in a sample of 33 individuals from a disease-free population at 1. These results are adequate to reject the null hypothesis and conclude that the population is free from disease (at the expected minimum disease prevalence of 10%) at the 0.9682 confidence level.

DISCUSSION

The completion of the Timor-Leste mainland ASF disease prevalence survey was successful in calculating an estimate of the level of ASFV infection present at a village level and the geographic extent of the spread of disease. The infected village

TABLE 3 | 2 × 2 risk table of pigs sampled for mainland prevalence and Atauro Island survey with or without pyrexia and ASF disease status.

Body temperature	ASF positive	ASF negative	Total
Pyrexia	4	19	23
No pyrexia	8	253	261
Total	12	272	284

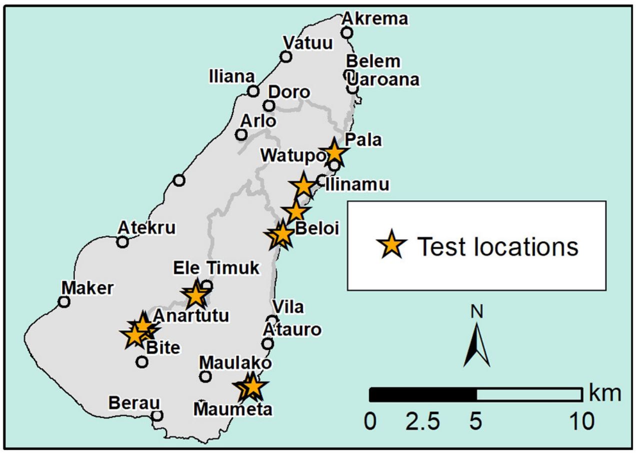


FIGURE 4 | Map showing sample results and location on Atauro Island.

prevalence estimate of 34% (95% CI 22–48%) indicates that whilst approximately one third of villages in Timor-Leste have ASFV infection, the level could be as high as nearly half or as low as one quarter of all villages. A more precise estimate would be ideal but the availability of resources and logistical challenges in collecting samples from remote villages are limiting factors in Timor-Leste. The value of the survey is not however, constrained to the accuracy of the estimate, but by a reckoning of the level and distribution of disease to inform a disease response.

The Timor-Leste mainland prevalence survey described the current geographic distribution of disease. ASFV infected villages were localized mainly in the west and the east of the mainland with no detectable disease in the far south east municipality of Cova Lima or in a group of 4 municipalities to the south of the capital Dili. The prevalence survey design assumed that ASF, if present, would be detected in 10% of villages, a fairly conservative estimate given the infectious nature of the virus, the time elapsed between its detection in early September 2019 and the time of the majority of sample collection in November and December 2019 and the size of the mainland. However, it is possible that if ASFV was present in < 10% of villages it would not have been detected in the numbers of villages sampled.

This prevalence survey detected discrepancies with the earlier unpublished phone survey reports of significant numbers of sick and dead pigs in most municipalities including Aileu, Manufahi, and Cova Lima. where there was no diagnostic evidence in the prevalence survey. It demonstrates the limitations of phone survey results based on reported clinical signs or without the addition of diagnostic testing to differentiate between other potential causes of sudden death and/or acute disease in pigs, including Classical Swine Fever (CSF). In this study 19 out of 23 pigs with pyrexia tested ASFV negative, suggesting other febrile causes of disease are common in Timor-Leste. CSF vaccination campaigns have been conducted by the government since 2003 but a study in 2015 estimated CSF seroprevalence at 34.4% with evidence of virus circulation and associated mortality events in village herds surveyed (20). In the CSF seroprevalence survey, pigs that has been vaccinated for CSF were more likely to have antibodies; however these pigs only accounted for a percentage of samples tested. There may also be language barriers that affect the accuracy of the information collected via phone surveys.

The first detection of disease in Timor-Leste occurred around Dili, Baucau and Liquicia (all northern coastal municipalities) (8). It is not known how ASFV was introduced but common routes of spread are noted to include movement of infected pigs or infected pork products (3). Timor-Leste has limited international transport options for live pigs via sea routes, and only one land border is with West Timor (a province of Indonesia that did had not declared an outbreak of ASF at the time of the Timor-Leste detection) so the opportunity for movement of infected live pigs into the country was limited. It is possible that there were imported ASFV infected pork products that were fed to domestic pigs or became available for local pigs to scavenge. ASFV can remain viable in fresh and frozen pork products for at least 105 days and the risk of introduction of disease via pigs accessing such pork products is well-documented (3, 21, 22). For example, between 5 November 2018 and 30 November 2019, Australian authorities intercepted over 34 tons of pork products on air travelers entering Australia (23, 24) of which a percentage (figure unpublished) tested positive for ASFV DNA. There are a significant number of foreign-aid funded capital works projects in Timor-Leste such as a new commercial port construction near Dili and road infrastructure projects that have associated risks of disease introduction via associated with foreign workers and imported machinery.

After the initial incursion of ASFV, spread of disease has occurred to the infected villages identified in this prevalence survey. Routes of spread typically involve the movement of infected pigs and contaminated pig products and/or equipment and people (1, 3, 22). In Timor-Leste cultural practices of both pig housing with minimal biosecurity and transporting pigs for traditional occasions of importance (4) could allow disease spread both at a local level within and between neighboring villages and translocation to new areas via transport of infected pigs and material via road or boat. The northern and southern municipalities of Timor-Leste are separated by a high range of mountains over 2,000 m above sea level and the few roads that cross are steep, windy and in poor condition in many places. This range may have limited the movement of pigs moving from north to south in some areas. There are police check points built on key routes that may in future be used in a disease control response to limit pig movements to restrict the spread of disease (pers.comms). Other types of transmission routes for ASFV that are of unknown significance in Timor-Leste include the role of ticks and biting insects and external parasites. External parasites including ticks and lice were observed on sampled pigs and potentially could act as vectors for ASF (3, 22). Further research is needed to elucidate the role of ticks and other biting insects in the transmission of ASFV in Timor-Leste.

ASF in pigs is commonly associated with pyrexia (3). Analysis of the association between pyrexia and the detection of ASFV showed that whilst pyrexia was a significant relative risk factor, not all ASFV positive pigs were pyrexic when sampled ($n = 4$). The logistical difficulties of blood collection from pigs in remote villages in Timor-Leste warrants the investigation of alternative sampling strategies that could be collected by less skilled local animal health staff as an alternative early detection system for ASFV and/or other diseases associated with pyrexia in pigs. However, in this study the usefulness of pyrexia as an indicator of infectious disease was limited. The use of other samples such as oral or fecal swabs are an area for future research in Timor-Leste.

The proof of freedom survey of Atauro Island gave a high level of confidence that there was unlikely to be ASF on the island at the expected minimum prevalence of 10%, at the 0.9682 confidence level. This informed an important disease control initiative based on the assumption that the pig population there was free from ASFV. The island was immediately quarantined by the Timor-Leste Ministry of Agriculture and Forestry on 8/11/2019 to prevent any further movement of pork or pigs to the island (pers.comms). Trade in pigs back to Dili remains as normal. An important consideration in Timor-Leste is that the Timor Warty Pig is only found on the islands of Timor. It is not only culturally important but is unique to the islands. Therefore, the preservation of the species is a priority. Disease free refuges of breeding stock are important for future restocking on the mainland.

Until this project was undertaken there was no diagnostic capability or capacity in Timor-Leste for ASF or other viral diseases including CSF affecting pigs. The use of LAMP technology in Timor-Leste has provided a fast, simply performed and robust test suitable for use in a basic laboratory or field situations. Test specificity and sensitivity appear very high (>99.9%) based on previous research (15) and preliminary validation work in Australia with serum samples from known ASF free animals and seeded manufactured DNA samples (unpublished data). Serum samples were used in this prevalence survey to maximize the familiarity of local field staff experience and the availability of blood tube supplies. Acknowledging that serum generally contains less viral genome than whole blood, preliminary LAMP testing was also conducted on whole blood samples in a variety of types of anticoagulants and is reported in a separate publication (15). The use of liquid reagents for the field tests undertaken with the LAMP machine created minor issues when the reagents were exposed to high ambient temperatures associated with the tropical climate in Timor-Leste. In the future, use of freeze dried reagents to increase stability in a variety of climates is expected to address this problem and future research is planned to verify that this is the case.

The completion of a prevalence survey to inform any jurisdictional response agency about disease distribution is a crucial step in planning any response to a new disease incursion (3, 9). As a result of this project, Timor-Leste has implemented a staged disease response that includes some movement controls, improving biosecurity awareness and practices amongst village pig owners, further sampling to ascertain the effectiveness of the implemented disease control measures and further research and training to enable the most effective use of available laboratory resources and in-country animal health staff.

DATA AVAILABILITY STATEMENT

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

ETHICS STATEMENT

Ethical review and approval was not required for the animal study because Samples were collected as part of an ongoing ASF outbreak investigation. Written informed consent for participation was not obtained from the owners because Verbal permission was obtained from owners of livestock and is considered normal practice in Timor-Leste.

AUTHOR CONTRIBUTIONS

DP: design of prevalence survey, proof of freedom survey, and field work. SL and PM: diagnostic test creation, laboratory support, and field application. GR: team leader and field work. FC: field work. JB: chief veterinary officer Timor-Leste and ministerial liaison. All authors contributed to the article and approved the submitted version.

ACKNOWLEDGMENTS

We thank the Department of Agriculture and the Department of Jobs Precincts and Regions for their support by providing funding for this research and travel cost to Timor-Leste. We thank Ian Shurvell from Department of Agriculture and the Department of Jobs Precincts and Regions for assistance with mapping images.

REFERENCES

1. Zhou X, Li N, Luo Y, Liu Y, Miao F, Chen T, et al. Emergence of African swine fever in China. *Transbound Emerg Dis.* (2018) 65:1482–4. doi: 10.1111/tbed.12989
2. OIE World Organization for Animal Health. *African Swine Fever (ASF) Report N° 48*. (2020). Available online at: https://www.oie.int/fileadmin/Home/eng/Animal_Health_in_the_World/docs/pdf/Disease_cards/ASF/Report_48_Current_situation_of_ASF.pdf (accessed July 12, 2020).
3. OIE World Organization for Animal Health. *Technical Disease Cards-ASF*. Department OSaT (2019). Available online at: https://www.oie.int/fileadmin/Home/eng/Our_scientific_expertise/docs/pdf/AFRICAN%20SWINE%20FEVER.pdf (accessed July 12, 2020).

4. Bettencourt EM, Tilman M, Narciso V, Carvalho ML, Henriques PD. The livestock roles in the wellbeing of rural communities of timor-leste. *Rev Econ Sociol Rural*. (2015) 53 (Suppl. 1):63–80. doi: 10.1590/1234-56781806-94790053s01005
5. Statistics Timor-Leste. *Statistics*. (2015). Available online at: https://www.statistics.gov.tl/category/publications/census-publications/ (accessed November 2019).
6. Australian Centre for International Agricultural Research (ACIAR). *Second Epidemic Threatening Timor-Leste*. Available online at: https://reachout.aciar.gov.au/second-epidemic-threatening-timorleste (accessed July 12, 2020).
7. Barnes TS, Morais O, Cargill C, Parke CR, Urlings A. First steps in managing the challenge of African swine fever in timor-leste. *One Health*. (2020) 10:1–3. doi: 10.1016/j.onehlt.2020.100151
8. OIE World Organization for Animal Health. *Timor-Leste ASF OIE Notification Report*. (2019). Available online at: https://www.oie.int/wahis_2/public/wahid.php/Reviewreport/Review?page_refer=MapFullEventReport&reportid=31960 (accessed July 12, 2020).
9. Australian Veterinary Emergency Plan (AUSVETPLAN), Canberra, ACT. *Response Strategy: African Swine Fever (Version 5)*. Available online at: https://www.animalhealthaustralia.com.au/our-publications/ausvetplan-manuals-and-documents/ (accessed November 2019).
10. OIE World Organization for Animal Health. *Report_31_Current_situation_of_ASF*. (2019).
11. Notomi T, Okayama H, Masubuchi H, Yonekawa T, Watanabe K, Amino N, et al. Loop-mediated isothermal amplification of DNA. *Nucleic Acids Res.* (2000) 28:e63. doi: 10.1093/nar/28.12.e63
12. Dhama K, Karthik K, Chakraborty S, Tiwari R, Kapoor S, Kumar A, et al. Loop-mediated isothermal amplification of DNA (LAMP): a new diagnostic tool lights the world of diagnosis of animal and human pathogens: a review. *Pak J Biol Sci.* (2014) 17:151–66. doi: 10.3923/pjbs.2014.151.166
13. Sergeant, ESG. *Epitools Epidemiological Calculators*. Sample size to estimate a simple proportion (apparent prevalence). (2018). Available online at: https://epitools.ausvet.com.au/oneproportion (accessed November 2019).
14. Sergeant, ESG. *Epitools Epidemiological Calculators*. Estimated true prevalence (2018). Available online at: https://epitools.ausvet.com.au/trueprevalence (accessed July 12, 2020).
15. Mee PT, Wong S, O'Riley KJ, da Conceição F, Bendita da Costa Jong J, Phillips DE, et al. Field verification of an African swine fever virus loop-mediated amplification (LAMP) assay during an outbreak in timor-leste. *Viruses*. (2020) 12:1444. doi: 10.3390/v12121444
16. Sergeant, ESG. *Epitools Epidemiological Calculators*. 1-Stage Freedom analysis. (2018). Available online at: https://epitools.ausvet.com.au/freecalcone (accessed November 2019).
17. OIE World Organization for Animal Health. *African Swine Fever, Indonesia*. (2019). Available online at: https://www.oie.int/wahis_2/public/wahid.php/Reviewreport/Review?reportid=32482 (accessed November 2019).
18. Sergeant, ESG. *Epitools Epidemiological Calculators.* Two by two table (2018). Available online at: https://epitools.ausvet.com.au/twobytwotable (accessed July 12, 2020).
19. James HE, Ebert K, McGonigle R, Reid SM, Boonham N, Tomlinson JA, et al. Detection of African swine fever virus by loop-mediated isothermal amplification. *J Virol Methods*. (2010) 164:68–74. doi: 10.1016/j.jviromet.2009.11.034
20. Sawford K, do Karmo A, da Conceicao F, Geong M, Tenaya IW, Hartawan DH, et al. An investigation of classical swine fever virus seroprevalence and risk factors in pigs in Timor-Leste. *Prev Vet Med.* (2015) 122:99–106. doi: 10.1016/j.prevetmed.2015.09.012
21. (AHAW) EPoAHaW. Scientific Opinion on African swine fever. *Eur Food Saf.* (2014) 12:3628. doi: 10.2903/j.efsa.2014.3628
22. Mazur-Panasiuk N, Zmudzki J, Wozniakowski G. African swine fever virus - persistence in different environmental conditions and the possibility of its indirect transmission. *J Vet Res.* (2019) 63:303–10. doi: 10.2478/jvetres-2019-0058
23. Department of Agriculture WatE. *Keeping African swine fever out of Australia African Swine Fever Response Package*. (2019). Available online at: https://www.agriculture.gov.au/pests-diseases-weeds/animal/asf#strengthened-biosecurity-measures-for-permitted-and-unpermitted-products (accessed July 12, 2020).
24. McFarlane F. *CSIROscope*. (2019). Available online at: https://blog.csiro.au/protecting-australia-from-african-swine-fever/

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

Copyright © 2021 Phillips, Mee, Lynch, da Conceição, Bendita da Costa Jong and Rawlin. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.

frontiers in Veterinary Science

ORIGINAL RESEARCH
published: 28 July 2021
doi: 10.3389/fvets.2021.689163

From National Biosecurity Measures to Territorial ASF Preparedness: The Case of Free-Range Pig Farming in Corsica, France

Marie Gisclard[1]*, *François Charrier*[1,2], *Bastien Trabucco*[1] *and François Casabianca*[3]

[1] SELMET-LRDE, INRAE, ACT Department, Corte, France, [2] LISIS, INRAE, ACT Department, Marne-la-Vallée, France, [3] INRAE, Centre de Corse, San Giuliano, France

OPEN ACCESS

Edited by:
Erika Chenais, National Veterinary Institute, Sweden

Reviewed by:
Federica Loi, Istituto Zooprofilattico Sperimentale della Sardegna (IZS), Italy
Laura Zani, Friedrich Loeffler Institute, Germany
Susanna Sternberg Lewerin, Swedish University of Agricultural Sciences, Sweden

***Correspondence:**
Marie Gisclard
marie.gisclard@inrae.fr

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

Received: 31 March 2021
Accepted: 23 June 2021
Published: 28 July 2021

Citation:
Gisclard M, Charrier F, Trabucco B and Casabianca F (2021) From National Biosecurity Measures to Territorial ASF Preparedness: The Case of Free-Range Pig Farming in Corsica, France. Front. Vet. Sci. 8:689163. doi: 10.3389/fvets.2021.689163

In response to African swine fever (ASF) outbreaks in wild boars in Belgium in 2018, the French authorities issued national biosecurity measures for all pig farms, regardless of their geographical and socio-technical scale. Considering the Corsican pig farmers' demonstrations against these measures (for geographical, cultural, and economic reasons), this article questions the suitability of standardized top-down national measures that potentially endanger traditional breeding systems, which are increasingly marginalized in relation to the dominant industrial model. From an action-research approach, the article analyzes how local stakeholders go beyond usual classical biosecurity issues to propose a territorialized preparedness. Mediating between Corsican farmers and the government representatives, a technical committee made up of actors from various regional research and development bodies drew up a socially acceptable preparedness proposal. Viewing the health risk from a local standpoint, the committee provided arguments for maintaining the extensive grazing that is non-negotiable for the farmers, while getting the farmers to agree to change other practices (reproduction control) as a measure against health hazards already present. Analysis of the preparedness process and the mediation process shows that a territorialized bottom-up approach to the governance of health risks can make biosecurity measures more acceptable to farmers. It also points to the legitimacy of a set of alternatives to top-down measures that standardize farming systems and may lead to the disappearance of small farmers and their traditional systems.

Keywords: African swine fever, Corsica, free-ranging farming system, territorial preparedness, biosecurity, social acceptability, outdoor farming system

INTRODUCTION

African swine fever (ASF) is a highly contagious viral disease specific to wild and domestic swine, with no danger to humans but with serious consequences for animal health. France has been free of ASF since 1974 (1), but the virus has been endemic since 1978 in Sardinia, an island only 12 km from the coast of Corsica. It entered Europe in 2007 through the Caucasus and has spread throughout Eastern Europe and Asia, where it threatens the pig industry in affected countries. In 2018, ASF was detected in Belgium (2). Shortly afterward, the French government issued a Ministerial Decree (3) prescribing biosecurity measures for all pig farms, regardless of their location and socio-technical characteristics. In the case of pig farming, biosecurity measures are designed to limit interactions with wildlife and with other farms by installing fences or confining the pigs. So, the decree includes strong measures to set up double enclosures and to fence all outdoor farms with grazing land.

Preparedness as "*a style of reasoning and a set of governmental techniques for approaching uncertain threats*" (4) and biosecurity, which has become a major pillar of preparedness for emerging infectious diseases [swine flu, ASF, severe acute respiratory syndrome (SARS), etc.], are often standardized (5, 6) despite the diversity of local conditions and farming practices (7). There can be wide discrepancies between biosecurity techniques and the technical characteristics of farming systems and between a national preparedness plan and a potentially wide range of local issues, which can go beyond disease management (8). Some studies show that national preparedness measures are out of step with local issues and situations (9, 10). Also, health risk is rarely considered from a territorial perspective (11). All these contribute to the global standardization of pig farming systems and the dissemination of the industrial farming model throughout the world (12, 13).

As a consequence, biosecurity plans and national preparedness may be rejected by livestock farmers and other health stakeholders (14) because of the diversity of contexts in which livestock disease outbreaks arise (15, 16). The decontextualized nature of classical biosecurity measures therefore constitutes a first obstacle for the design of an effective, applicable preparedness plan in a given local territory.

In fact, pig farmers on the French Mediterranean island of Corsica mobilized to contest the implementation of the national decree. They consider the control measures as unapplicable because of the predominant free-ranging farming systems, the mountain topography and land tenure issues. Indeed, classical biosecurity measures are much harder to implement when pigs have access to pastures shared by different herds (17) or with wild boars nearby. Corsica's pig farming systems have been considered unconventional (18) in comparison to both indoor and outdoor pig farming systems in mainland France. Corsica's pigs are destined for dry-cured meat production, processed and retailed by the farmer him/herself, with small herds averaging 90 to 200 pigs slaughtered per year (19). Huge areas of unfenced pastureland are vital to these systems, as they provide the chestnuts and acorns that are key to the pigs' diet and are mandatory stipulated in the Protected Designation of Origin (PDO) specifications (20). The pasturelands are thus a significant resource for the Corsican pig sector's development and the typicality and renown of its products. They are also a source of public subsidies for their contribution to countryside maintenance. So, the announcement of the new national biosecurity obligations raised major cultural and economic issues and made farmers fear the disappearance of their traditional farming systems.

However, from an epidemiological point of view, Corsica is a vulnerable territory because of its geography and the interaction between livestock and wild boars on the unfenced pasturelands (19, 21, 22). The epidemiological situation may be considered worrying, as the Aujeszky virus is circulating at a high rate (23) and bovine tuberculosis is reemerging (24). Epidemiological surveillance and management are complicated by the presence of informal farming and clandestine on-farm slaughtering. So, it seems very difficult to implement national biosecurity measures against African swine fever virus (ASFV) introduction but unrealistic to maintain the status quo. Following farmers' protests, several research and development organizations got together to form a technical committee (TC). The TC evaluated the overall situation as an opportunity to address the weaknesses of health management in the Corsican pig sector.

The notion of acceptability (8, 25) allows to understand the potential gap between management measures based on official expert risk assessments and the implementation of those measures and the social conflicts that arise (15). The notion of acceptability points to a dynamic process (26) through which a compromise can emerge and stabilize. It is achieved through important phases of contestation, deliberation, and negotiation to reach a compromise between administrators and citizens of the territories concerned (27, 28). The construction of compromise is "intermediated" through the emergence of various actors or groups of actors (consumers, farmers, associations, etc.) who coordinate to achieve change (29). Looking at mediation as a way of building compromise required us to particularly analyze the actor legitimacy, the stability of local collectives, and the ability of local actors to carry the process through.

Classical biosecurity measures against ASF call into question the existence and legitimacy of small farms that use pasturelands classified as at-risk. French outdoor pig farmers have already negotiated marginal adjustments, including the possibility of penning animals behind fences rather than walls. This is a perfect illustration of the fact that acceptability tests are often carried out by a statistically marginal minority and/or concern some aspect of the project that only affects "marginal" actors (28).

However, Corsican free-range farmers cannot be considered a statistically marginal minority. Although marginal in terms of the French pork sector (<1% of national production), they nevertheless represent the vast majority of the 350 (30) island's pig farmers, whose farming systems are almost unique to Corsica and are only marginal in relation to the rest of France. So, the question of acceptability is raised not at the level of individual farmers but concerns a whole territory.

The uniqueness of Corsica therefore puts to the test a "prescribed" global or universal (14) standardizing approach to biosecurity. Prescription alone cannot work in Corsica without risking serious social, economic, and land management consequences. The traditional system would be doomed to disappear, evolve into a system similar to "outdoor" systems found on the mainland, or go underground. But while the acceptability of biosecurity measures imposing mandatory confinement of animals seems complicated for Corsican farmers, the acceptability of negotiating this central point of the national measures is also not obvious: biosecurity concerns the management of a diffuse risk, in this case, a Category 1 disease whose management is the responsibility of the state. Animal health also has implications for public health (risk of zoonotic diseases, though not in the case of ASF), the agri-food economy, etc.

The aim of this paper is to analyze how the stakeholders of a subnational territory with small farmers practicing free-range livestock systems that deviate sharply from the top-down public policy standard design and negotiate adaptations to its specific features.

Our hypothesis is based on two assumptions:

1. The acceptability of the adaptations cannot be limited to marginal adjustments but must involve building a genuine preparedness that meets the challenges of the local farming system.
2. Local preparedness is a complex organizational process involving different acceptability tests by farmers and the authorities, which will be easier to achieve with someone to mediate between the two groups.

MATERIALS AND METHODS

This paper is the result of an action research approach that used qualitative methods: participant observation and semi-structured interviews. In action research, the key element to be analyzed and interpreted is the various collective processes triggered by the researchers' practical involvement alongside other actors seeking change. It follows from the idea of making complex mechanisms (especially social mechanisms) visible and analyzable through real-world intervention (31–33).

Empirical Data: Participatory Observation and Intervention Research in the Corsican Pig Sector

The first type of material collected was essentially empirical and came from participant observation carried out by the authors, who were members of the TC. As such, they first attended the first two farmers' meetings, at which the farmers formed a collective (the farmers' collective) to protest against the unacceptability of the national ASF biosecurity measures.

Following the creation of this farmers' collective, the TC included multidisciplinary Corsican stakeholders concerned with animal health: the Groupement de Défense Sanitaire (GDS–farmers' association for livestock health protection), the Groupement Technique Vétérinaire (GTV–regional association of veterinarians), the Chambers of Agriculture of the two districts of Corsica, the Regional Chamber of Agriculture (that covers all of Corsica), INRAE, the two departmental hunting federations, the Corsican Office of Agricultural and Rural Development (ODARC), and representatives of the main farmers' organizations. Its aims were (i) to preserve Corsican pig farming by proposing adaptations of the national biosecurity measures and (ii) to improve the health management of pig farming in Corsica, where several pig diseases are already present, by building a Regional Health Plan.

The meetings that are part of our material and have therefore been analyzed concern:

- The farmers' collective meetings (2). The farmers' positions were reported to and discussed by TC members at TC meetings.
- All the TC meetings (17)
- The meeting where the TC presented its work to the pig farmers' collective, at which the farmers adopted the proposed plan and agreed to formally submit it to the authorities
- The three meetings between the TC and the authorities. The first was to make sure the authorities would be willing to consider alternative proposals. The second was for the TC, accompanied by representatives of the farmers' collective, to present its proposals. At the third, government experts gave their opinions on the acceptability (to the authorities) of the proposals put forward, asked for clarifications, and launched a series of actions to obtain agreement from the Ministry of Agriculture. Once the proposals were submitted to the decentralized state services, the latter conducted the negotiations with the Ministry of Agriculture at the national level (specifically, the General Inspector of Veterinary Public Health).

All these meetings, which were moments of construction, discussion, and negotiation between stakeholders (**Figure 1**), are listed in **Table 1**. A report was prepared after each meeting so that the progress of the preparedness process and the negotiations could be monitored and analyzed.

Semi-Structured Interviews

To supplement the material obtained by participant observation, we then conducted comprehensive semi-structured interviews (34, 35) to shed more light on the different actors' positions as they appeared to us in the various meetings and to gain a better understanding of what was acceptable or unacceptable to them (**Table 2**). We held these interviews with (i) approximately 30 pig farmers; (ii) two government officials responsible for animal health issues at the regional level about the organization of health management and health surveillance capacity on pig farms; and (iii) five veterinarians, on their relations with farmers (36). The sample of farmers (that represents about 10% of the pig farmers) was selected to be representative of the diversity of Corsican farming systems, classed into four groups according to their level of risk for the introduction of emerging diseases (19). The face-to-face interviews focused on their husbandry practices and the impact of these on pig health in general, their perceptions of the risk of spreading diseases such as ASF, and their knowledge of unsafe practices. The interviews lasted 2 h on average. They were recorded, transcribed in full, and analyzed thematically.

Framework for Analyzing Acceptability Testing

We observed the work of the TC, which was aimed at making proposals acceptable to both the farmers and the government. We analyzed the different stages of the acceptability testing for both the national measures and the TC's proposals. We also analyzed the issues at stake at the time of the testing.

- We first identified the diversity of actors concerned and their positions with regard to the national biosafety measures

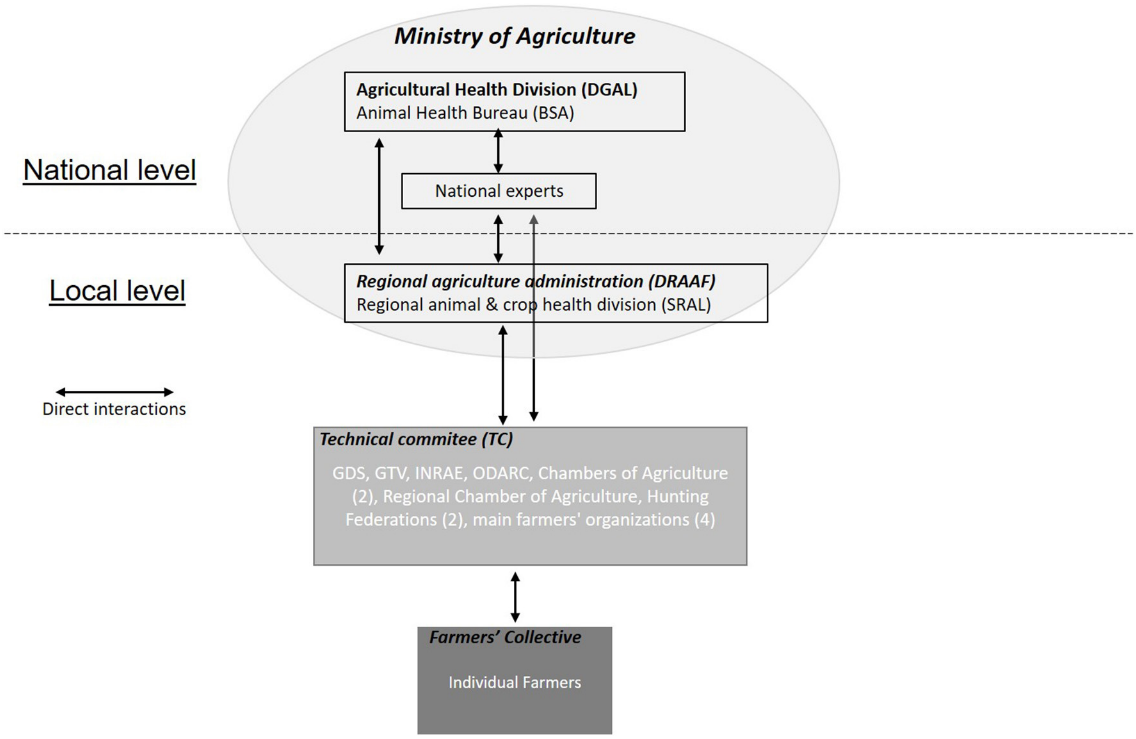


FIGURE 1 | Interactions between the different actors in the territorial preparedness process against African swine fever (ASF) in Corsica (2019–2021).

TABLE 1 | Number and purpose of the meetings conducted in the territorial preparedness process against ASF in Corsica (2019–2021).

Meetings	Number of meetings	Period	Purpose of the meeting
Pig farmers	2	April and June 2019	Mobilization to contest the ministerial decree
TC	17	From July 2019 to September 2020	Building a preparedness process proposing alternatives to national biosecurity measures
Breeders and TC	1	September 2020	Validation of TC proposals by farmers
TC and decentralized state services	2	September 2019 and November 2020	Validation of the alternative proposal process Validation of a preparedness approach
TC, decentralized state services, national experts	1	January 2021	Discussion of the proposals with the experts, identification of sensitive points to work on, and validation of the proposals as a whole
Decentralized State services and national state services (Agriculture Ministry)	2	February and March 2021	Negotiation for government's acceptance of the preparedness proposal

ASF, African swine fever; TC, technical committee.

and the adaptation proposals. We constructed a thematic analysis (37, 38) that makes explicit the standpoint of each stakeholder group toward the application of the national biosecurity measures in Corsica in terms of "problems," "objects of negotiation," and "acceptable solutions." We listed (i) what was problematic for the farmers in the biosecurity measures, (ii) what the authorities saw as problematic in the Corsican pig farming system, and (iii) what the stakeholder groups envisaged doing based on their interpretation of the problem. This highlighted the diversity of positions within each party (the farmers and the authorities) and enabled us to identify the objectives and problems that were critical for each party and which the negotiations were to address.

- Next, we assessed the acceptability testing of the TC proposals using the criteria suggested by Barbier and Nadaï (2015): (i) they make sense to everyone, (ii) they are robust (no other preferable alternatives), (iii) they have safeguards in the event of interference with inappropriate behavior, and (iv) they take into account the diversity of interests and values concerned. We examined how they constituted responses to the elements considered unacceptable by each of the parties. To do this, we compared the TC's solutions with the factors the various stakeholders considered problematic (**Tables 3**, **4**).

TABLE 2 | Farmers' positions at the first two meetings of the pig farmers' collective mobilized against the French national biosecurity measures to fight African swine fever.

Farmers' positions	Problematic/unacceptable elements in the decree	Proposals for solving the problem	Subject of negotiation	"Acceptable" proposal
"Warrior" (ready to fight the state)	Lack of control of grazing land to be fenced Authoritarian behavior of the state	Preserving the pasturelands Closing Corsica's borders to meat imports Arm wrestling with the state	No negotiation possible	Status quo
"Passive" (resistant to any change)	Not treating insularity as a means of protection from the outside world Ignoring the precedence of husbandry practices presented as ancient and traditional	Closing Corsica's borders to meat imports	Maintaining and improving current border controls	Better state control of illegal imports and increased tourist awareness
"Fatalist" (anyway the authorities make the decisions)	Everything is acceptable, since, in any case, the authorities will do what they have already decided.	Waiting for the obligations to come into effect	Nothing to negotiate	Compliance with the ministerial decree
"Pro-active" (finding suitable solutions)	The end of open upland grazing and therefore of an ancestral activity. PDO specifications would be impossible to meet. Lack of control over land that would have to be fenced. The authoritarian, top-down approach. Too-short deadlines	Closure of Corsica's borders to meat import Designing a gradual plan that would leave no one behind	Assessing the state's ability to control livestock health	Structuring farms Opening a dialogue between organizations and public authorities
"Demanding" (resources for making changes)	Cost of structuring the farm Intolerable financial cost and technical difficulty of fencing pastureland	To free up exceptional resources	Public funding for restructuring the farms Formal commitments of funding authorities	Creating a budget for public funding Compensation for dead animals

TABLE 3 | Proposals from the local technical committee on the unacceptable elements for Corsican pig farmers of the national biosecurity measures against African swine fever.

Problematic/unacceptable elements in the decree	Suggestions for solving the problem	"Acceptable" proposal
Lack of measures specific to island territory	Insert a component specifically designed to protect against the introduction of new health hazards	Effective implementation of measures at ports and airports Raising awareness among importing deli producers Communication with tourists and visitors
Health management problems with many health hazards already present	Local preparedness involving farmers, state, vets, hunters, slaughterhouses	Redistribution of responsibilities between all health actors
Difficulty of building barriers	Realistic, effective changes to herd management Feasibility, gradual change	Maintaining the pasturelands by preventing sexual interaction between wild boar and domestic animals Keep breeding animals penned and accept the risk of deli meat loss Adapt the biosecurity measures to Corsican farms (cancel inappropriate standards, add appropriate, effective elements) Gradually upgrade farms according to their initial situation

Validation of the various elements at successive meetings (TC meeting, then meeting between the TC and the farmers' organizations, and finally meeting between the TC and the authorities) was considered in each case a successful step in the acceptability test.

- Lastly, to analyze the role of the TC's mediation work in the acceptability testing process, we established a "storyline" of the preparedness process. The resulting chronicle captures the essential moments in the process of designing and negotiating acceptability and the combinations of actors and arguments that comprised those moments. It shows the temporal sequences and specific focuses (39) that led to the Regional Swine Health Plan. The legitimacy of the TC and its ability to conduct the mediation process were assessed in terms of the continuity and regular timing of the meetings it organized and the discussions it fostered between different stakeholders. The success of the mediation and the stabilization of the negotiation process were judged by the establishment of compromises between stakeholders, giving rise each time to a new stage in the negotiation process.

RESULTS

Our results show three steps in the acceptability process: (i) a collective acknowledgment of the unacceptability of the national biosecurity measures, (ii) a collective design process

TABLE 4 | Positions of local and national authorities in the regional health plan negotiations in the territorial preparedness process against ASF in Corsica (2019–2021).

Negotiating actors		Problematic/unacceptable elements	Proposals for solving the problem	Subject of negotiation	"Acceptable" proposal
State	Regional state	Risk of ASF introduction and dissemination to French pig farms Representative professional organizations	Facilitation to help the sector implement the Regional Health Plan	Corsica's island status	The health status of Corsican farms The risk of the spread of ASF in case of introduction The lack of animal identification
	National state representative in the region (Prefect)	Risk of dissemination to the mainland	Role of the Conseil Régional d'Orientation de la Politique Sanitaire Animale et Végétale (Regional Council for the Orientation of Animal and Plant Health Policy)	Health situation of the island	Not spreading a virus to the continent
	National state (central government)	Health hazards present	Treating bovine tuberculosis (zoonosis)	Specific measures to be activated as soon as possible	Manage the timescale of the various measures of the Community Plan
Regional Community	Agricultural and Rural Development Office	Lack of structure (farm structure and physical structures)	Conditions for aid Nature of reciprocal commitments	Allocation of funds	Creating rules for eligibility of individual applications

ASF, African swine fever.

aimed at proposing a territorial preparedness appropriate to Corsica's farming systems and addressing the elements considered acceptable or unacceptable by different actors, (iii) and a negotiation dynamic between a diversity of entities. For each step, we highlight the TC's role as mediator for the acceptability of the Regional Health Plan, with the farmers on one hand and the government authorities on the other.

Arguing the Unacceptability of the National Measures

When the national biosecurity measures were announced, the farmers' collective expressed their rejection of these measures. The reasons are many: Corsica's rugged terrain, the use of large areas of pastureland, and lack of control over these vast expanses, which, furthermore, overlap between private and common land. On the other hand, the "traditional" nature of Corsican farming systems would be undermined by penning the animals behind fences. They see the injunction to confine their animals to protect them as a top-down imposition and a denial of local farming practices.

The concept of "pastureland" cannot be reduced to "outdoor" pig keeping (in fenced pens). Pastureland grazing is the main criterion that differentiates Corsica's pig system and its products. Its disappearance is considered non-negotiable by some, especially those farmers registered in the PDO, whose specifications require the pigs to be grazed on pastureland.

At these meetings of the farmers' collective and in the semi-structured interviews, we identified various positions among the farmers. **Table 2** includes five different positions and details the main characteristics of each.

Between the meetings of the farmers' collective, we observed quite noticeable changes in the positions of those in attendance. First of all, while the "warriors" took an uncompromising position against the government at the first meeting, they seemed to disappear, or spoke much less, at the second: Had they understood that most farmers are not sufficiently motivated to rebel against the authorities? Similarly, the "passive" and the "fatalists," although present at both meetings, appeared less numerous at the second: Were they already tempted to withdraw and join the informal sector? At this second meeting, the "demanding" and "pro-active" who expressed the desire to make proposals to negotiate for appropriate ways and means to meet the health challenge were mostly still present and responsive.

One particular point of tension is felt in the discussions: some farmers (mainly the "passive" ones) think that being an island is in itself a complete solution for protecting Corsica and avoiding the need to restructure the farms. In fact, the lack of infection despite the weakness of the special protective measures between Corsica and Sardinia has lessened farmers' fears. Many feel that the government biosecurity solutions are out of proportion to the danger (still remote and without apparent urgency). The farmers see border control as the main measure to be implemented. The discussions brought to light a practice of purchasing live animals or pork meat from outside the island and mixing local and imported raw materials in "farmhouse" products (that are supposed to consist only of raw materials from animals born and raised on the farm). This opportunistic behavior by some farmers was denounced as a collective risk with regard to the virus. The provisional conclusion from these discussions was that using insularity cannot be considered sufficient: it is necessary to restructure pig farms to make them less vulnerable, especially to the many health hazards already present on the island.

Some farmers agreed that while the biosecurity measures imposed are not acceptable, doing nothing is not acceptable either and certainly will not be accepted by the authorities. There is also the risk of prompting the state to take an authoritarian attitude that would drive the majority of farms into the informal economy. Preparing against ASF means first knowing how to combat the health hazards already present.

This first phase led the farmers' collective to agree on the unacceptability of national measures, but also to three conclusions:

(i) preparation against ASF is an opportunity to tackle the sector's health issues more generally;
(ii) farmers are not alone in having to make efforts (as indicated by the issue of border controls, the state must also be able to protect the island), and it will be necessary to organize a sharing of responsibilities and the mobilization of adequate resources; and
(iii) the need for a TC composed of regional research and development actors to draw up practical proposals to address the local situation.

Building Locally Acceptable Responses: Toward Territorial Negotiation

The TC first aimed to bring together people working in scientific and technical support for the pig sector. Its composition includes representatives of the hunters (because of the need for wildlife surveillance), and it was suggested that the representatives of the slaughterhouses should also be integrated. One question remained: what should be the place for the professional representatives of the farmers' organizations? How to manage representativeness and balances within the TC? With an *ad hoc* body created from scratch, special care must be taken in establishing its operating rules, with a pre-agreed agenda and minutes taken down by members collectively appointed as secretaries, taking turns. In order to structure the work, the TC drew up a schedule to identify the issues to address over the course of the meetings.

First, the TC carried out a systemic analysis of the situation. Thus, the TC extended its thinking beyond ASF to the health hazards already present as a real emergency. In particular, bovine tuberculosis, which affects some pig farms, appears to be particularly relevant. Designing a regional health plan therefore means including the danger posed by ASF along with the diseases to be considered. As far as flows are concerned, waste management is a very sensitive point and a very effective dissemination route in the current situation. Hunting (abandoned remains) and farm processing (deli waste) are the greatest risks of health hazards in the wild. Major efforts will have to be made to limit these risks.

The TC met mainly in plenary sessions, but at a certain stage, it proved necessary to set up a special "Farm Biosecurity" group in order to adapt the biosecurity measures to the Corsica free-range farming. Several meetings (in working groups and then at a plenary meeting) enabled us to compare points of view and to make proposals that balanced protection of the animals with maintenance of extensive grazing on pastureland. From the hierarchy of risks expressed by farmers and incorporated in its work, the TC identified the main line of its proposals: limiting direct interaction between animals by reproductive control. The sow in heat attracts males from a wide area, leading to intense interaction. This initial reasoning logically led to a set of provisions such as mating confinement and oophorectomy of non-breeding females. This reasoning drew on earlier discussions within the local Nustrale breed selection scheme, a networked genetic management arrangement among pig farmers. Many of the pig farmers already perform oophorectomy on their sows (23). The extra cost to those farmers who do not do it should be paid by ODARC, the Corsican Office of Agricultural and Rural Development (one member of the TC is on the staff of this body), with which the funding of the Regional Health Plan had to be negotiated (**Text Box 1**).

BOX 1 | Main measures of the regional health plan negotiated between pig farmers, local stakeholders, and national authorities in the territorial preparedness process against African swine fever in Corsica (2019–2021).

The regional health plan is based on three objectives: (1) preventing the disease from entering the territory, (2) detecting its arrival early so as to reduce its impact, and (3) managing actions for its eradication.

First, to achieve these objectives, the TC identified 12 sub-goals and 40 actions and listed the actors responsible for implementing each action. Some of the main actions identified are as follows:

- Improving identification of animals and farmers
- Raising the awareness of farmers and hunters to the issue of managing the waste from hunting and butchery
- Raising farmers' awareness of the importance of using the abattoirs for slaughtering
- Making sure the abattoirs have the capacity to meet all the island's slaughtering needs
- Improving border controls and tourist awareness of the issue
- Setting up experimental management plans for Aujeszky's disease and tuberculosis

The TC then proposed adaptations of the national biosafety measures, involving the following:

- Keeping breeding animals behind double fences
- Using grazing land for castrated animals only to avoid sexual interaction with wild pigs and animals from other farms
- Returning leader sows to the farm as soon as possible after their quarantine
- Creating a quarantine zone on the pastureland in the event of a health danger
- Bringing farms up to standard in staggered order, to allow time for farms that are lagging behind to adapt gradually

The TC then conducted checks along the way with a small number of diverse farmers: would they agree to guard against direct sexual interactions by protecting their sow units? Most of these small farmers both farrow and fatten, with self-replacement of the sows. They confirmed, whatever their position at the start of the debates, that sows and boars represent their basic genetic heritage and that protecting them as operating capital will enable them to continue their business even if there is disease in the environment. But they accepted the possible risk of indirect contact with wildlife or between herds on the pasturelands. Farmers also argued that pregnant sows should continue to have access to the pasturelands. In particular, "leader sows" (older females), followed by their offspring, play a major role in animal-to-animal learning (knowledge of feeding, watering, and sleeping areas) and in managing the herd. The TC then designed a procedure to allow pregnant sows to remain on the pasturelands, returning to the protected breeding unit for a quarantine period before giving birth.

However, increasing the level of reproductive control and getting equipped with the necessary breeding arrangements will require training, time, and resources. The TC then held thorough-going discussions on the changes that would allow for the diversity of the farms: obviously not all farmers start from the same point, and they cannot all go at the same speed. The authorities will have to understand the need for gradual change: a progressive approach should be designed, with stages of compliance and timetables. It should allow those who want to go fast to do so while making sure to support all the farmers, regardless of their starting point.

Resources for the Regional Health Plan should be provided by ODARC through grants for farm restructuring. The TC made an initial estimate of the credits to be allocated. It has also reflected on the eligibility conditions for these subsidies and the commitments farmers would have to make to benefit from them. The aim is to ensure equal treatment between all the farmers.

The final step in this phase was the validation of the TC's work by the farmers' collective. The TC presented its results to stakeholders in three stages:

(i) consultation with the professional leaders of the four farmers' organizations;

(ii) design of a flier listing all the proposals, which was sent to all the farmers;

(iii) a regional debriefing meeting of the farmers' collective to present the work of the TC.

Negotiating Acceptability With the Authorities

Once the farmers' collective had validated the TC's proposals, it was a question of meeting the expectations of the local officials of the state. Aware of the inadequacy of national measures with the Corsican context, the local officials of the state were ready to listen to the farmers' collective and TC proposals. They quickly accepted much of the reasoning behind the TC proposals and were ready to support the Regional Health Plan as a whole. These initial contacts between the farmers' collective (accompanied by the TC) and the local officials led to discussions about the proposals and the issues of biosecurity training, timelines, and controls (a requirement that the national authorities had imposed on the local officials). As a result, negotiations with national authorities were partially facilitated by the progressive enrollment of local officials to the Regional Health Plan.

The local officials clearly understood the broad scope of the Regional Health Plan, not only the issue of biosecurity on farms. In particular, there was intensive discussion of the issues of waste, hunting, slaughterhouses, and vehicle traffic between farms. The TC's work on these aspects provides a systemic vision of the issues connected with the dissemination of health hazards.

However, farm biosecurity remained a key element of the overall plan. The notion of pastureland and the hierarchy of risks between breeding stock and deli meat pigs soon arose in the discussions, along with the issues of oophorectomy and gestation control. However, the concept of the "leading sow" was the subject of in-depth reflection as the movement of these animals between protected and open areas can introduce significant risks.

The representativeness of the four farmers' organizations within the farmers' collective remained a sensitive point. Not all the identified positions were represented, and everyone was well-aware that the Plan was not spontaneously acceptable to all the farmers. But, the implementation of the Plan could isolate the recalcitrants, giving pledges to farmers willing to make efforts. Therefore, leaving the informality of a number of farmers while improving the structure of the sector as a whole became a medium-term objective of the Plan. So preparedness is an effective opportunity to stimulate the sector, and successful negotiation has major implications for solving the difficulties of a "problem" sector (slaughterhouses, trichinellosis, tuberculosis). This perspective makes it all the more important spending every effort to involve all parties, even those who resist.

Discussions with the national experts revealed another issue for negotiation: adaptations designed for one territory must not be available to all on the mainland. This was a condition the national authorities imposed to enable negotiations without losing control of the situation nationwide. In addition, the Regional Health Plan proposal includes the idea of taking specific measures to deal with a worrying zoonosis, bovine tuberculosis, with specific means and a timetable.

Finally, this phase complicated the acceptability testing insofar as differences of appreciation arose within the local officials and between them and the national authorities. Having a role for local specialist services in the decision chain has been essential for getting the authorities to understand the situation on the ground. In these discussions, the national experts played an important role in defining the acceptable and opening the way for local adaptations. So the process has involved a complex interplay between local experts and national experts on the one hand and local and national authorities on the other. The TC acts as a mediator in discussions to negotiate a solution (**Figure 1**).

This negotiation period is still ongoing at the time of writing, and it is still too early to know the final results.

DISCUSSION

When Territorial Preparedness Meets "Local Universality"

In animal health management, the notion of "local universality" (40) is based on the idea that biosecurity measures are universal if they can be adapted to local contexts. It addresses the formal or informal negotiations made at the individual level that can make biosecurity measures practicable (41). However, when there is too great a gap between management principles built on a non-contextualized understanding of risk and locally specific configurations of a livestock sector, minor adaptations are not sufficient. This is especially true for the pig farming sector in Corsica, where a statistically marginal group includes the majority of farmers. Even local or minor adaptations of national biosecurity obligations would not have been acceptable to the farmers because its main thrust (keeping pigs off the open pasturelands) is in total contradiction with the Corsican systems.

The process of territorial preparedness is not a process of adaptation (in the sense of local universality) or a simple variation on a national measure according to a local context (42, in 11), but a bottom-up construction that creates new collective modes of pig health management at the level of a subnational territory. It transcends the usual barrier-based way of thinking about biosecurity measures (6). It is a collective construction that starts from a specific, territorial, multi-issue perspective (taking account of Corsican pig farming systems, proximity to Sardinia, insularity, the presence of other pig diseases, etc.) that does not rely only on the epidemiological point of view (5). In a sense, as territorial preparedness fosters a "bottom-up perspective" encompassing specific territorial configurations, it encounters the "top-down" perspective of local universality, stressing the creative capacities of local stakeholders, including the regional health administration.

The outcome of the process is not yet known, but it could represent an "[...] *autonomous system of collective action [...], empowered by its specific modes of governance in accordance with local values and behaviors*" (Dubresson and Jaglin, 2005, 11)—a shift to genuinely subnational risk management. If the plan is accepted, the island of Corsica cannot be considered an "area at risk" or a "sentinel island" from an epidemiological point of view (21) because of "particular ways" of breeding pigs that pose a particularly high risk of disease spillover. Instead, it would be a "risk-prepared territory" (11), thanks to the reframing of the risk in a "*singular, situated, and dated relation to a society and a territory*" (11). So, as this territorial preparedness takes into account the specific technical features of the Corsican pig farming systems and the epidemiological risk of ASF, the French government is likely to accept this alternative. There are two final arguments in favor of such acceptance. First, the fact that Corsica is an island limits the risk of ASF spillover to mainland France. Second, by acknowledging Corsica's particularities, the state authorities can strictly limit the proposed biosecurity norms to this territory without opening the door to administrative divisions on the mainland where similar difficulties may occur.

Finding the Way Toward Compromise: The Role of Local Expertise in the Mediation Process

Our results show several steps of acceptability testing in the process of building subnational territorial preparedness mediated through the work of the TC. Mediation process is crucial for territorial preparedness at subnational levels. The negotiations were not between two coherent groups (government vs. farmers). The pig sector includes a wide diversity of farming systems (and a diversity of positions), and the public authorities also are not homogeneous. Public servants in the region played a crucial role in technical discussions and the negotiation round with the national authorities. The diverse nature of the public authorities in terms of local anchorage and practices is an important point from a public management point of view (43, 44) for any further investigation of the dynamics of building territorial preparedness.

The preparedness reasoning was carried out by "local expertise," and government experts opened a space for discussion of technical and organizational issues in participative settings. This eased the potential political tensions such as those that often emerge when government policy is implemented in a top-down manner (45). Taking part in essentially technical and organizational discussions, the researchers and development officials avoided adopting advocacy positions. Being both internal actors (as experts) and external actors (drawing no benefit from the results of the negotiation), they avoided, in analysis and interpretation of results, the possible biases such as those that have been highlighted in previous research on participative approaches (46, 47). The best reflection of this is the credibility that the State representatives accorded the proposals. The involvement of public sector researchers can help small, poorly organized farming systems on the margins of mainstream agricultural production by providing a discussion space for exploring their prospects.

One illustration of this is the "traditional" aspect of Corsica's pig sector. As a major justification for the PDO application, the traditional practices shaped the requirements linking the way the pigs are herded with the typicality of the deli meat products. However, in the early discussions, tradition was used (particularly by the "passive" farmers) as an argument for rejecting any change imposed by the national biosecurity plan. This argument was refuted by old breeding control practices: traditionally, hybridization was prevented by locking up the sows during the mating season (48). The current, recently adopted practices (lack of breeding control in full free-range) cannot be presented as "traditional" (even if the "passive" farmers do so). The proposed changes for an adapted biosecurity may be seen as a return to the real tradition in which domestic pigs and wild boars were strictly separated in the mating season. In fact, "tradition" is an interpretation of the past from the standpoint of the interests and opinions of the present (49).

As a result, local farming systems gained legitimacy not on a "heritage" basis (the supposed tradition) but on the local stakeholders' commitment to transform the pig sector in order to improve general biosecurity and preparedness. This shows a kind of paradox, in that preserving Corsica's pig farming systems depends on changing them. This "normalization" is acceptable to the farmers because it preserves their mode of production (use of pasturelands) and the associated benefits (government subsidies) and offers them the possibility of negotiating for additional subsidies to enable farmers to reach the collectively established norms. Under these conditions, Corsican farmers get guarantees from the state, unlike other places such as Sardinia, where the implementation of biosecurity standards drove free-range systems to extinction by declaring them illegal (50). Without the mediated process, there was likely to be widespread rejection of the national biosecurity plan, with many farmers joining the informal sector. The mediation process made it possible to develop such considerations and get them acknowledged, facilitating learning and building trust through shared consideration of each participant's issues (27). Judging by our experience with small farmers' issues, such trust building is a key condition for success in collective action.

The End of an Embarrassing Notion: Toward Democratic Acceptability

When social acceptability is treated as a dynamic process, it is no longer an "embarrassing notion" (26, 28) that would imply getting local actors to accept measures they do not want. The territorialized preparedness process is the result of a collective bottom-up dynamic that legitimizes not only the biosecurity co-construction process but also the actors who carried it out. At the local level, the farmers' collective, representing the interests of all the farmers, and the TC are emerging as recognized actors in health management. They transcend the old divisions between individual farmers and between organizations (each with its own economic or socio-technical objectives) and outline a new form of collective action for health that the existing farmers' organizations did not provide (51). We observed here the start of a completely new form of consultation within the sector: all the pig farmers united against a common danger. The collective dimension of animal health management is thus affirmed. The authorities—both national and local—now recognize the TC and the farmers' collective as negotiating partners and acknowledge the preparedness-building process and its output, the Regional Health Plan, which could lead to subnational-level health governance (52).

The legitimacy of the actors involved in the social acceptability process is central (27). The legitimacy of the TC was built up during the process, with each member of the TC earning recognition within the TC and the TC becoming legitimate in the eyes of both the state and the farmers, specifically through its collective local expertise, but also because it brought together all the actors connected with livestock health. This approach to preparedness, built on a process-based, bottom-up, regionally differentiated mode ((53), in 26), makes traditional Corsican farming systems acceptable, despite being unacceptable from the standpoint of national biosecurity standards. Moreover, the whole process, through technical and organizational discussions, has made biosecurity and stakeholder issues on the island more visible and comprehensible. It helped to build trust between stakeholders, TC members, the authorities, and farmers, so that they could pursue the co-production process (27).

The acceptability of territorial preparedness is a democratic process. On the one hand, Corsican farmers and other stakeholders have become actors in their own future (26); on the other hand, the state has agreed to negotiate with a marginal region that views norms in light of its own issues. In so doing, it recognizes as legitimate the extensive farming systems. In terms of biosecurity and risk management, the real problem is not the farming system but the way in which the territory and its stakeholders are involved in decisions about management measures. Marginal systems can be regarded as threats to the proper functioning of society or they can be a hotbed of innovation, fostering democratic experimentation (54). If the government accepts Corsica's preparedness project, this will probably be due to the fact that both the territory and the farming system are marginal. The democratic experiment will be more easily accepted in the Corsican case because it will remain circumscribed to this island territory, a condition set by the state from the outset.

This collective experiment in co-production of an acceptable ASF preparedness specific to the island highlights the emergence of a "style of reasoning" about preparedness (4). By including stakeholders' particular issues and representations and generating local legitimacy, it may avoid the programmed failure of national guidelines, procedures, and instruments (4, 10) in animal disease prevention.

For One Health or planetary health to be perhaps more effective and operationalizable, it seems important not to stigmatize marginal areas and alternative farming systems by forcing change on them. Instead, there should be coordination to build the conditions for biosecurity measures that farmers can accept. A striking counter-example is Sardinia, where outlawed extensive farming is largely responsible for the failure of a number of eradication plans. After a 40-year struggle against ASF, a coordination of various local experts, the *Unita di progetto* (55), has recently been formed and seems to be producing good results. This example and the Corsican preparedness plan are strong arguments for integrated, coordinated, locally oriented approaches to emerging diseases rather than standardized top-down approaches.

CONCLUSION

This article has described and analyzed the building of an alternative preparedness solution to fight against ASF by means of action research conducted by the authors of this article.

First, we demonstrate the unacceptability of the national measures from the viewpoint of the farmers concerned and formalize the arguments that forged it. We explain and analyze their arguments and the various positions they reveal. The clash between these arguments led to the creation of a new body, the regional TC. Then, through a long iterative process, the TC developed a Regional Health Plan that takes into account the specific features of the smallholder farmers' situation and incorporates the need to protect them from health hazards, not only the emerging one of ASF but also those that are already present. The TC first submitted the proposed Plan to the smallholder farmers and their organizations because many of these smallholders are not prepared to make major changes to their farming practices. Finally, this Regional Health Plan, which includes biosecurity measures specific to local farms, became the subject of negotiations with the authorities.

The process is original in several respects. (i) The TC did not simply seek to adapt the national biosecurity standards to Corsican farms. It constructed new proposals that constitute overall ASF preparedness for a specific territory. This locally specific preparedness plan engages the responsibility of a multiplicity of actors, not only the farmers, and addresses not only the ASF risk but also health hazards already present. Biosecurity and the husbandry measures were designed to preserve the use of the free range while avoiding interactions with wildlife. (ii) The TC, as a committee of experts, not only made proposals but also acted as intermediary between the farmers and the state, making sure the proposals were acceptable first to the farmers and then to the authorities. The TC organized the conditions that made negotiation possible. (iii) The collective action initiated by the TC seems to inaugurate a new way of thinking about the governance of animal health in Corsica. More generally, the crucial role played by the TC in the process offers useful ideas about empowering public action through local mediation and co-production capacities, especially in France, where animal health matters are centrally governed.

The process of territorial preparedness in Corsica shows that there are alternatives to standardized biosecurity and the risk of disappearance of small farmers and their traditional systems. The legitimacy of these farms should be established in partnership with other local stakeholders through a regional approach to risk and bottom-up construction of preparedness.

DATA AVAILABILITY STATEMENT

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

ETHICS STATEMENT

Ethical approval was not provided for this study on human participants because an oral agreement is established on the researchers role in such collective process. Participants of this study were informed in advance about details of how the data would be used, assuring anonymity, and informed consent was orally obtained. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

AUTHOR CONTRIBUTIONS

MG and FCa contributed to the initiation and supervision of research. MG, FCa, and BT participated in the action-research process and data production. MG, FCa, FCh, and BT contributed to the conception, data analysis, visualization and writing, and manuscript revision. All authors contributed to the article and approved the submitted version.

FUNDING

This study was supported by the INRAE Animal Health division as part of the Gcoppa5 project (Territorial Dynamics and Management of African Swine Fever: A comparative approach between Belgium, French Ardennes, French South West, Corsica and Sardinia) and the Collectivité de Corse as part of the NovPath project.

REFERENCES

1. Rose N, Le Potier MF. L'épizootie de peste porcine africaine: virologie, épidémiologie et perspectives de contrôle. *INRAE Productions Animales.* (2020) 33:65–80. doi: 10.20870/productions-animales.2020.33.2.3857
2. Chenais E, Depner K, Guberti V, Dietze K, Viltrop A. Ståhl K. Epidemiological considerations on African swine fever in Europe 2014-2018. *Porc Health Manag.* (2019) 5:6. doi: 10.1186/s40813-018-0109-2
3. Arrêté ministériel du 16 octobre 2018. AGRG1828116A. (2018). Available online at: https://www.legifrance.gouv.fr/jorf/jo/2018/10/17/0240 (accessed April 20, 2021).
4. Lakoff A. *Global Health in a Time of Emergency*. Oakland, CA: University of California Press (2017).
5. Enticott G, Franklin A. Biosecurity, expertise and the institutional void: the case of bovine tuberculosis. *Sociologia Ruralis.* (2009) 49:375–93. doi: 10.1111/j.1467-9523.2009.00496.x
6. Hinchliffe S, Allen J, Lavau S, Bingham N, Carter S. Biosecurity and the topologies of infected life: from borderlines to borderlands. *Transations.* (2012) 38:531–43. doi: 10.1111/j.1475-5661.2012.00538.x
7. McConnell, Stark A. A. Bureaucratic failure and the UK's lack of preparedness for foot and mouth disease. *Public Policy Adm.* (2002) 17:39–54. doi: 10.1177/095207670201700404
8. Bronner A, Hénaux V, Fortané N, Hendrikx P, Calavas D. Why do farmers and veterinarians not report all bovine abortions, as requested by the clinical brucellosis surveillance system in France? *BMC Vet Res.* (2014) 10:93. doi: 10.1186/1746-6148-10-93
9. Dekens J. *Local Knowledge for Disaster Preparedness: A Literature Review*. Kahtmandu: ICIMOD, ECHO (2007).
10. Deville J, Guggenheim M, Hrdličková Z. Concrete governmentality: shelters and the transformations of preparedness. *Soc Rev.* (2014) 62:183–210. doi: 10.1111/1467-954X.12129
11. Reghezza-Zitt M. Territorialiser ou ne pas territorialiser le risque et l'incertitude. La gestion territorialisée à l'épreuve du risque d'inondation en Île-de-France. *L'espace politique.* (2015) 26. doi: 10.4000/espacepolitique.3543
12. Frelih-Larsen A. Semi-subsistence producers and biosecurity in the Slovenian Alps. *Sociol Ruralis.* (2009) 49:330–42. doi: 10.1111/j.1467-9523.2009.00481.x
13. Leclair L. *Pandémies, une production industrielle*. Paris: Seuil (2020).
14. Enticott G. The spaces of biosecurity: prescribing and negotiating solutions to bovine tuberculosis. *Environ Plan.* (2008) 40:1558–82. doi: 10.1068/a40304
15. Manceron V. Grippe aviaire et disputes contagieuses. La Dombes dans la tourmente. *Ethnol Fr.* (2009) 39:57–68. doi: 10.3917/ethn.091.0057
16. Law, Moser JI. Contexts and culling. *Sci Technol Hum Values.* (2012) 37:332–54. doi: 10.1177/0162243911425055
17. Delsart M, Pol F, Dufour B, Rose N, Fablet C. Pig farming in alternative systems: strengths and challenges in terms of animal welfare, biosecurity, animal health and pork safety. *Agriculture.* (2020) 4:261. doi: 10.3390/agriculture10070261
18. Sainte Marie de, Ch., Casabianca F. Entre logique individuelle et intégration: la≪ fruitière≫ comme modèle d'organisation pour des producteurs fermiers de charcuterie en Corse. *Etudes et Recherche sur les Systèmes Agraires et le Développement.* (1998) 31:297–315.
19. Relun A, Charrier F, Trabucco B, Maestrini O, Molia S, Chavernac D, et al. Multivariate analysis of traditional pig management practices and their potential impact on the spread of infectious diseases in Corsica. *Prev Vet Med.* (2015) 121:246–56. doi: 10.1016/j.prevetmed.2015.07.004
20. Lambert-Derkimba A, Verrier E, Casabianca F. Tensions entre ressources génétiques locales et ancrage territorial des produits: le cas du porc Nustrale et du projet d'AOP charcuterie de Corse. *Écon Rurale.* (2011) 322:39–49. doi: 10.4000/economierurale.2982
21. Goutard F, Cornélis D, Chevalier V, Etter E, Charrier F, Jori F, et al. *Risk analysis in Corsica, sentinel island in Mediterranean basin, ed OIE. Risk Analysis as a tool for the control of Animal Diseases and Zoonoses in the Mediterranean Basin*. Teramo, Italy (2013).
22. Calba C, Antoine-Moussiaux N, Charrier F, Hendrikx P, Saegerman C, Peyre M, et al. Applying participatory approaches in the evaluation of surveillance systems: a pilot study on swine fevers in Corsica. *Prev Vet Med.* (2015) 122:389–98. doi: 10.1016/j.prevetmed.2015.10.001
23. Charrier F, Rossi S, Jori F, Maestrini O, Richomme C, Casabianca F, et al. M.F. Aujeszky's disease and hepatitis e viruses transmission between domestic

pigs and wild boars in corsica : evaluating the importance of wild/domestic interactions and the efficacy of management measures. *Front Vet Sci.* (2018) 5:1-11. doi: 10.3389/fvets.2018.00001

24. Richomme C, Boschiroli ML, Hars J, Casabianca F, Ducrot C. Bovine tuberculosis in livestock and wild boar on the mediterranean island, Corsica. *J Wildl Dis.* (2010) 46:627–31. doi: 10.7589/0090-3558-46.2.627
25. Ducrot C, Pécaud D, Petit É, Krebs S, Viet, A-F,Durand B, et al. Qualification sanitaire des troupeaux, représentations du risque selon les acteurs et les disciplines. *Nat Sci Soc.* (2010) 18:3–13. doi: 10.1051/nss/2010002
26. Fournis Y, Fortin MJ. Une définition territoriale de l'acceptabilité sociale: pièges et défis conceptuels. VertigO. (2015) 15. doi: 10.4000/vertigo.16682
27. Borraz O, Salomon D. Reconfiguration des systèmes d'acteurs et construction de l'acceptabilité sociale: le cas des épandages de boues d'épuration urbaines. In: Gilbert C, editor. *Risques et crises. Bilan et Perspectives*. Paris: L'Harmattan (2002). p. 345–67.
28. Barbier B, Nadaï A. Acceptabilité sociale: partager l'embarras. *VertigO—la revue électronique en sciences de l'environnement.* (2015) 5. doi: 10.4000/vertigo.16686
29. Steyaert P, Cerf M, Barbier M, Levain A, Loconto A. Role of intermediation in the management of complex socio-technical transitions. In: *Communication au 2e Séminaire International System innovation towards Sustainable Agriculture*. Paris (2014).
30. Agreste-Draaf de Corse. *Panorama de l'agriculture corse 1970–2015*. Ajaccio: Draaf (2017).
31. Aggeri F. La recherche-intervention : fondements et pratiques. In: Barthélemy J, Mottis N, editors. *A la pointe du management. Ce que la recherche apporte au manager*. Paris: Dunod (2016). p. 79–100.
32. David A. La recherche intervention, un cadre général pour les sciences de gestion? In: *IX^{ème} Conférence Internationale de Management Stratégique*. Montpellier (2000).
33. David A, Hatchuel A, Laufer R. *Les Nouvelles Fondations des sciences de gestion*. Paris: Presses de Mines (2012).
34. Romelaer P. "L'entretien de recherche", In: Roussel P, Wacheux F, editors. *Management des ressources humaines: méthodes de recherche en sciences humaines et sociales*. Louvain-la-Neuve: De Boeck (2005). p. 101–37.
35. Kaufmann JC. *L'entretien compréhensif*. Paris: Nathan (1996).
36. Toulet N. Biosécurité et avenir de l'élevage porcin sur parcours en contexte de perte porcine africaine. Mise en regard de la ≪preparedness≫ en Corse et de 40 ans de lutte en Sardaigne (master's thesis). Clermont-Ferrand: VetAgroSup/INRAE (2008).
37. Miles MB, Huberman M. In: Miles MB, Huberman M, editors. *Qualitative Data Analysis*. 2nd ed. Sage Publications (1994).
38. Dumez H. Qu'est-ce que la recherche qualitative? Problèmes épistémologiques, méthodologiques et de théorisation. *Gérer et Comprendre.* (2013) 112:29–42. doi: 10.3917/geco.112.0029
39. Dumez H, Jeunemaitre A. Reviving narratives in economics and management: towards an integrated perspective of modelling, statistical inference and narratives. *Eur Manag Rev.* (2006) 3:32–43. doi: 10.1057/palgrave.emr.1500054
40. Timmermans S, Berg M. Standardization in action: achieving local universality through medical protocols. *Soc Stud Sci.* (1997) 27:273–305. doi: 10.1177/030631297027002003
41. Enticott G. The local universality of veterinary expertise and the geography of animal disease. *Trans Inst Br Geogr.* (2012) 37:75–88. doi: 10.1111/j.1475-5661.2011.00452.x
42. Dubresson A, Jaglin S. Gouvernance, régulation et territorialisation des espaces urbanisés: approches et méthode. In: Antheaume B, Giraut F, editors. *Le territoire est mort: vive les territoires! Une refabrication au nom du développement*. Paris: IRD (2005). p. 337–52.
43. Frederickson G. Whatever happened to public administration? Governance, governance everywhere. In: Ferlie E, Lynn JLE, Pollitt C. *The Oxford Handbook of Public Management*. Oxford: Oxford University Press (2005). p. 281–304.
44. Dubois V. Ethnographier l'action publique. Les transformations de l'État social au prisme de l'enquête de terrain. *Gouvernement et Action Publique.* (2012) 1:83–101. doi: 10.3917/gap.121.0083
45. Gisclard M, Chantre E, Cerf M, Guichard L. Coclick'eau: une demarche d'intermédiation pour la construction d'une action collective locale? Nat Sci Soc. (2015) 3:3–13. doi: 10.1111/j.1475-5661.2011.0045245
46. Albaladejo C. Casabianca F. *La recherche-action: ambitions, pratiques, débats*. Etudes et Recherches sur les Systèmes Agraires et le Développement. Paris: INRA (1997).
47. Barnaud C. La participation, une légitimité en question. *Nat Sci Soc.* (2013) 34:24–34. doi: 10.1051/nss/2013062
48. Molenat M, Casabianca F. *Contribution à la maîtrise de l'élevage porcin extensif en Corse*. Paris: Bull Tech du Département de Génétique Animale, INRA. (1979). p. 32–72.
49. Lenclud G. La tradition n'est plus ce qu'elle était. *Terrain.* (1987) 9:110–23. doi: 10.4000/terrain.3195
50. Laddomada A, Rolesu S, Loi F, Cappai S, Oggiano A, Madrau AP, et al. Surveillance and control of African swine fever in free-ranging pigs in sardinia. *Transbound Emerg Dis.* (2019) 66:1114–9. doi: 10.1111/tbed.13138
51. Gisclard M, Devleeshouwer P, Charrier F, Casabianca F. Action collective et gestion sanitaire des élevages porcins en Corse. *Développement Durable et Territoires.* (2021) 12. doi: 10.4000/developpementdurable.18618
52. Guériaux D, Soubeyran E, Francart J, Canivet N. La nouvelle gouvernance sanitaire française se met en place. *Bulletin Épidémiologique Santé Animale-Alimentation.* (2012) 55:30–1.
53. Lascoumes P, Le Bourhis JP. Le bien commun comme construit territorial. Identités d'action et procédures. *Politix.* (1998) 11:37–66. doi: 10.3406/polix.1998.1724
54. Graeber D. *The Democracy Project: A History, a Crisis, a Movement*. New-York: Spiegel and Grau (2013).
55. Laddomada A. *The Last Mile in the Eradication of ASF in Sardinia*. Paris: OIE Bulletin PANORAMA (2020).

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

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

Copyright © 2021 Gisclard, Charrier, Trabucco and Casabianca. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.

frontiers in Veterinary Science

ORIGINAL RESEARCH
published: 30 July 2021
doi: 10.3389/fvets.2021.692448

African Swine Fever in Smallholder Sardinian Farms: Last 10 Years of Network Transmission Reconstruction and Analysis

Sandro Rolesu [1†], Daniela Mandas [1†], Federica Loi [1*†], Annalisa Oggiano [2], Silvia Dei Giudici [2], Giulia Franzoni [2], Vittorio Guberti [3] and Stefano Cappai [1]

[1] Sardinian Regional Veterinary Epidemiological Observatory, Istituto Zooprofilattico Sperimentale della Sardegna "G. Pegreffi", Cagliari, Italy, [2] Department of Animal Health, Istituto Zooprofilattico Sperimentale Della Sardegna, Sassari, Italy, [3] ISPRA—Institute for Environmental Protection and Research, Rome, Italy

OPEN ACCESS

Edited by:
Mary-Louise Penrith,
University of Pretoria, South Africa

Reviewed by:
Solenne Costard,
EpiX Analytics, United States
Claire Guinat,
ETH Zürich, Switzerland

***Correspondence:**
Federica Loi
federica.loi@izs-sardegna.it

†These authors have contributed equally to this work and share first authorship

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

Received: 08 April 2021
Accepted: 30 June 2021
Published: 30 July 2021

Citation:
Rolesu S, Mandas D, Loi F, Oggiano A, Dei Giudici S, Franzoni G, Guberti V and Cappai S (2021) African Swine Fever in Smallholder Sardinian Farms: Last 10 Years of Network Transmission Reconstruction and Analysis. Front. Vet. Sci. 8:692448.
doi: 10.3389/fvets.2021.692448

African swine fever (ASF) is a viral disease of suids that frequently leads to death. There are neither licensed vaccines nor treatments available, and even though humans are not susceptible to the disease, the serious socio-economic consequences associated with ASF have made it one of the most serious animal diseases of the last century. In this context, prevention and early detection play a key role in controlling the disease and avoiding losses in the pig value chain. Target biosecurity measures are a strong strategy against ASF virus (ASFV) incursions in farms nowadays, but to be efficient, these measures must be well-defined and easy to implement, both in commercial holdings and in the backyard sector. Furthermore, the backyard sector is of great importance in low-income settings, mainly for social and cultural practices that are highly specific to certain areas and communities. These contexts need to be addressed when authorities decide upon the provisions that should be applied in the case of infection or decide to combine them with strict preventive measures to mitigate the risk of virus spread. The need for a deeper understanding of the smallholder context is essential to prevent ASFV incursion and spread. Precise indications for pig breeding and risk estimation for ASFV introduction, spread and maintenance, taking into account the fact that these recommendations would be inapplicable in some contexts, are the keys for efficient target control measures. The aim of this work is to describe the 305 outbreaks that occurred in domestic pigs in Sardinia during the last epidemic season (2010–2018) in depth, providing essential features associated with intensive and backyard farms where the outbreaks occurred. In addition, the study estimates the average of secondary cases by kernel transmission network. Considering the current absence of ASF outbreaks in domestic pig farms in Sardinia since 2018, this work is a valid tool to specifically estimate the risk associated with different farm types and update our knowledge in this area.

Keywords: African swine fever, smallholder farms, traditional pig farming system, outdoor pig farm, biosecurity measure, secondary case, kernel function, mathematical model

INTRODUCTION

African swine fever (ASF) is a devastating disease of domestic and wild pigs, frequently resulting in the death of infected animals. The disease causes significant losses in the pig sector due to its transcontinental spread and the lack of a licensed vaccine or treatment; thus, it currently represents one of the most important infectious and lethal swine diseases (1). The aetiological agent is the ASF virus (ASFV), a large double-stranded DNA virus that mainly infects myeloid cells, such as monocytes, macrophages, and dendritic cells (2, 3). Currently, 24 ASFV genotypes have been identified based on a fragment of the variable region of the B646L gene, which encode for the major protein p72 (3). So far, only genotype I ASFV isolates have been reported in Sardinia (4–6). Specific ASFV antibodies appear 7–10 days post-infection (dpi) (7), while clinical symptoms strictly depend on the different forms of the disease (8). The most common symptoms are fever, loss of appetite, lack of energy, abortion and hemorrhage (9). Sudden death may occur. Virulent ASFV isolates are generally fatal (death occurs within 10 days), while animals infected with attenuated ASFV strains may not show typical clinical signs (8). Even though the human population is not susceptible to the disease, ASF represents a global threat, given the associated considerable sanitary and socio-economic consequences. In fact, to date, ASF is widespread in over 30% of European, Asian and African countries, with a total of 8,551 ongoing outbreaks worldwide and Europe accounting for 67% of those reported outbreaks (10). Greater concerns are associated with the spread of the disease in China, which retains the largest pig production market (11, 12). There is a lack of information about ASF epidemiology, particularly in relation to different farm types. Despite the fact that the overall spread has been quantified (13, 14), ASFV's capacity for transmission between different farm types has never been defined. Furthermore, different basic reproduction number estimations have been provided for both wild and bred pig populations (4, 15–25), but are limited to a specific epidemic period and do not allow for a comparison to be made between different farm types. Despite the fact that the main risk factors are well-known overall, they are not specifically tailored to commercial or backyard farms (26). Several problems arise from the definition of secondary ASF cases. In fact, even though the ASF Diagnostic Manual (27) includes the condition "secondary cases epidemiologically correlated to primary case" for an outbreak declaration, the lack of a specific epidemiological correlation definition in terms of space and time makes this condition difficult to apply. The ASF risk estimation is even more complicated when considering the three different types of European pig farms described by the Working Document of the Directorate General for Health and Food Safety: "African swine fever strategy for Eastern part of the European Union" (SANTE/7113/2015-Rev 12). In this document, pig farms are classified as non-commercial, commercial, and outdoor farms. As underlined by Bellini et al. (28), this classification takes into account the commercial attitude of the holdings rather than the size of the farm or the type of establishment, thus making the application of most established biosecurity measures difficult (28–30). Furthermore, the last EFSA opinion on ASF and outdoor farming system underlines the lack of specific and harmonized system to categorize different types of pig farms (31). Considering the limited number of studies available on smallholder pig farms, in-depth evaluation of field data is required to define ASF risk factors specific to these types of farms, evaluate target biosecurity measures, and estimate the efficiency of these measures in European countries (32–36). Otherwise, finding the right context for such a specific, in-depth study could be difficult for several reasons. In fact, a robust epidemiological evaluation is more complete and detailed if the epidemic is halted or if there is epidemiological silence for at least 1 year (37). In addition, backyard farms are not common in all countries or not present in all forms (i.e., indoor, and outdoor). Even though Sardinia has not yet been declared free from ASF, the island context seems to be appropriate for the purpose of this work, given that the last ASFV outbreak in domestic pigs dates back to 2018 and the last virus finding in the wild boar to April 2019 (38). This allows to provide in details the risk factors associated with the occurrence of ASF at farm level. The aim of this work is to provide a descriptive analysis of the Sardinian farms where ASF outbreaks occurred during the past 10 years. Details on the farm type, biosecurity measures applied, ASFV laboratory results and clinical signs are included. Furthermore, this study aims to estimate the most likelihood ASF transmission network applying nearest-neighbor and uniform kernel function and compare these networks with that one described by official veterinarian reports. Finally, multilevel logistic mixed models were applied to establish the main farm' characteristics involved in the probability of observing an untimely outbreak.

MATERIALS AND METHODS

The Epidemiology of ASF in Sardinia

Sardinia has been affected by ASFV since 1978 and presents a particular ASF epidemiological context that is worth describing. While the rest of Europe is infected by ASFV genotype II, the island of Sardinia is the only part of the continent where ASFV genotype I has spread (4–6). Sardinia is the only area where ASFV has infected three porcine populations (i.e., domestic pigs, wild boar, and illegal free-ranging pigs) (6, 39, 40). As described by Wilkinson (41), free-ranging pig breeding has been a fundamental part of the agropastoral Sardinian culture for several decades. Despite the fact that free-range pig keeping is illegal in Sardinia, it was largely practiced until a few years ago, when several culling actions have been taken to reduce this population (39). During these actions, several ASFV-positive animals were detected (6, 39). In Sardinia, swine husbandry has been a secondary activity compared to sheep livestock production (40–43). Thus, domestic pig farms have a familiar or working relationship with other farms or are mainly for self-consumption, and only 5% are commercial farms (44). Furthermore, over about 16,000 total farms officially recorded in National Italian Database (BDN), the proportion of indoor farms was significantly higher (75–80%) than outdoor farms (20–25%) (**Figure 1A**), as well as the total number of domestic pig bred (**Figure 1B**). The number of pigs bred in indoor farms remained constant all over the years, while this increased in outdoor farms from an average of 7

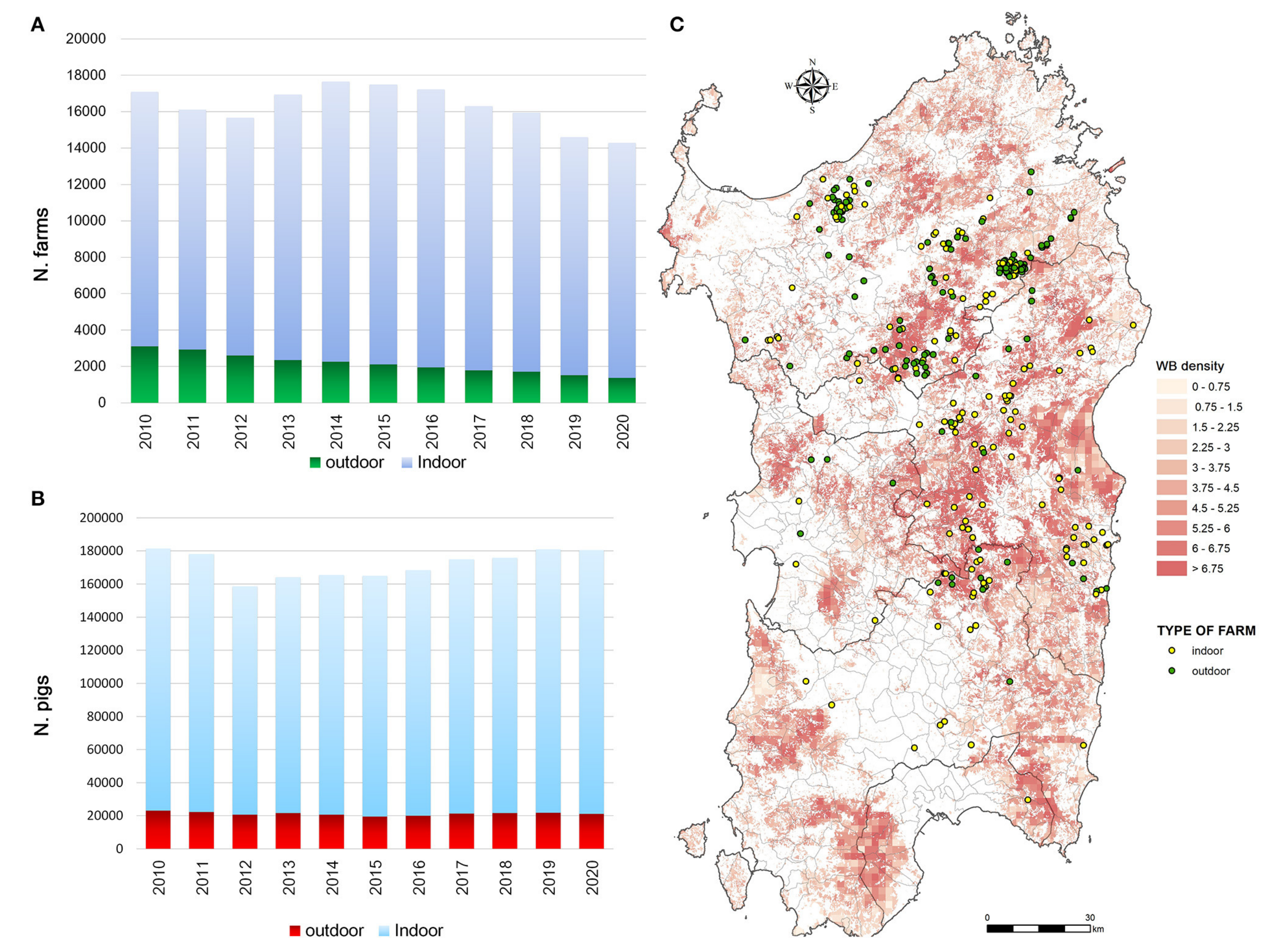


FIGURE 1 | Sardinian epidemiological context. **(A)** Total number of farms in Sardinia and **(B)** the number of domestic pigs bred in domestic pig farms by years, from 2010 to 2020. Data are collected by the Italian National Database and correspond to the annual animal census (30th June). **(C)** Outbreaks occurred in indoor and outdoor domestic pig farms from 2010 to 2018 over the wild boar density by km2.

pigs/farm to 15 pigs/farm. The last Sardinian Eradication Plan of 2015–2018 (ASF-EP15/18), adopted in December 2012, but fully implemented by 2016, confirmed the banning of free-range pig keeping (Regional Decree n.69, 18th December, 2012, approved by Decision 2011/807/UE) and imposed biosecurity regulations on outdoor Sardinian farms. Incentives were provided to farmers to ensure respect of biosecurity rules and to abandon illegal practices, while disease awareness-raising campaigns were also carried out. Previous studies have shown the efficacy of the measures adopted in Sardinia in the last years to contain and eradicate ASF (40). Since 2014 the number of outdoor farms drastically decreased given the measures adopted by the last ASF eradication program (ASF-EP15/18) [https://www.vetinfo.it/j6_statistiche/#/report-pbi/31]. To evaluate a whole epidemic season, this study covers a 10-year period of analysis (2010–2020), as shown in **Figure 2**. Based on official data recorded in the Italian National Information System for the Notification of Infectious Animal Disease (SIMAN) database, an ASF outbreak in a domestic pig farm is defined as a diagnosed disease event, in accordance with the World Organization for Animal Health (OIE) Manual of Diagnostic Tests (27). As described in our past studies (22, 40, 42), after some years of few outbreaks occurrence (2006–2009), since 2010 the number of outbreaks in both wild boar and domestic pig populations increased, peaking in 2013 and then decreasing in 2015 (**Figure 2**). In September 2018, the virus was detected for the last time in domestic pigs, while the last PCR-positive illegal free-ranging pigs and wild boar were detected in January 2019 and April 2019, respectively (26, 37, 39). Since then, 42 seropositive cases in wild boar have been reported as outbreaks.

Free-Ranging, Outdoor, and Indoor Sardinian Farms

Considering the lack of a specific legislative and universal definition for outdoor farms (31) and given that the outdoor farm definition provided by the working document SANTE/7113/2015 does not fully fit outdoor pig farms in Sardinia, in this work, we provided a definition for each of the three farm type

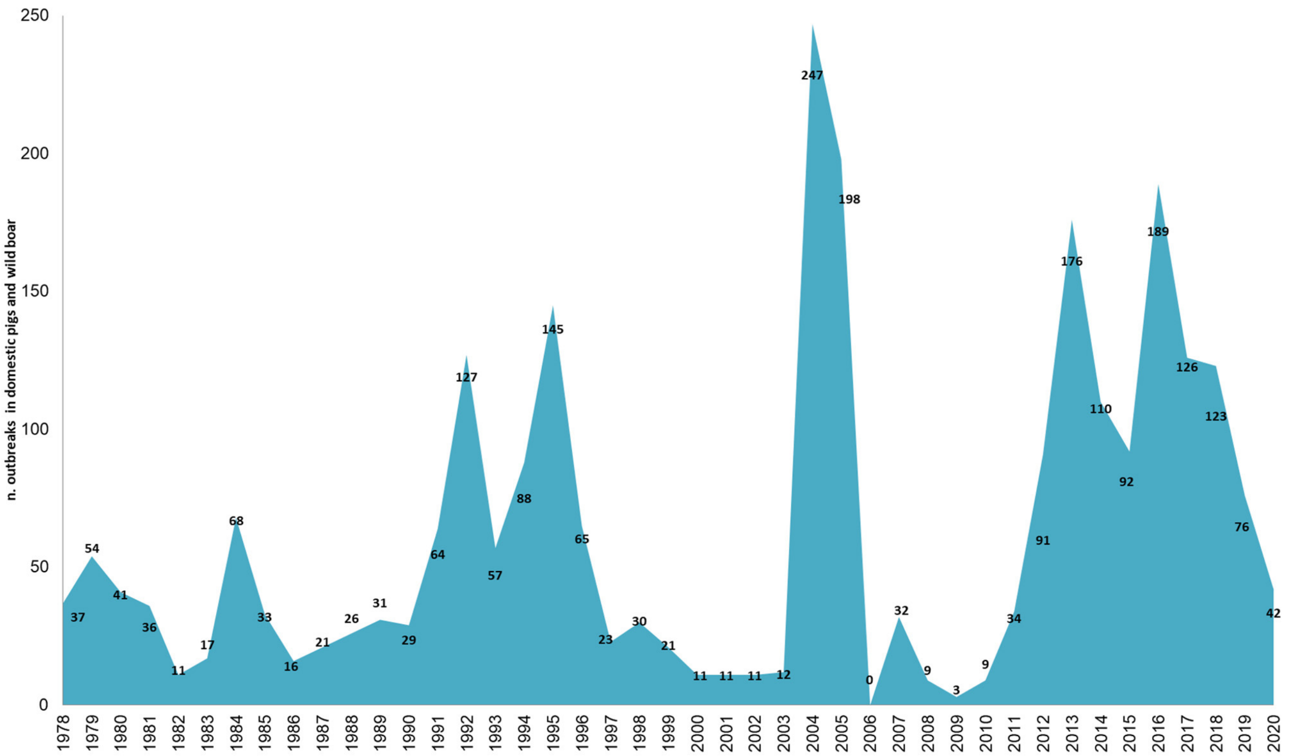


FIGURE 2 | Number of African swine fever cases (i.e., outbreaks in domestic pig farms or in illegal free-ranging pigs, and cases in wild boar) reported in Sardinia from 1978 (by suspicion data on SIMAN) to 2020. The last notified outbreak in domestic pig farms occurred in September 2018. From April 2019, ASF outbreaks are limited to seropositive wild boar.

characterizing the Sardinian pig-breeding systems. In this paper, we refer to:

(i) Illegal free-ranging pigs: animals kept permanently outdoors, not fenced, with unlimited access to fields, pastures, forest or woodlands, without buildings or shelters, without an official and clearly defined ownership, neither registration in the BDN. As above stated, these farms type are illegal in Sardinia;
(ii) Outdoor farms: commercial or non-commercial farms where domestic pigs are bred in the open-air, with access to fields pasture limited by concrete-fences with buildings or shelters for feeding or rest, with a defined ownership registered in the BDN;
(iii) Indoor farms: farms where domestic pigs are bred in closed buildings or shelters, without access to fields pasture, with a defined ownership registered in the BDN.

African Swine Fever Surveillance in Domestic Pig Farms and Epidemiological Investigation Tool

The surveillance program implemented by the ASF-EP15/18 includes different measures to control the disease, such as outbreaks identification by screening checks or for suspicion of disease (42, 43). With each subsequent ASF outbreak diagnosed, during the stamping out, the veterinary authority (VA) conducts an inspection aimed at identifying the origin of ASFV introduction (Legislative Decree n.54, 20 February 2004). During that inspection, the VA draws up an epidemiological investigation and uploads it to SIMAN. Furthermore, according to ASF-EP15/18 rules, all farms located in a radius of 3 km and 10 km around outbreak location are included in "protective" and "surveillance" zones, respectively. The validity period of these zones is defined by regional decrees, which establish a start-end period during which animal movements are not allowed except under specific permission for slaughtering (Legislative Decree n. 54/2004 available at http://www.camera.it/parlam/leggi/deleghe/04054dl.htm). For the present study, all the available epidemiological investigations were collected from SIMAN and evaluated based on inclusion/exclusion criteria. An essential inclusion criterion was the presence of a farm code referring to the epidemiological investigation, with a corresponding entry in the BDN, in order to exclude all outbreaks occurring in wild porcine without a clear ownership (i.e., wild boar, pigs found dead, illegal outdoor pigs). The epidemiological investigation report includes specific session about farm data (i.e., location and owner), animals bred (i.e., type of production, number of animals by species), animal census by categories, farm network (i.e., number and type of the relationships with other farms), animal movements, external visits in farm (i.e., veterinarians, breeders, salesmen), clinical evaluation (i.e., number of dead and symptomatic pigs, date of disease suspicion, date of first symptom, type of symptoms, number of pigs serologically and virologically tested, number of pigs detected as ASFV positive and ASFV antibody positive). Specific session about epidemiological context included the presence/absence of wild boar near to the farm, the most probably origin of the contagion. If the veterinarian suspected that the virus introduction was associated to previous outbreak (i.e., supposing epidemiological correlation) the farm codes of the origin outbreak were reported. The outbreaks were defined as primary or secondary cases based on the European Commission Decision 2003/422/CE. An *ad hoc* database in an electronic closed-response data collection instrument (Microsoft Access, Microsoft Corporation, Redmond, WA, USA) was created. The list of variables collected is reported in **Supplementary Table 1**.

Statistical Analysis

Data quality and completeness were tested, and an extensive data check was carried out to evaluate the correspondence between census data (BDN and SIMAN) and those reported in the epidemiological investigations. To evaluate possible differences in farm characteristics and management between indoor and outdoor farms that could be associated with ASF outbreak development, baseline descriptive statistics were grouped by farm type. Quantitative variables were summarized as mean and standard deviation (SD), or median and interquartile ranges (IQRs) as appropriate, whereas qualitative variables were summarized as frequencies and percentages. To compare qualitative variables, either the Chi-square test or Fisher's exact test were applied. Differences between quantitative variables were assessed by the Kruskal–Wallis non-parametric test. To account for the large number of comparisons and to reduce the likelihood of identifying a statistically significant association by chance, a $p < 0.01$ was considered statistically significant, with p values between 0.01 and 0.05 considered indicative of a statistical association but epidemiologically weak. Furthermore, in order to fully evaluate the epidemiological neighbor context of each outbreak occurred, features regarding wild boar, illegal free-ranging pigs and domestic pig farms density have been collected based on a 10 km radius around each outbreak farm. This size has been chosen considering both the maximum radius of ASF surveillance system in domestic pigs (i.e., surveillance zone) and the estimated moving radius of wild boar in Sardinia (44). All the statistical analyses were performed using the open-source R software v.4.0.5 and a $p < 0.05$ was considered as statistically significance.

Estimation of Possible Transmission Network

Given the need to estimate the ASFV transmission distance more appropriate for the Sardinian rural context two context-specific considerations have been taken into account: (a) the epidemiological investigations collected reported a mean values of distance between primary and secondary cases of 3 km and a maximum value of 10 km, while long-distance transmission (>10 km) are limited; (b) long-distance transmission routes are associated to infected food waste, while most of the illegal animals movements [mainly identified as movement of male for reproduction (42)] occurred in proximity of the farm.

Two probability algorithms based on transmission kernel functions f following nearest-neighbor and uniform-kernel-smoothed distribution were applied (45–50). The first would reflect the disease transmission by legal trade or wild boar movements, and thus the unit closest to the secondary case was selected as primary case. For the nearest-neighbor algorithm the transmission distance was limited to a radius r estimated based on a Pert distribution ranging from 0.5 to 10 km, and the most probable distance value of 3 km. These values allowed to reflect the legal animal movements based on surveillance and protective zones, and the wild boar movements. Considering that the uniform-kernel attributes equal probabilities, the second transmission kernel takes into account long-distance transmission human mediated. The two algorithms implemented depending solely on the distance between paired outbreaks, under the following assumptions:

(i) The ASF incubation period followed a Pert distribution ranging from 3 to 20 days, with 6 days as the most probable value (51–53).
(ii) The outbreak start date (defined by the ASF suspicion date) associated with a secondary case must be at least equal to the start date of the paired primary case, plus the estimated incubation period for ASFV.
(iii) The onset of the secondary outbreak must begin before the closure/extinction of the primary outbreak, minus the incubation period.
(iv) The outbreak end date was obtained by fitting a Pert distribution and considering 6, 60, and 30 days as the minimum, maximum, and most probable values, respectively (45).

The distributions of the three variables related to the epidemiological neighbor context between indoor and outdoor farms were evaluated. If one or more variables were differently distributed the kernel functions were corrected using these variables as covariates. A smooth searching neighborhood was applied in order to limit the range of the kernel at the 95% confidence interval (95% CI). A weight wij of each primary i and secondary j case pair was assigned to the respective value of the kernel function $f(i,j|°)$, if the assumptions above were not violated. Otherwise, the weight wij was set to zero. Normalizing correction was applied to define the transmission probabilities pij for each primary case as:

$$p_{ij} = \frac{w_{ij}}{\sum_{i=1}^{N} w_{ij}}, j = 1 \ldots N$$

The secondary case is linked to a single primary case by sampling from a binomial distribution. When $pij = 0$, linkage between primary and secondary case does not occur (i.e., the primary outbreak). Binomial sampling was used to build the transmission network. Once a primary case was identified, no other primary cases could be linked to its associated secondary cases (54). When a network transmission cluster was identified, the ASFV transmission distance was calculated from each secondary case using latitude and longitude coordinates to the centroid of the cluster, and reported in kilometers.

Finally, we calculated the time difference (*delta_time*) between each secondary case and its associated primary case, and described this time as mean (95% CI). The transmission networks resulting from both the applied kernel functions were compared to the epidemiological correlation network reported in the official epidemiological reports. The agreement between the two network described by the algorithms and the network described by the epidemiological investigations in identify the secondary cases was first evaluated in a contingency table. The degree of accuracy and reliability in secondary cases classification was evaluated applying the Cohen's kappa coefficient (55), and the 95% CI were calculated by the method proposed by Fleiss et al. (55). The kappa coefficients were evaluated using the guideline outlined by Landis and Koch (56), where the strength of the kappa coefficients is slight if $K = 0.01–0.20$; fair if $K = 0.21–0.40$; moderate if $K = 0.41–0.60$; substantial if $K = 0.61–0.80$ and almost perfect if $K = 0.81–1.00$. This comparison would provide an evaluation of the ability of the VA in detect illegal trade and well-traceability of the contact between farms. Even if the secondary case definition does not perfectly match the basic reproduction number, which is the average number of secondary cases due to the introduction of a primary case in a completely susceptible population (57–61), the secondary case estimation could be interpreted as a proxy able to quantify the spread of an infection predicting its speed. Thus, the epidemic is in decline if the average of secondary cases is ≤ 1 and on the rise if >1 (61). In order to test the hypothesis of ASFV transmission decline following the control measures against illegal free-ranging pigs fully implemented in 2016 (39), comparisons in the number of secondary cases before/after this period are presented. Finally, characterizing the number of "faster than average" spreading outbreaks matter, vs. "normal outbreaks" is of great concern in order to evaluate if these outbreaks were also associated with larger number of secondary cases, increasing the geographical spread and making harder the application of efficacy control measures. Preliminary data evaluation regarding the number of secondary cases and the number of "*fast*" outbreaks generated by each cluster was performed by graphical tool and Pearson correlation coefficient. Kernel functions and transmission networks were implemented in open-source R software v.4.0.5 and Q-Gis v.3.18.3.

Multivariable Analysis

To evaluate which farm characteristics could have contributed to speed up the ASFV transmission, each secondary outbreak was classified as "*normal*" or "*fast*" based on the delta_time value. Considering the reported outbreak as the epidemiological unit, the outbreak was defined as "*normal*" if the delta_time was equal or higher the mean value, "*fast*" if lower. Two logistic mixed models (62) were fitted based on the two kernel transmission networks. The final aim of these models was to establish the main farm' characteristics involved in the probability of observing an untimely outbreak respect to on-time outbreak. Correlation coefficients between variables were calculated using Spearman non-parametric test, multi-collinearity between variables was tested (63) and the variance inflation factor (VIF) > 2 was used to identify and delete potentially redundant features (64, 65). Assuming that the observations between years and clusters

TABLE 1 | Baseline descriptive statistics of the farm features, by farm type (indoor and outdoor).

Variables	Outbreaks in indoor farms ($n = 158$)	Outbreaks in outdoor farms ($n = 147$)
Data of ASF outbreak		
2010	5 (3%)	2 (1%)
2011	16 (11%)	15 (10%)
2012	29 (18%)	40 (27%)
2013	31 (19%)	72 (49%)
2014	32 (20%)	8 (6%)
2015	11 (7%)	5 (3%)
2016	14 (9%)	4 (3%)
2017	15 (10%)	1 (1%)
2018	5 (3%)	0 (0%)
Production type		
Closed-cycle	128 (81%)	144 (98%)
Open cycle	5 (3%)	3 (2%)
Self-consumption	25 (16%)	0 (0%)
N. of animals	15 [11–28]	15 [5–23]
N. of animals by categories		
Boar	1 [1–1]	1 [1–2]
Sows	3 [2–6]	4 [3–9]
Hogs	1 [0–4]	1 [0–3]
Piglets	0 [0–10]	1 [1–9]
Distance from other farms (meters)		
<500 m	107 (68%)	109 (72%)
500–1,000 m	37 (23%)	35 (26%)
>1,000 m	14 (9%)	3 (2%)
Declared relationship with other farms*		
Family relationship	71 (45%)	88 (60%)
Working collaboration	25 (16%)	47 (32%)
No relationship	62 (39%)	12 (8%)
Presence of slaughterhouse in farm		
Yes	2 (1%)	0 (0%)
Not	156 (99%)	147 (100%)
Type of fence*		
Double fence	33 (21%)	15 (10%)
Single solid fence	78 (49%)	22 (15%)
Single metal fence	30 (19%)	93 (63%)
Not fenced	17 (11%)	17 (12%)
Suspected contact with wild boar		
Yes	44 (28%)	66 (45%)
Not	101 (64%)	74 (50%)
Not specified	13 (8%)	7 (5%)
Shelter*		
Open	30 (19%)	104 (71%)
Close	128 (81%)	43 (29%)
Loading and unloading		
Inside farm	73 (46%)	66 (45%)
Outside farm	85 (54%)	81 (55%)
Quarantine new animals*		
Yes	142 (90%)	0 (0%)
Not	16 (10%)	147 (100%)
Animal identification		
Yes	123 (78%)	135 (92%)
Not	35 (22%)	12 (8%)
Farm register compiled		
Yes	115 (73%)	110 (75%)
Not	43 (27%)	37 (25%)

(Continued)

TABLE 1 | Continued

Variables	Outbreaks in indoor farms (*n* = 158)	Outbreaks in outdoor farms (*n* = 147)
Disinfection		
Yes	126 (80%)	100 (68%)
Not	32 (20%)	47 (32%)
Disposable clothing		
Yes	19 (12%)	0 (0%)
Not	139 (88%)	147 (100%)
Animal separation by categories* **		
Yes	57 (36%)	7 (5%)
Not	68 (43%)	37 (25%)
Not specified	33 (21%)	103 (70%)
Storage of livestock waste/manure/uneaten food* **		
Yes	122 (77%)	50 (34%)
Not	36 (23%)	97 (66%)
Carcass storage* **		
Incineration in farm	14 (9%)	4 (3%)
Burial in farm	118 (75%)	36 (24%)
Not stored/specified	26 (16%)	107 (73%)
Biting pigs with kitchen waste		
Yes	33 (21%)	25 (17%)
Not	119 (75%)	115 (78%)
Not specified	6 (4%)	7 (5%)
Farmer as a hunter**		
Yes	36 (23%)	60 (41%)
Not	122 (77%)	87 (59%)
ASF tested animals		
PCR+ /Ab+	2 [1–5]	1 [1–4]
PCR+/Ab–	1 [1–4]	1 [1–3]
PCR–/Ab+	1 [0–1]	1 [0–2]
PCR–/Ab–	5 [2–15]	6 [4–10]
Virus isolation	38 (24%)	34 (23%)
Days for outbreak confirmation (from suspicion data)	5 [2–11]	8 [4–12]
Days for stamping out (from suspicion data)	7 [4–9]	10 [5–13]
N. died animals	1 [1–3]	1 [1–3]
N. animals with symptoms	2 [1–4]	1 [1–3]
Epidemiologically correlated		
Yes	78 (49%)	85 (58%)
Not	64 (40%)	47 (32%)
Not specified	16 (11%)	15 (10%)
Hypothesized origin of contagious		
Contact with wild boar	28 (18%)	73 (50%)
Human factor	113 (71%)	59 (40%)
Unknown	17 (11%)	15 (10%)

Data are presented as mean (standard deviation), median [I-III quartile], frequency (percentage). Statistically significant differences are identified by a p-value < 0.0001 (***), or p-value between 0.05–0.0001 (**).

were not independent, we applied a logistic multilevel mixed model, including the year and the cluster as random effects to control the between-year and cluster differences. Given that no outbreak reoccurrence was identified in the same farm, no random effect associated with the farm was included. Risk factors selection was performed by a stepwise selection process (66), and the best fitting was established based on adjusted R2, and Akaike's information criterion (AIC) (67) values. Considering the completely absence of quarantine of new animals in outdoor farms, the role of this variable was evaluated as confounding factor. Thus, the inclusion in the final multivariable models of quarantine and/or type of farm as explicative variables was evaluated by AIC value. The logistic multilevel mixed model results were presented as adjusted odds ratio (OR_{adj}) calculated with the logistic regression method (61). Often model validation is performed using data referred to some years as training dataset, and the rest as test dataset. Considering the need of including the "year" as random effect, the model validation was performed on random selected groups of data, with 1:1 proportion.

RESULTS

From 2010 to 2020, a total of 1068 ASF outbreaks were reported in Sardinia in all the target populations (i.e., wild boar, domestic and outdoor pigs) (**Figure 2**). Of these, 695 outbreaks were excluded from our analysis because ASFV genome or ASF antibodies were detected in wild boar and 68 because outbreaks occurred in illegal free-ranging pigs. Thus, considering the main aim of this study, only the 305 outbreaks occurred in domestic pig farms from 2010 to 2018 were included. Farms were indoor or outdoor, each associated with a farm code recorded in the BDN (**Table 1**). Of these 305 outbreaks, 48% (147) occurred in outdoor farms, while 52% (158) in indoor farms (**Figure 1C**). Most of the outbreaks occurred in 2012 (69, 23%) and 2013 (34%), specifically in May (72, 24%) and June (61, 20%). Considering that the "reproduction period" is the phase in which piglets destined for fattening and replacement are produced, and the "fattening period" is the production of pigs for slaughter, farms were identified as (1) "*close-cycle breeding*", referring to those farms where both phases are carried out, (2) "*open-cycle breeding*" where only one phase is carried out (i.e., reproduction or fattening), (3) "*for self-consumption*", not intended for selling but for self-consumption by the farm holder and his household (**Table 1**). The infected farms were mainly closed-cycle production in both indoor (128, 81%) and outdoor (144, 98%) farms, with the median number of bred pigs being 19 (IQR = 11–28 and 5–23, respectively). Sows were the main animal category, with a median value of 3 (IQR = 2–6) and 4 (3–9) in indoor and outdoor farms, respectively (**Table 1**). Similar distributions were found between indoor and outdoor farms for management characteristics such as distance from other farms, slaughterhouse within the farm, loading and unloading facilities, animal identification and compilation of the farm's register, disinfection, disposal clothing and feeding pigs with kitchen waste.

Considering the overall population of Sardinian farms during each year in study (mean = 16,671, SD = 756), of which about the 85% (mean = 14,456, SD = 927) were indoor and the 15% (mean = 2216, *SD* = 415) wereoutdoor farms, the baseline probability to be infected was six times more in outdoor farms than indoor farms (OR = 6.069, 95% CI = 4.827–7.631, *p*

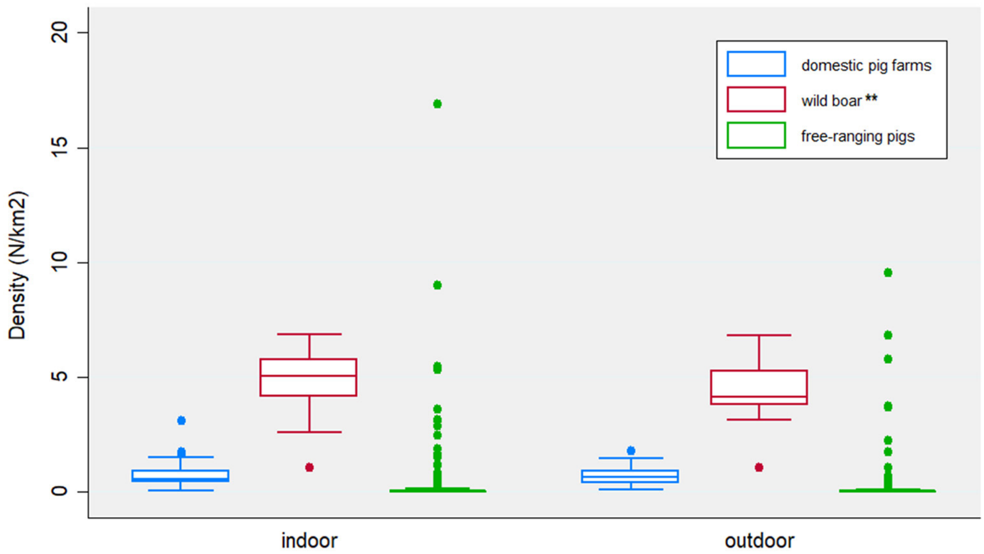


FIGURE 3 | Distribution of the density of domestic pig farms, wild boar and free-ranging pigs, expressed as number/km^2, by indoor and outdoor farms. Features were collected based on 10 km^2 radius around each epidemiological unit (i.e., outbreak farm). Statistically significant differences between indoor and outdoor farms are identified by a *p*-value <0.0001 (***), or *p*-value between 0.05–0.0001 (**).

< 0.0001). Statistically significant differences between outdoor and indoor farms were detected in the declared relationship with other farms, reported as working collaboration or familiar relationship (i.e., father, son, cousins, etc.) [$\chi^2_{(1, N=305)} = 41.98$, $p < 0.0001$], type of fence [$\chi^2_{(1, N=305)} = 70.07$, $p < 0.0001$], suspected contact with wild boar [$\chi^2_{(1, N=305)} = 9.98$, $p = 0.007$], type of shelter [$\chi^2_{(1, N=305)} = 82.83$, $p < 0.0001$], application of quarantine for the new animals [Fisher (1, $N = 305$) = 0.0001, $p < 0.0001$] and their separation by categories [$\chi^2_{(2, N=305)} = 83.95$, $p < 0.0001$], storage of livestock waste/manure/uneaten food [$\chi^2_{(1, N=305)} = 57.79$, $p < 0.0001$], the concomitant role of the farmer as a hunter [$\chi^2_{(1, N=305)} = 11.48$, $p = 0.0007$] and carcass storage [$\chi^2_{(1, N=305)} = 98.27$, $p < 0.0001$]. Laboratory tests revealed that, during the outbreaks, the median number of pigs in the initial phase of the disease (ASFV positive and ASF antibody negative) was 2 (IQR = 1–5) in indoor farms and 1 (IQR = 1–4) in outdoor farms. A median value of 1 pig (IQR = 1–4 and 1–3, respectively) that developed antibodies during virus replication (ASFV positive and ASF antibody positive) was recorded in both types of farms. A median of 1 animal (IQR = 0–1 and 0–2, respectively) survived the disease and tested ASFV negative and ASF antibody positive. The virus was isolated by Malmquist or immunofluorescence laboratory tests in about 24% of the outbreaks, with a median value of 1 dead pig (IQR = 1–3). A median of 2 pigs (IQR = 1–4) and 1 pig (IQR = 1–3) showed common symptoms in indoor and outdoor farms, respectively. Overall, 70% (213) of the outbreaks were recorded after symptoms were reported, mainly by the farmer (78%, 166) or veterinarians (22%, 47). Common symptoms were anorexia, hemorrhage, fever, loss of appetite, non-coordinated movements, dyspnoea, cyanosis, fatigue, abortion, diarrhea, epistasis, haematuria, and cough. In 59% (180) of the outbreaks, the farmer reported disease suspicion after moderate symptoms; in 17% (52) of the outbreaks, the farmer reported disease suspicion after sudden death in combination with other symptoms; and 24% (73) of the outbreaks were either not reported by the farmer (i.e., disease reporting by veterinarians) or were reported by the farmer to the veterinarian only after the death of a second pig. A median of 5 (IQR = 2–11) and 8 (IQR = 4–12) days from the ASF suspicion date was necessary to confirm the disease suspicion based on the OIE Diagnostic Manual for indoor and outdoor farms, respectively. Furthermore, even more days [7 (IQR = 4–9) and 10 (IQR = 5–13)] from the ASF suspicion date were necessary to apply stamping-out measures. According to the epidemiological investigation carried out by the veterinarians, the virus introduction in indoor farms was mainly associated (113, 71%) with human activities (i.e., people's movements between farms, uncontrolled animal introduction, low biosecurity, inadequate disinfection, or kitchen waste), followed by the contact with wild boar for pigs belonging to the outdoor farms. Otherwise, the contact with wild boar seems to be the first way of ASFV introduction in outdoor farms (73, 50%).

The VA defined as epidemiologically correlated a total of 78 (49%) outbreaks occurred in indoor farms and 85 (58%) in outdoor farms. The features related to the epidemiological context are reported in **Figure 3**. The density of wild boar is statistically significant higher ($p = 0.0004$) around indoor (mean = 4.95/km^2, *SD* = 1.03) rather than outdoor farms (mean = 4.56/km^2, *SD* = 0.89). Otherwise, similar distributions of domestic pig farms and illegal free-ranging pigs have been detected in indoor and outdoor farms.

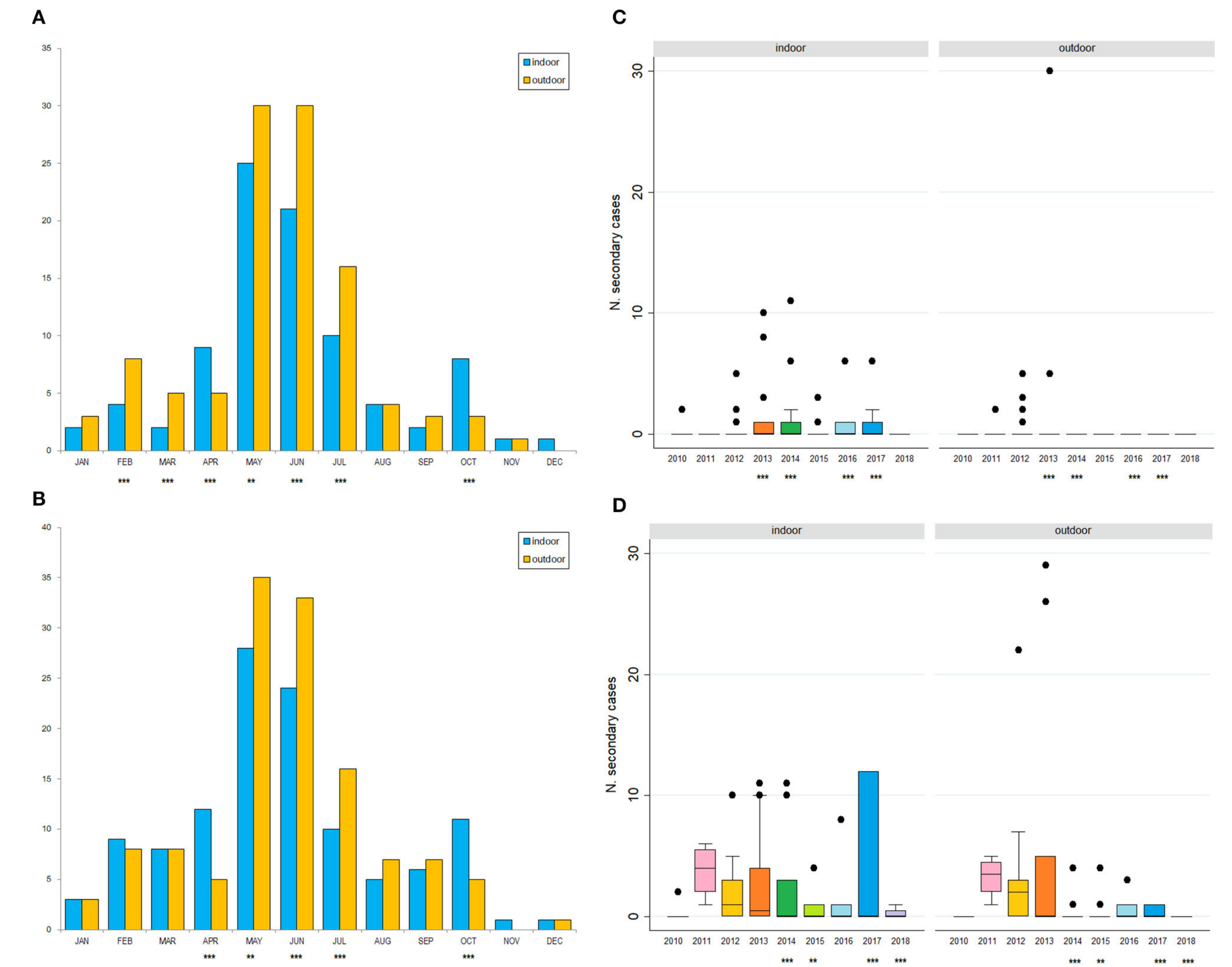


FIGURE 4 | Number of the secondary cases by year distribution **(A–C)** and overall month distribution **(B–D)** from 2010 to 2018. Data are represented by the number of secondary cases defined by nearest-neighbor **(A,B)** or uniform-smoothed kernel functions **(C,D)**. Statistically significant differences between indoor and outdoor farms are identified by a *p*-value <0.0001 (***), or *p*-value between 0.05–0.0001 (**).

Nearest-Neighbor Kernel Transmission Network

Of the 305 outbreaks, 108 primary cases occurred from 1st January 2010 to 10th September 2018. In addition, 197 secondary cases were generated, mainly in 2012 (44, 22%), 2013 (88; 45%). The average number of secondary cases was 0.5 (95% CI = 0.0–0.9) in 2010 and increased to 1.9 (95% CI = 0.1–2.6) in 2013 (**Figure 4A**). In particular, most of the secondary cases occurred during May (55, 28%) and June (51, 26%) each year (**Figure 4B**). **Figure 5A** reports the nearest-neighbor transmission network of ASF spread among infected domestic pig farms in Sardinia. The estimated mean transmission distance was 3.87 km (95% CI = 3.51–4.23), and the average time interval (delta_time) was 16 days (95% CI = 14.3–20.6) between paired cases (**Figure 5B**). Overall, from each primary case, a mean of 1.86 (95% CI = 1.62–2.82) secondary cases was generated. Disease transmission drastically reduced from the second half of 2017 (average number of secondary cases <1) (**Figure 6**). No outbreaks, neither primary nor secondary, occurred in registered pig farms after September 2018. Worth to highlight that the number of secondary cases increased when the time needed for both virus isolation and stamping out increased as shown in **Figure 7**: after 4 days for virus isolation and 5 days for stamping out, each day of delay corresponded to a doubling of secondary cases. The number of secondary cases associated with primary indoor farms or primary outdoor farms was similar with a mean of 0.45 (95% CI = 0.32–0.58) and 0.68 (95% CI = 0.51–0.84), respectively. Three main clusters arose from outdoor farms located in Bitti (2012), Padru (2013) and Bulzi (2013). The primary case of these clusters generated 17, 39 and 36 secondary cases, infecting about 10% of the total farms located in the radius, and the spread of the disease spanned 44,

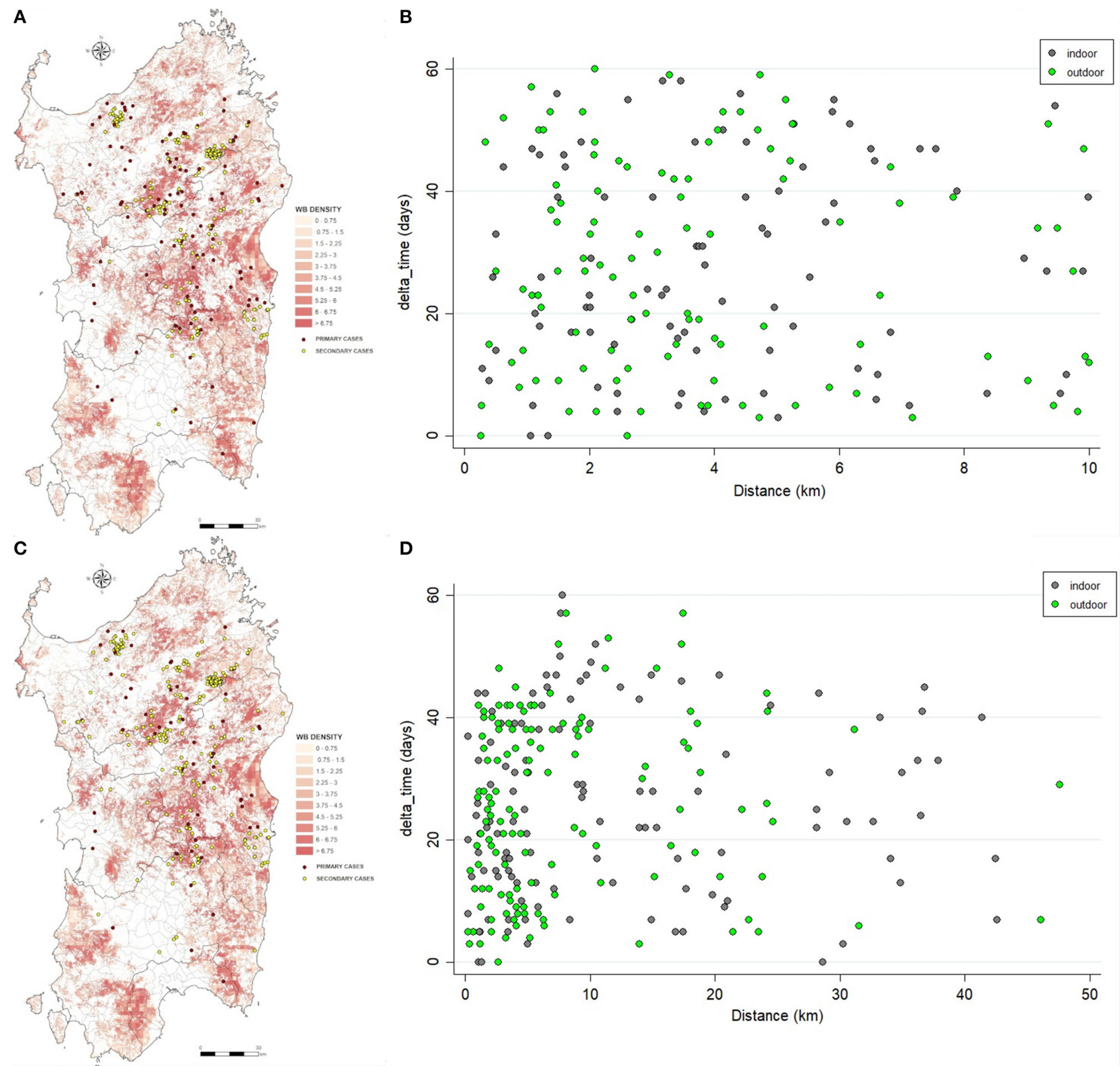


FIGURE 5 | Spatial distribution of the primary (red) and secondary cases (yellow) detected by nearest-neighbor **(A)** or uniform-smoothed kernel functions **(C)**. Scatterplots shown the relation between difference time and distance between the secondary outbreak and its primary outbreak, by nearest-neighbor **(B)** or uniform-smoothed kernel functions **(D)**.

58, and 55 days, respectively. The epidemiological landscape of these three clusters was similar, with an average farm density of 10 farms/10 km^2 (SD = 7 farms/km^2) and an outdoor farm density of about 5 farms/10 km^2 (SD = 4 farms/km^2), in which a median of 11 (IQR = 6–30) pigs were bred. In the first cluster of Bitti, most of the secondary cases (15, 88%) occurred in outdoor farms, with an average of 5 (SD = 1.2) symptomatic pigs reported in each outbreak. Similar percentage of secondary cases in outdoor farms was reported in Padru and Bulzi, but with significantly lower average of symptomatic pigs (mean = 1.6, SD = 0.5; mean = 0.5, SD = 0.03, respectively). Furthermore, in the area where the Bitti and Padru clusters occurred the presence of illegal free-ranging pigs had historically been reported, while these animals were never detected in the hunting management unit of Anglona-Gallura, where Bulzi is located (22).

Uniform-Kernel-Smoothed Transmission Network

A total of 60 primary and 245 secondary cases were detected by uniform-kernel-smoothed transmission network. Most of the secondary cases occurred in 2012 (60, 24%) and 2013 (93, 38%), particularly in May (63, 26%) and June (57, 23%). The average number of secondary cases was 0.2 (95% CI = 0.0–0.59) in 2010 and increased to 4.35 (95% CI = 0.59–8.11) in 2013 (**Figures 4C,D**). **Figure 5C** reports the nearest-neighbor transmission network of ASF spread among infected domestic pig farms in Sardinia. The estimated mean transmission distance was 11.2 km (95% CI = 9.91–12.35), and the average time interval (delta_time) was 20 days (95% CI = 17.4–22.5) between paired cases (**Figure 5D**). Overall, from each primary case, a mean of 4.16 (95% CI = 3.09–5.23) secondary cases was generated. The number of secondary cases associated with primary indoor farms or primary outdoor farms was similar with a mean of 2.01 (95% CI = 1.14–2.88) and 2.11 (95% CI = 0.64–3.58), respectively. The estimated average number of secondary cases over the first 6 years in this study is significantly higher with respect to that estimated in 2016–2018, ($\mu_{2010-2015} = 0.98$, $SD_{2010-2015} = 0.35$, $\mu_{2016-2018} = 0.43$, $SD_{2010-2015} = 0.24$, $p < 0.001$), indicating a reduction in ASF spread and disease extinction in domestic pigs, given that the number of secondary cases is equal or lower than 1 since 2017. As well as in the nearest-neighbor transmission network, the same three main clusters arose from outdoor farms located in Bitti (2012), Padru (2013), and Bulzi (2013) were detected. Both the fitted kernels were adjusted for the wild boar density given its different distribution between the two types of farms (indoor and outdoor), as reported in **Table 2**. An exponentially increasing intensity of secondary cases with increasing wild boar population density values when the population density is expressed as a log is represented in **Supplementary Figure 1**.

Transmission Networks' Agreement

The degree of accuracy and reliability of epidemiological investigation tools was estimated based on the two kernel transmission networks. Comparisons were applied only for 274 outbreaks where the origin of ASFV introduction or specific epidemiological correlation were detailed in the veterinary reports. The ability of the epidemiological investigation reports to correctly detect secondary cases in accordance to the kernel transmission models is reported in **Table 3**. The epidemiological investigations reported 111 primary cases and 163 secondary cases. In comparison with nearest-neighbor kernel transmission network, 89 primary and 154 and secondary cases were equally identified with a substantial agreement of 89.9% (Cohen's *k*: 0.76, 95% CI =0.68–0.84). In comparison with uniform-kernel-smoothed transmission network, the epidemiological investigation reports agreed in defining 55 and 158 primary and secondary, respectively, with a moderate agreement of 77.8% (Cohen's *k*: 0.50, 95% CI =0.39–0.61). Thus, epidemiological investigations carried out by veterinarians are more able to detect small-distance secondary cases rather than ASFV long-distance transmissions. A focus on the false-secondary cases identified underlines that the five incorrectly secondary cases of the uniform kernel occurred after a period longer than 70 days from the previous outbreaks, and thus excluded as secondary cases for the models assumptions. These outbreaks associated with human-mediated spread occurred in 2011 in indoor farms in Oristano Province (Central-West Sardinia) and in 2017 in

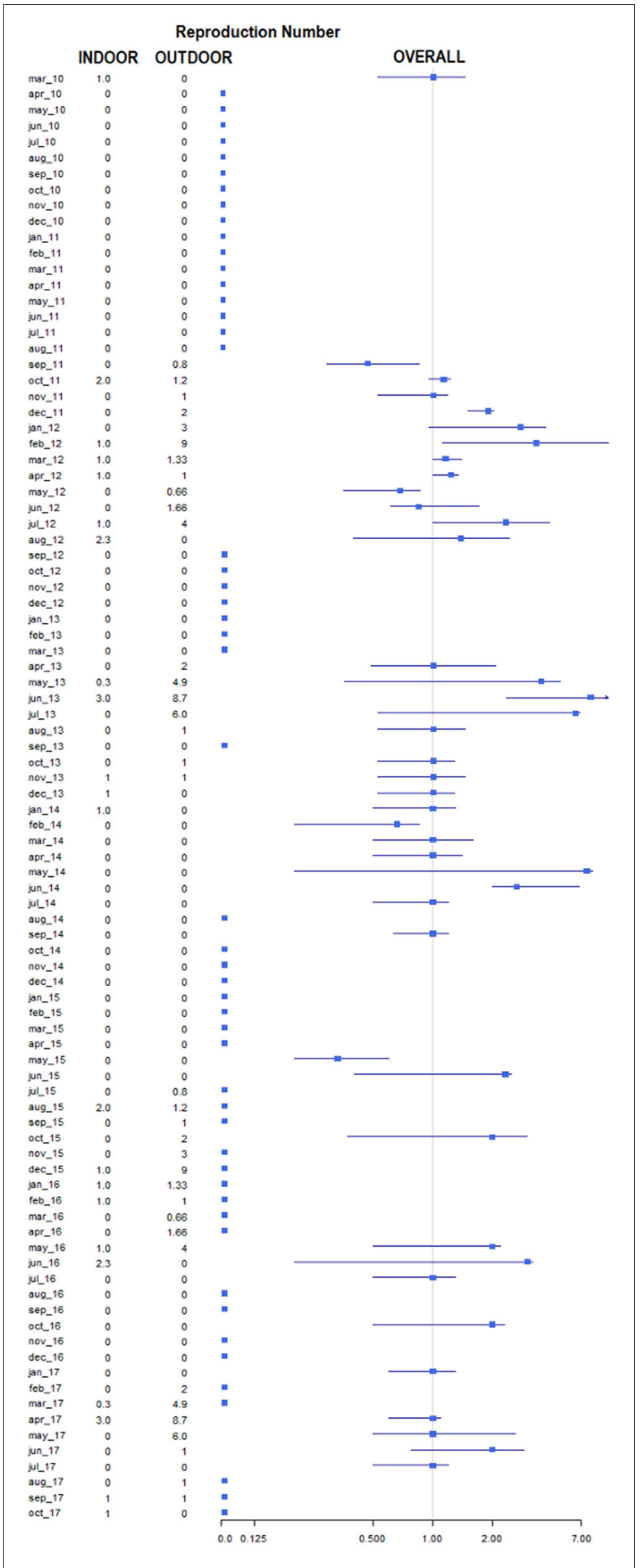


FIGURE 6 | Forestplot representing the average number of secondary cases (reproduction number) by month and year. Data are reported as overall (squares represent the estimates, lines indicate the 95% confidence intervals), average number in indoor and outdoor.

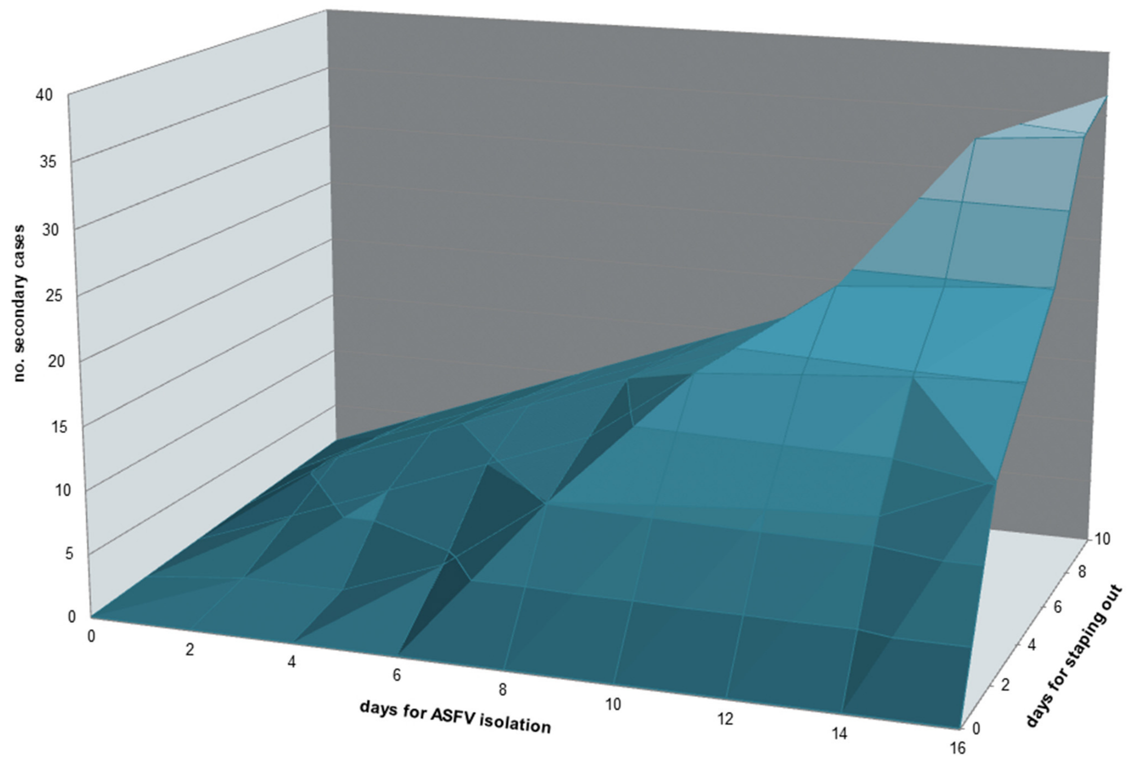


FIGURE 7 | Contour plot representing the relation between time (days) used for ASFV isolation and time (days) used for stamping out in the primary outbreak with the number of secondary cases associated.

Cagliari province. The epidemiological investigation reports specified that these were generated through frozen infected food waste from Central-East Sardinia.

Characterizing the Faster ASF Outbreaks

The outcome defined by delta_time values generated by nearest-neighbor and uniform-kernel-smoothed function characterized 135 "*normal*" and 62 "*fast*" outbreaks, and 154 "*normal*" and 94 "*fast*" outbreaks, respectively. The graph in **Figure 8** suggests a linearly increasing relationship between the number of secondary cases and the number of "*fast*" outbreaks using both the kernel functions. Furthermore, the Pearson's correlation coefficient equal to 0.916 ($p < 0.0001$) confirms this association.

The logistic mixed model results fitted on the delta_time values generated by nearest-neighbor kernel function highlighting the main features associated with the probability of observing a "*fast*" outbreak with respect to a "*normal*" outbreak (**Table 4**). This probability was 1.36 times more in outdoor farms compared to indoor farms ($OR_{adj} = 1.36$, 95% CI = 1.12–3.77, $p = 0.044$) and approximately three times more if the farm was not fenced ($OR_{adj} = 2.65$, 95% CI = 1.90–3.69, $p < 0.0001$). Furthermore, the probability to observe speed outbreak increase of 8.56 times if the farm was located a distance <3.87 (mean value of the network) from the centroid of the cluster ($OR_{adj} = 8.56$, 95% CI = 4.90–14.98, $p < 0.0001$). Increasing by one the number of days needed for outbreak confirmation and the number of symptomatic pigs, the probability of "*fast*" outbreak occurrence increased of 3% ($OR_{adj} = 1.03$, 95% CI = 1.01–1.05, $p = 0.004$) and 8% ($OR_{adj} = 1.08$, 95% CI = 1.02–1.11, $p = 0.005$), respectively. Otherwise, the fast outbreak probability was about half when <10 pigs were breed in the farm ($OR_{adj} = 0.53$, 95% CI = 0.31–0.89, $p = 0.016$), when no relationship with other farms were detected ($OR_{adj} = 0.49$, 95% CI = 0.25–0.96, $p = 0.028$), or when no hunting activities by the farmer ($OR_{adj} = 0.45$, 95% CI = 0.25–0.83, $p = 0.002$) are reported in epidemiological investigation reports. Finally, the probability of observing "*fast*" outbreak decreased of about 80% in farms that declare disposal

TABLE 2 | Descriptive statistics of the epidemiological context features based on 10 km of radius around each outbreak farm, by farm type (indoor and outdoor).

Variables	Outbreaks in indoor farms ($n = 158$)	Outbreaks in outdoor farms ($n = 147$)
Wild boar density (km^2)**	4.95 (1.03)	4.56 (0.89)
Domestic pig farms density (km^2)	0.71 (0.42)	0.72 (0.35)
Illegal free-ranging pigs density (km^2)	0 [0–0.8]	0.3 [0–0.4]

Data are presented as mean (standard deviation), median [I-III quartile]. Statistically significant differences are identified by a p-value <0.0001 (***), or p-value between 0.05–0.0001 (**).

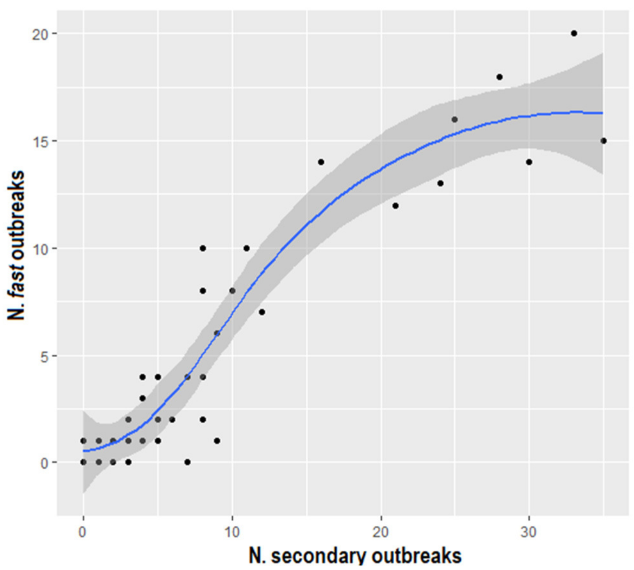


FIGURE 8 | Scatter plot displaying the number of fast outbreaks versus the number of secondary outbreaks, using both the nearest-neighbor and the uniform kernel functions.

clothing usage ($OR_{adj} = 0.81$, 95% CI = 0.70–0.94, $p = 0.005$). No year random effect was included given the lower AIC associated with the model which excluded this effect (AIC = 1,754.33, delta AIC = 17.57).

The logistic mixed model results are reported in **Table 5**. The probability to observe a "*fast*" outbreak compared to "*normal*" outbreak was about 3 times more for farms located a distance <11.2 (mean value of the network) from the centroid of the cluster ($OR_{adj} = 3.85$, 95% CI = 2.05–7.20, $p < 0.0001$) and about 2 times if the farm was not fenced ($OR_{adj} = 1.79$, 95% CI = 1.65–1.97, $p = 0.027$). Increasing by one the number of days needed for outbreak confirmation and the number of symptomatic pigs, the probability of "*fast*" outbreak occurrence raised of 1% ($OR_{adj} = 1.01$, 95% CI = 1.01–1.02, $p < 0.0001$) and 7% ($OR_{adj} = 1.07$, 95% CI = 1.03–1.13, $p = 0.001$), respectively. Otherwise, the probability was about half when no one relationship with other farms was reported ($OR_{adj} = 0.45$, 95% CI = 0.22–0.76, $p = 0.011$), and reduced of about 60% when disposal clothing usage was declared ($OR_{adj} = 0.63$, 95% CI = 0.45–0.77, $p < 0.0001$). Border line higher probability ($p = 0.045$) was associated to those farms in which disinfection was not carried out ($OR_{adj} = 1.05$, 95% CI = 1.02–3.81). Considering the lower AIC value associated (AIC = 2254.33, delta AIC = 61.89), disinfection variable was included in the final model even if borderline. The predicted performance of the final models was tested by analyzing the regression's residuals, both within the "training dataset" (i.e., internal validation) and the "test dataset" (i.e., external validation). The models showed to be able to predict the correct outcome properly with a strong goodness-of-fit, according to internal and external validation criteria (residuals' mean, SD, Spearman's correlation coefficient). The root mean

TABLE 3 | Agreement table matrix.

		Epidemiological investigation			
		Primary	**Secondary**	**Total**	**Agreement**
Nearest-neighbor kernel	**Primary**	89	9	98	Substantial agreement (89.9%), Cohen's k: 0.76 (95% CI =0.68–0.84)
	Secondary	22	154	176	
Uniform kernel	**Primary**	55	5	60	Moderate agreement (77.8%), Cohen's k: 0.50 (95% CI =0.39–0.61)
	Secondary	56	158	214	
	Total	111	163	**274**	

Agreement values are presented as overall agreement frequency, Cohen's kappa coefficients and 95% confidence intervals (95% CI).

square tests were insignificant for both datasets indicating no evidence of failure.

DISCUSSION

The present study examines 10 years of ASF outbreaks in domestic pig farms in Sardinia in depth and provides specific transmission network estimations for smallholder farms. Given their often low biosecurity level, smallholder farms are considered particularly susceptible to ASFV introduction and are of particular interest in disease prevention and control (36). In addition, even though small-scale farming represents a fundamental part of agricultural practices and is common in rural areas (67), biosecurity and management practices have been described mainly for intensive pig farms (68–71) and focus on backyard farms in non-European countries (35, 72–74). Due to the spread of ASF in European countries with a relevant backyard pig production, it is likely that this issue is even more widespread (32). A pioneering European study focusing on smallholder traditional pig management practices was carried out in Corsica in 2015 and quantified the risk associated with free-range breeding, improper storage of carcasses and distribution of kitchen waste in pastures (75). More recently, in Romania, most of the outbreaks have been significantly associated with the immediate context (<2 km) of ASFV circulation (i.e., increasing number of outbreaks in domestic farms and wild boar around these farms). Importantly, the same study associated the risk of ASF introduction in backyard farms with the herd size, visits by professionals working on farms and pigs foraging in ASF-affected areas (33). Most of these studies recognize humans as being mainly responsible for both long-distance transmission and virus introduction in domestic pig farms, which are mostly comprised of small-scale pig holdings in rural areas (34–36). All of these studies underline the need for awareness-raising campaigns among all stakeholders to sensitize farmers to proper biosecurity practices and the provision of incentives for farmers to report suspected outbreaks to authorities for rapid confirmation (30–35, 72–75). Furthermore, all these studies

TABLE 4 | Logistic mixed model results using fast ($y=1$) or normal ($y=0$) outbreaks as outcome, with a cut-off <16 or ≥16 days from primary case for categories definition, based on Nearest-neighbor kernel function.

Outcome = fast outbreak detected by Nearest-neighbor kernel function			
Variable	**OR_{adj}**	**95% CI**	***p***
Type of farm			
Indoor	Ref.		
Outdoor	1.36	1.12–3.77	0.044
Distance < 3.87 km	8.56	4.90–14.98	<0.0001
Days for outbreak confirmation	1.03	1.01–1.05	0.004
N. animals with symptoms	1.08	1.02–1.11	0.005
Type of fence	Ref.		
Fenced§	Ref.		
Not fenced	2.65	1.90–3.69	<0.0001
N. pigs			
>10	Ref.		
≤10	0.53	0.31–0.89	0.016
Relationship with other farms			
Yes	Ref.		
Not	0.49	0.25–0.96	0.028
Disposable clothing			
Not	Ref.		
Yes	0.81	0.70–0.94	0.005
Farmer as a hunter			
Yes	Ref.		
Not	0.45	0.25–0.83	0.002
Random effect	**Est**	**SE**	**95% CI**
Cluster	1.29	0.28	0.83–1.98
LR test vs. logistic regression:	30.54, $p < 0.0000$		
Residual mean (SD)	$3.32 * 10^{-6}$ ($1.12 * 10^{-6}$)		
Spearman's correlation coefficient	0.850, $p < 0.0001$		
Root MSE training dataset	0.191, $p = 0.63$		
Root MSE test dataset	0.188, $p = 0.72$		

Data are presented as adjusted Odds Ratio (OR_{adj}), 95% confidence intervals (95% CI) and p-value. §Fenced is referred to all types of fences (double, single solid or metal fences).

TABLE 5 | Logistic mixed model results using *fast* (1) or *normal* (0) outbreaks as outcome, with a time cut-off from primary case <20 days for categories definition, based on uniform-kernel-smoothed function.

Outcome = fast outbreak detected by Uniform-kernel-smoothed function			
Variable	**OR_{adj}**	**95% CI**	***p***
Distance < 11.2 km	3.85	2.05–7.20	<0.0001
Days for outbreak confirmation	1.01	1.01–1.02	<0.0001
No animals with symptoms	1.07	1.03–1.13	0.001
Disinfection			
Yes	Ref.		
Not	1.05	1.02–3.81	0.045
Type of fence			
Fenced§	Ref.		
Not fenced	1.79	1.65–1.97	0.027
Relationship with other farms			
Yes	Ref.		
Not	0.45	0.22–0.76	0.011
Disposable clothing			
Yes	Ref.		
Not	0.63	0.45–0.77	<0.0001
Random effect	**Est**	**SE**	**95% CI**
Year	0.63	0.25	0.22–1.54
Cluster	1.18	0.35	0.65–2.11
LR test vs. logistic regression:	9.49, $p = 0.001$		
Residual mean (SD)	$1.52 * 10^{-6}$ ($0.22 * 10^{-6}$)		
Spearman's correlation coefficient	0.790, $p < 0.0001$		
Root MSE training dataset	0.119, $p = 0.32$		
Root MSE test dataset	0.208, $p = 0.55$		

Data are presented as odds ration adjusted (OR_{adj}), 95% confidence intervals (95% CI) and p-value. §Fenced is referred to all types of fences (double, single solid or metal fences).

underlined the need of take into account the context when dealing with non-commercial holdings, in order to ensure survival of these traditional farming methods that express the cultural identity of many countries (42, 74–76). However, despite the fact that these studies provide risk factor estimation, they lack comparisons between intensive and small-scale holdings and a measure of disease spread. To the best of our knowledge, this is the first study able to investigate smallholders' practices concerning biosecurity measures in European countries, and to provide details and estimation of the target smallholder farms where the virus could spread more faster. Furthermore, this study highlight the need of detailed epidemiological farm investigations, including the tracing of contact farms to identify sources of infection, essential for early detection and stop the virus spread (77). ASFV has remained in circulation in Sardinia for more than 40 years, and even though the last PCR-positive detection dates back to 2019 in wild boar, the island still remains categorized amongst the highest risk areas in the EU, according to the newly adopted Commission Implementing Regulation n. 2021/605, with consequent very severe trade restrictions still already in place. Given the strong correlation between the number of *fast* outbreaks and the number of secondary outbreaks in each cluster, characterizing the features associated with the *fast* outbreaks is of great concern to risk evaluation. These fast outbreaks tend to spread to more farms, and thus complicate control efforts and increase costs to both farmers and authorities. Some of the key features associated with faster virus spread highlighted in this study (i.e., outdoor farms, familiar or working relationship with other farms, low-distance, number of animals breed, absence of adequate disinfection) are common risk factors identified in previous studies focusing on smallholder pig farms (32–36, 42, 43, 73–78). The baseline ASF risk of outdoor farms identified in this study (15–20%) well-reflects the last estimation published by EFSA in an hypothetical scenario where no outdoor-specific biosecurity measures are implemented (31). Even if the number of secondary cases within the cluster was similar if the primary case was indoor or outdoor, the nearest-neighbor analysis underlined the higher probability of outdoor to be untimely infected by

ASFV rather than indoor farms, suggesting the central role of direct contact between animals in space-limited clusters, particularly in farms where the animals have access to yard or runs. Furthermore, applying the kernel transmission functions, measures of association and risk estimation that have never been published before were provided, highlighting the low probability of fast outbreak if the farm is adequately fenced, the importance of hygiene and disinfection in preventing the speed of disease transmission and the key role of farmers who hunt wild boar. Indeed, the analysis show the clear effect of the last control measures implemented against free-ranging pigs (39) on the decreasing incidence of outbreaks in Sardinia. The results underline the central role of free-ranging pigs as population link between domestic and wild population. Furthermore, the mean transmission distance estimation suggests the key role of farmers and, more generally, of the human population, in the spread of ASFV in Sardinia. However, this study highlighted a flaw in the surveillance system before 2016: undetected outbreaks with associated spreading of the disease throughout the infected zone and possible unreported cases were not considered in this study. The comparison between the possible transmission network described by epidemiological investigations and those generated by kernels functions highlights the substantial agreement of this tool in estimating epidemiological correlation between near outbreaks, but its moderate agreement in matching long-distance events. Otherwise, statistical models are unable to predict unlikely events, such as ASFV transmission by frozen meat over 70 days without virus detection. Veterinarians on field experience may be more efficient in this regards. The number of secondary cases estimated by both the kernel functions confirm the period between April and June as the at most risk period for ASFV transmission, as previously underlined by the same authors (40). Furthermore, the data source represented by the epidemiological investigations could have generated some reporting errors, affecting, at least partially, the robustness of the study as well as the possible reporting delay by veterinarian authorities. The recent systematic review carried out by Hayes et al. (79) empathizes the need of take into account the epidemiological context, particularly incorporating ASF transmission between pigs and boar in transmission models (79). We tried to cover at least partially this gap implementing the kernel functions with the wild boar density which play a strategic role in ASFV transmission and disease endemicity (6, 39). Finally, the parameters estimated have to be carefully evaluated before generalization, given the particular Sardinian context, not only for the presence of three suid populations typical of the island (6, 39, 40), but also for the types of domestic pig farms that are mainly intended for self-consumption. Otherwise, the applied methods and the obtained results could be efficiently applied in other contexts where outdoor farming system is a traditional farming methods, or in EU countries close to eradication. Considering the partial identification of outdoor farms as the target population for the ASFV, the author strictly agree with the need of specific support (i.e., economic, veterinary services) for smallholders to ensure survival of these traditional farm and not to put them at a disadvantage (75, 77). Indeed, the feasibility and sustainability of specific control measures such as double fence and not outdoor access must be evaluated in each context to encourage ongoing improvement of on-farm biosecurity (31), avoiding stronger measures inapplicable, which could likely generate farmer disagreement or even more illegality (78). Otherwise, identify the most at risk period and the target farm population is essential to put in place efficient control measures.

CONCLUSION

The main conclusions that can be drawn from our results on ASF occurrence in pig farms in Sardinia are as follows:

(1) Faster spread of the disease was influenced by the type of farm, distance between them, management and epidemiological context;
(2) Considering the number of secondary cases estimated, this study underline the importance of the epidemiological investigation report and the need of improve this tool, in order to speed up its ability in detecting long-distance epidemiological correlations;
(3) The detection system has not always led to early virus detection in relation to secondary outbreaks, thus the sensitivity of the early detection system needs to be estimated and the system adjusted accordingly;
(4) The measures recommended to obtain high biosecurity levels should be flexible and should take into account local conditions;
(5) The results of this study confirm that the overall measures adopted to eradicate ASF in Sardinia in the last years have had a major favorable impact on disease occurrence in pig farms.

DATA AVAILABILITY STATEMENT

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

AUTHOR CONTRIBUTIONS

SR, FL, and SC: conceptualization. FL and VG: methodology. DM and FL: software and validation. FL: formal analysis, resources, project administration, and funding acquisition. DM: investigation and data curation. FL and SC: writing—original draft preparation and visualization. SR, DM, FL, AO, SD, GF, VG, and SC: writing—review and editing. SR, AO, VG, and SC: supervision. All authors have read and agreed to the published version of the manuscript.

FUNDING

The funding was provided by the Italian Ministry of Health for the Research ASFEND—Modellizzazione della sorveglianza passiva come strumento chiave per l'African swine fever Exit Strategy, grant number 01/20 IZSSA.

ACKNOWLEDGMENTS

The authors would like to acknowledge Andrea Gervelmeyer, Andy Hart, Sotiria-Eleni Antoniou, Gene Rowe, Abby Colson, Fergus Bolger, Merel Postma, Saul Jimenez Ruiz, Georgi Chobanov, Simon More, Sandra Blome, Christian Gortàzar Schmidt and the EFSA working group for their inspiring discussions and for sharing their different points of view about outdoor farms in European countries; Andrea Scrugli and Annalisa Ghironi for technical informatics support in data extraction. Riccardo Bazzardi for the administrative and scientific support in research project. The authors would also like to thank the reviewers that have enabled the authors to drastically improve the manuscript through their constructive criticism, doubts and suggestions.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fvets.2021.692448/full#supplementary-material

Supplementary Figure 1 | Exponentially increasing intensity of secondary cases with increasing wild boar population density values (wild boar/km2), when the population density is expressed as a log. The colored envelopes represent the 95% confidence intervals.

Supplementary Table 1 | List of the variable collected by the Epidemiological Investigation tools.

REFERENCES

1. Martins C, Boinas FS, Iacolina L, Ruinz-Fons F, Gavier-Widen D. African swine fever (ASF), the pig health challenge of the century. In: Iacolina L, Penrith M-L, Bellini S, Chenais E, Jori F, Montoya M, Ståhl K, Gavier-Widén D, editors. *Understanding and combatting African Swine Fever*. Wageningen: Wageningen Academic Publishers (2021). p. 11–24. doi: 10.3920/978-90-8686-910-7_1
2. Franzoni G, Dei Giudici S, Oggiano A. Infection, modulation and responses of antigen-presenting cells to African swine fever viruses. *Virus Res*. (2018) 258:73–80. doi: 10.1016/j.virusres.2018.10.007
3. Dixon LK, Sun H, Roberts H. African swine fever. *Antiviral Res*. (2019) 165:34–41. doi: 10.1016/j.antiviral.2019.02.018
4. Sanna G, Dei Giudici S, Bacciu D, Angioi PP, Giammarioli M, De Mia GM, et al. Improved strategy for molecular characterization of African swine fever virus from Sardinia, based on analysis of p30, CD2V and I73R/I329L variable regions. *Transbound Emerg Dis*. (2017) 64:1280–6. doi: 10.1111/tbed.12504
5. Torresi C, Fiori M, Bertolotti L, Floris M, Colitti B, Giammarioli M, et al. The evolution of African swine fever virus in Sardinia (1978–2014) as revealed by whole-genome sequencing and comparative analysis. *Transbound Emerg Dis*. (2020) 67:1971–80. doi: 10.1111/tbed.13540
6. Franzoni G, Dei Giudici S, Loi F, Sanna D, Floris M, Fiori M, et al. African swine fever circulation among free-ranging pigs in sardinia: data from the eradication program. *Vaccines*. (2020) 8:549. doi: 10.3390/vaccines8030549
7. Blome S, Franzke K, Beer M. African swine fever – a review of current knowledge. *Virus Res*. (2020) 287:1–15. doi: 10.1016/j.virusres.2020.198099
8. Beltran-Alcrudo D, Arias M, Gallardo C, Kramer SA, Penrith ML, Kamata A, et al. *African Swine Fever: Detection and Diagnosis*. FAO Animal Production and Health Manual (2017). No.19.
9. Gallardo C, Soler A, Nieto R, Sánchez MA, Martins C, Pelayo V, et al. Experimental transmission of african swine fever (ASF) low virulent isolate NH/P68 by surviving pigs. *Transbound Emerg Dis*. (2015) 62:612–22. doi: 10.1111/tbed.12431
10. World Organization for Animal Health. African Swine Fever (ASF) Report N° 64: February 05 to February 18 (2021). Available online at: https://www.oie.int/fileadmin/Home/eng/Animal_Health_in_the_World/docs/pdf/Disease_cards/ASF/Report_64_Current_situation_of_ASF.pdf (accessed March 26, 2021)
11. Wang T, Sun Y, Qiu HJ. African swine fever: an unprecedented disaster and challenge to China. *Infect Dis Poverty*. (2018) 7:111. doi: 10.1186/s40249-018-0495-3
12. Zhou X, Li N, Luo Y, Liu Y, Miao F, Chen T, et al. Emergence of African Swine Fever in China, 2018. *Transbound Emerg Dis*. (2018) 65:1482–4. doi: 10.1111/tbed.12989
13. Iglesias I, Martínez M, Montes F, de la Torre A. Velocity of ASF spread in wild boar in the European Union (2014–2017). *Int J Inf Dis*. (2019) 79:69. doi: 10.1016/j.ijid.2018.11.177
14. Jung-Hyang S. How far can African swine fever spread? *J Vet Sci*. (2019) 20:e41. doi: 10.4142/jvs.2019.20.e41
15. Barongo MB, Ståhl K, Bett B, Bishop RP, Fèvre EM, Aliro T, et al. Estimating the Basic Reproductive Number (R0) for African Swine Fever Virus (ASFV) Transmission between Pig Herds in Uganda. *PLoS ONE*. (2015) 4:10:e0125842. doi: 10.1371/journal.pone.0125842
16. Hu B, Gonzales JL, Gubbins S. Bayesian inference of epidemiological parameters from transmission experiments. *Sci Rep*. (2017) 7:16774. doi: 10.1038/s41598-017-17174-8
17. de Carvalho Ferreira HC, Backer JA, Weesendorp E, Klinkenberg D, Stegeman JA, Loeffen WL. Transmission rate of African swine fever virus under experimental conditions. *Vet Microbiol*. (2013) 165:296–304. doi: 10.1016/j.vetmic.2013.03.026
18. Guinat C, Gogin A, Blome S, Keil G, Pollin R, Pfeiffer DU, et al. Transmission routes of African swine fever virus to domestic pigs: current knowledge and future research directions. *Vet Rec*. (2016) 178:262–7. doi: 10.1136/vr.103593
19. Guinat C, Porphyre T, Gogin A, Dixon L, Pfeiffer DU, Gubbins S. Inferring within-herd transmission parameters for African swine fever virus using mortality data from outbreaks in the Russian Federation. *Transbound Emerg Dis*. (2018) 65:e264–71. doi: 10.1111/tbed.12748
20. Gulenkin VM, Korennoy FI, Karaulov AK, Dudnikov SA. Cartographical analysis of African swine fever outbreaks in the territory of the Russian Federation and computer modeling of the basic reproduction ratio. *Prev Vet Med*. (2011) 102:167–74. doi: 10.1016/j.prevetmed.2011.07.004
21. Iglesias I, Muñoz MJ, Montes F, Perez A, Gogin A, Kolbasov D, et al. Reproductive ratio for the local spread of African Swine fever in wild boars in the Russian federation. *Transbound Emerg Dis*. (2016) 63:e237–45. doi: 10.1111/tbed.12337
22. Loi F, Cappai S, Laddomada A, Feliziani F, Oggiano A, Franzoni G, et al. Mathematical approach to estimating the main epidemiological parameters of African Swine fever in wild boar. *Vaccines*. (2020) 8:521. doi: 10.3390/vaccines8030521
23. Marcon A, Linden A, Satran P, Gervasi V, Licoppe A, Guberti V. R0 Estimation for the African Swine Fever Epidemics in wild boar of Czech Republic and Belgium. *Vet Sci*. (2019) 7:2. doi: 10.3390/vetsci7010002
24. Nielsen JP, Larsen TS, Halasa T, Christiansen LE. Estimation of the transmission dynamics of African swine fever virus within a swine house. *Epidemiol Infect*. (2017) 145:2787–96. doi: 10.1017/S0950268817001613
25. Pietschmann J, Guinat C, Beer M, Pronin V, Tauscher K, Petrov A, et al. Course and transmission characteristics of oral low-dose infection of domestic pigs and European wild boar with a Caucasian African swine fever virus isolate. *Arch Virol*. (2015) 160:1657–67. doi: 10.1007/s00705-015-2430-2
26. Viltrop A, Boinas F, Depner K, Jori F, Kolbasov D, Laddomada A, et al. African swine fever epidemiology, surveillance and control. In: Iacolina L, Penrith M-L, Bellini S, Chenais E, Jori F, Montoya M, Ståhl K, Gavier-Widén D, editors. *Understanding and Combatting African Swine Fever*. Wageningen: Wageningen Academic Publishers (2021). p. 229−61.
27. World Organization for Animal Health (OIE). African swine fever (Infection with African swine fever virus). In: Oura CAL, Arias M, editors. *Manual of*

Diagnostic Tests and Vaccines for Terrestrial Animals. OIE: Paris (2019). p. 1–18.
28. Bellini S, Casadei G, De Lorenzi G, Tamba M. A review of risk factors of African Swine Fever Incursion in pig farming within the European Union Scenario. *Pathogens*. (2021) 10:84. doi: 10.3390/pathogens10010084
29. Bellini S, Rutili D, Guberti V. Preventive measures aimed at minimizing the risk of African swine fever virus spread in pig farming systems. *Acta Vet Scand*. (2016) 58:82. doi: 10.1186/s13028-016-0264-x
30. Alarcón LV, Allepuz A, Mateu E. Biosecurity in pig farms: a review. *Porcine Health Manag*. (2021). 7:5. doi: 10.1186/s40813-021-00202-5
31. European Food Safety Authority (EFSA), Nielsen SS, Alvarez J, Bicout DJ, Calistri P, Canali E, et al. African swine fever and outdoor farming of pigs. *EFSA J*. (2021) 19:60–65. doi: 10.2903/j.efsa.2021.6639
32. Beltràn-Alcrudo D, Kukielka EA, de Groot N, Dietze K, Sokhadze M, Marti'nez-Lo'pez B. Descriptive and multivariate analysis of the pig sector in Georgia and its implications for disease transmission. *PLoS ONE*. (2018) 13:e0202800. doi: 10.1371/journal.pone.0202800
33. Boklund A, Dhollander S, Chesnoiu Vasile T, Abrahantes JC, Bøtner A, Gogin A, et al. Risk factors for African swine fever incursion in Romanian domestic farms during 2019. *Sci Rep*. (2020) 10:10215. doi: 10.1038/s41598-020-66381-3
34. Chenais E, Depner K, Guberti V, Dietze K, Viltrop A, Ståhl K. Epidemiological considerations on African swine fever in Europe 2014–2018. *Porc Health Manag*. (2019) 5:6. doi: 10.1186/s40813-018-0109-2
35. Dione MM, Akol J, Roesel K, Kungu J, Ouma EA, Wieland B, et al. Risk factors for African Swine Fever in smallholder pig production systems in Uganda. *Transbound Emerg Dis*. (2017) 64:872–82. doi: 10.1111/tbed.12452
36. Zani L, Dietze K, Dimova Z, Forth JH, Denev D, Depner K, Alexandrov T. African swine fever in a bulgarian backyard farm—a case report. *Vet Sci*. (2019) 6:94. doi: 10.3390/vetsci6040094
37. European Food Safety Authority (EFSA), Nielsen SS, Alvarez J, Bicout DJ, Calistri P, Depner K, et al. ASF exit strategy: providing cumulative evidence of the absence of African swine fever virus circulation in wild boar populations using standard surveillance measures. *EFSA J*. (2021) 19:e06419. doi: 10.2903/j.efsa.2021.6419
38. Sánchez-Vizcaíno JM, Laddomada A, Martínez Avilés M. Editorial: african swine fever. *Front Vet Sci*. (2021) 7:632292. doi: 10.3389/fvets.2020.632292
39. Laddomada A, Rolesu S, Loi F, Cappai S, Oggiano A, Madrau MP, et al. Surveillance and control of African Swine Fever in free-ranging pigs in Sardinia. *Transbound Emerg Dis*. (2019) 66:1114–9. doi: 10.1111/tbed.13138
40. Loi F, Cappai S, Coccollone A, Rolesu S. Standardized risk analysis approach aimed to evaluate the last African swine fever eradication program performance, in Sardinia. *Front Vet Sci*. (2019) 6:299. doi: 10.3389/fvets.2019.00299
41. Wilkinson P. The persistence of African swine fever in Africa and the Mediterranean. *Prev Vet Med*. (1984) 2:71–82. doi: 10.1016/0167-5877(84)90050-3
42. Cappai S, Rolesu S, Coccollone A, Laddomada A, Loi F. Evaluation of biological and socio-economic factors related to persistence of African swine fever in Sardinia. *Prev Vet Med*. (2018) 152:1–11. doi: 10.1016/j.prevetmed.2018.01.004
43. Cappai S, Rolesu S, Feliziani F, Desini P, Guberti V, Loi, F. Standardized methodology for target surveillance against african swine fever. *Vaccines*. (2020) 8:723. doi: 10.3390/vaccines8040723
44. Mur L, Atzeni M, Martinez-Lopez B, Feliziani F, Rolesu S, Sanchez-Vizcaino JM. 35-year presence of african swine fever in sardinia: history, evolution and risk factors for disease maintenance. *Transbound Emerg Dis*. (2014). 3:113. doi: 10.1111/tbed.12264
45. Kraemer MUG, Faria NR, Reiner RC, Golding N, Nikolay B, Stasse S, et al. Spread of yellow fever virus outbreak in angola and the democratic Republic of the Congo 2015-16: a modelling study. *Lancet Infect Dis*. (2017) 17:330–8. doi: 10.1016/S1473-3099(16)30513-8
46. Riley S, Eames K, Isham V, Mollison D, Trapman P. Five challenges for spatial epidemic models. *Epidemics*. (2015) 10:68–71. doi: 10.1016/j.epidem.2014.07.001
47. Viboud C, Bjørnstad ON, Smith DL, Simonsen L, Miller MA, Grenfell BT. Synchron, waves, and spatial hierarchies in the spread of influenza. *Science*. (2006) 312:447–51. doi: 10.1126/science.1125237
48. Gallardo C, Soler A, Nieto R, Cano C, Pelayo V, Sanchez MA, et al. Experimental infection of domestic pigs with African swine fever virus lithuania 2014. Genotype II field isolate. *Transbound Emerg Dis*. (2017) 64:300–4. doi: 10.1111/tbed.12346
49. Akhmetzhanov AR, Jung S, Lee H, Linton N, Yang Y, Yuan B, et al. Reconstruction and analysis of the transmission network of African swine fever in People's Republic of China, August 2018–September 2019. *bioRxiv*. (2020) 12:199760. doi: 10.1101/2020.07.12.199760
50. Bosch J, Barasona JA, Cadenas-Fernandez E, Jurado C, Pintore A, Denurra D, et al. Retrospective spatial analysis for African swine fever in endemic areas to assess interactions between susceptible host populations. *PLoS ONE*. (2020) 15:e0233473. doi: 10.1371/journal.pone.0233473
51. Olesen AS, Lohse L, Boklund A, Halasa T, Gallardo C, Pejsak Z, et al. Transmission of African swine fever virus from infected pigs by direct contact and aerosol routes. *Vet Microbiol*. (2017) 211:92–102. doi: 10.1016/j.vetmic.2017.10.004
52. Walczak M, Zmudzki J, Mazur-Panasiuk N, Juszkiewicz M, Wozniakowski G. Analysis of the clinical course of experimental infection with highly pathogenic african swine fever strain, isolated from an outbreak in poland. aspects related to the disease suspicion at the farm level. *Pathogens*. (2020) 9:237. doi: 10.3390/pathogens9030237
53. Cohen J. A coefficient of agreement for nominal scales. *Educational and Psychological Measurement*. (1960). 1, 37–46. doi: 10.1177/001316446002000104
54. European Food Safety Authority (EFSA), Desmecht D, Gerbier G, Gortazar Schmidt C, Grigaliuniene V, Helyes G, et al. Epidemiological analysis of African swine fever in the European Union (September 2019 to August 2020). *EFSA J*. (2021) 19:101. doi: 10.2903/j.efsa.2021.6572
55. Fleiss JL, Cohen J, Everitt BS. Large sample standard errors of kappa and weighted kappa. *Psychol Bull*. (1969) 72:323–7. doi: 10.1037/h0028106
56. Landis JR, Koch GG. The measurement of observer agreement for categorical data. *Biometrics*. (1977) 33:159–74. doi: 10.2307/2529310
57. Bailey NTJ. *The Mathematical Theory of Infectious Diseases and Its Applications*, *2nd Edn*. Hafner: New York, NY (1975).
58. Anderson RM, May RM. *Infectious Diseases of Humans: Dynamics and Control*, *2nd Edn*. Oxford: Oxford university press. (1991).
59. Nishiura H, Chowell G. The effective reproduction number as a prelude to statistical estimation of time-dependent epidemic trends. In: *Math Stat Estimation Approaches Epidemiology*. (2009). p. 103–21. doi: 10.1007/978-90-481-2313-1_5
60. Lemeshow SA, D. W. Hosmer Jr. Logistic regression. In: Armitage P, Colton T, editors. *Vol. 2 of Encyclopedia of Biostatistics*. Chichester: Wiley (2005). p. 2870–80. doi: 10.1002/0470011815.b2a10029
61. Yu H, Jiang S, Land KC. Multicollinearity in hierarchical linear models. *Soc Sci Res*. (2015) 53:118–36. doi: 10.1016/j.ssresearch.2015.04.008
62. Piccolo D. *Statistica*. Ed. Il Mulino, 3rd Edn (1998). p. 872–900.
63. Bollen KA. *Structural Equations With Latent Variables*. New York, NY: John Wiley & Sons (1989).
64. Efroymson MA. Multiple regression analysis. In: Ralson A, Wilf HS, edItors. *Mathematical Methods for Digital Computers*. New York, NY: John Wiley & Sons (1960). p. 191–20.
65. Akaike H. Information theory and an extension of the maximum likelihood principle. In: Petrov BN, Csáki F. *2nd International Symposium on Information Theory*, Tsahkadsor, Armenia, USSR. Budapest: Akadémiai Kiadó (1973). p. 267–81.
66. World Bank. *World Development Report 2008: Agriculture for Development*. Washington, DC: World Bank (2007).
67. Hurnik D, Dohoo IR, Donald A, Robinson NP. Factor analysis of swine farm management practices on Prince Edward Island. *Prev Vet Med*. (1994) 20:135–46. doi: 10.1016/0167-5877(94)90112-0
68. Boklund A, Alban L, Mortensen S, Houe H. Biosecurity in 116 Danish fattening swineherds: descriptive results and factor analysis. *Prev Vet Med*. (2004) 66:49–62. doi: 10.1016/j.prevetmed.2004.08.004
69. Casal J, De Manuel A, Mateu E, Martin M. Biosecurity measures on swine farms in Spain: perceptions by farmers and their relationship to current on-farm measures. *Prev Vet Med*. (2007) 82:138–50. doi: 10.1016/j.prevetmed.2007.05.012

70. Ribbens S, Dewulf J, Koenen F, Mintiens K, De Sadeleer L, de Kruif A, et al. A survey on biosecurity and management practices in Belgian pig herds. *Prev Vet Med*. (2008) 83:228–41. doi: 10.1016/j.prevetmed.2007.07.009
71. Costard S, Porphyre V, Messad S, Rakotondrahanta S, Vidon H, Roger F, et al. Multivariate analysis of management and biosecurity practices in smallholder pig farms in Madagascar. *Prev Vet Med*. (2009) 92:199–209. doi: 10.1016/j.prevetmed.2009.08.010
72. Nantima N, Ocaido M, Ouma E, Davies J, Dione M, Okoth E, et al. Risk factors associated with occurrence of African swine fever outbreaks in smallholder pig farms in four districts along the Uganda-Kenya border. *Trop Anim Health Prod*. (2015) 47:589–95. doi: 10.1007/s11250-015-0768-9
73. Penrith ML, Bastos A, Chenais E. With or without a vaccine—a review of complementary and alternative approaches to managing African swine fever in resource-constrained smallholder settings. *Vaccines*. (2021) 9:116. doi: 10.3390/vaccines9020116
74. Relun A, Grosbois V, Sánchez-Vizcaíno JM, Alexandrov T, Feliziani F, Waret-Szkuta A, et al. Spatial and functional organization of pig trade in different European Production Systems: implications for disease prevention and control. *Front Vet Sci*. (2016) 3:4. doi: 10.3389/fvets.2016.00004
75. Martinez M, de la Torre A, Sánchez-Vizcaíno JM, Bellini S. Biosecurity measures against African swine fever in domestic pigs. In: Iacolina L, Penrith M-L, Bellini S, Chenais E, Jori F, Montoya M, Ståhl K, Gavier-Widén D, editors. *Understanding and Combatting African Swine Fever*. Wageningen: Wageningen Academic Publishers (2021). p .263–81.
76. Busch F, Haumont C, Penrith ML, Laddomada A, Dietze K, Globig A, et al. Evidence-based African Swine Fever Policies: do we address virus and host adequately? *Front Vet Sci*. (2021) 8:637487. doi: 10.3389/fvets.2021.637487
77. Martínez-López B, Perez Andres M, Feliziani F, Rolesu S, Mur L, Sánchez-Vizcaíno JM. Evaluation of the risk factors contributing to the African swine fever occurrence in Sardinia, Italy. *Front Microbiol*. (2015) 6:314. doi: 10.3389/fmicb.2015.00314
78. Gisclard M, Charrier F, Trabucco B, Casabianca F. From national biosecurity measures to territorial preparedness for ASF: the case of extensive pig farming systems in Corsica (France). *Front Vet Sci*. (2021). doi: 10.3389/fvets.2021.689163
79. Hayes BH, Andraud M, Salazar LG, Rose N, Vergne T. Mechanistic modelling of African swine fever: a systematic review. *Prev Vet Med*. (2021) 191:105358. doi: 10.1016/j.prevetmed.2021.105358

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

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

Copyright © 2021 Rolesu, Mandas, Loi, Oggiano, Dei Giudici, Franzoni, Guberti and Cappai. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.

frontiers in Veterinary Science

REVIEW
published: 02 August 2021
doi: 10.3389/fvets.2021.689811

The Context of Application of Biosecurity for Control of African Swine Fever in Smallholder Pig Systems: *Current Gaps and Recommendations*

Florence Mutua[1†] and Michel Dione[2*†]*

[1] *Animal and Human Health Program, International Livestock Research Institute, Nairobi, Kenya,* [2] *Animal and Human Health Program, International Livestock Research Institute, Dakar, Senegal*

OPEN ACCESS

Edited by:
Ioannis Magouras, City University of Hong Kong, Hong Kong

Reviewed by:
Gustavo Machado, North Carolina State University, United States
Frank Busch, Friedrich-Loeffler-Institute, Germany

***Correspondence:**
Florence Mutua
f.mutua@cgiar.org
Michel Dione
m.dione@cgiar.org

† *These authors have contributed equally to this work*

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

Received: *01 April 2021*
Accepted: *15 June 2021*
Published: *02 August 2021*

Citation:
Mutua F and Dione M (2021) The Context of Application of Biosecurity for Control of African Swine Fever in Smallholder Pig Systems: Current Gaps and Recommendations. Front. Vet. Sci. 8:689811. doi: 10.3389/fvets.2021.689811

African swine fever (ASF) is a highly fatal disease of pigs. It is a threat to the pig industry as it lowers production and significantly impacts on livelihoods. ASF has no cure and a vaccine against it is yet to be developed. Outbreaks continue to be reported in Africa and Asia, where the setting of the pig value chain (farm, market, and slaughter practices) coupled with the risky behaviors of actors, contribute to persistence of the virus in pig populations. The role of these factors in the epidemiology of the disease is reviewed with a focus on smallholder pig systems in Africa. Biosecurity at the farm level is particularly emphasized, and factors influencing its adoption highlighted. Socio-cultural factors and weaknesses at the disease control policy level are critical and should not be ignored. Gender and equity are important aspects and ought to be considered in discussions to improve the sector. The findings are expected to define priorities for interventions to improve pig productivity (as these regions wait for the vaccine to be developed).

Keywords: biosecurity, African swine fever, African swine fever virus, disease outbreaks, smallholder pig systems

INTRODUCTION

The world population continues to increase, and the food insecurity challenge has been worsened by the COVID-19 pandemic. Livestock are important livelihood assets especially for the poor who use the income from their sales to meet important household needs. Animal source foods are nutrient dense. They are a source of protein and provide micronutrients in forms that are available for the body (iron, calcium, vitamin B12) (1). Demand for food has been growing in developing countries (2) and this trend is likely to continue in the future, given the predicted increases in human population, challenge of urbanization and rising incomes.

Small livestock species, such as pigs, can easily be raised by people with limited resources (3) providing opportunities for regular supply of protein. Also, the demand for pork has increased and many rural and peri-urban communities have discovered the cost-effectiveness of keeping pigs (4). Because of this, pigs in many developing countries are being reared as important income sources (3). Pork is one of the cheapest forms of animal proteins (5). It is reportedly the world's most widely eaten meat (accounting for over 36% of total meat eaten) (6). Consumption is increasing (7) and has been projected to increase by 154.9% in sub-saharian Africa between 2000 and 2030 (8).

The increase in demand for pork is driving growth of the sector, presenting opportunities for farmers to invest and gain from pig production. In sub-Saharan Africa (SSA), the majority of pigs are kept by smallholder farmers who manage them either under extensive or semi extensive systems (9, 10). Pigs are easily integrated into small-scale farming systems. They can be fed with by-products from crops that cannot be consumed or used more efficiently by households. Their manure can be used as fertilizer as well as for energy production (11). Pigs can farrow at least two times in a year and have the potential to yield large litter sizes. Offspring can be sold or reared to maturity. Apart from regions with cultural and religious reservations toward pork, pigs are a potentially viable and valuable investment option for producers, and an important diversification enterprise especially for women (12, 13). The full potential of pig production in SSA is yet to be tapped and this is mainly because of the challenges of feeding and disease.

African swine fever (ASF) is a threat to the pig industry, especially in countries that are still developing (14–17). The impact of ASF is felt more in countries with high pig numbers including Uganda which has the second highest pig population density in sub-Saharan Africa (16). The high mortality and ability to spread to non-infected areas makes ASF a concern to the pig industry, globally (18). Its widespread occurrence implies gaps in disease prevention and control. Several factors are thought to contribute to ASF outbreaks among them poor husbandry practices, weak implementation of biosecurity measures (including allowing pigs to free range), inappropriate behaviors of value chain actors, particularly the illegal live pig trades that happen during outbreak (referred as "panic sales"), the inappropriate practices of pork butchers, and the low financial capability of farmers that limits how much they can invest in disease control (19, 20). Asymptomatic carriers remain a concern (21, 22); and if their role in the persistence of the virus in pig populations is fully demonstrated, the situation will further complicate implementation of control measures.

Although research on vaccine development has been ongoing for some time, neither a vaccine nor a therapeutic product for ASF are currently available, a situation that makes disease control more demanding. The impact of ASF can therefore only be minimized through the adoption of biosecurity measures (23, 24). It has been predicted that biosecurity measures implemented within 14 days of the onset of an epidemic can avert up to 74% of deaths due to ASF (25). Biosecurity measures are not adequately implemented in most smallholder pig farms and this is mainly because the farmers lack the capacity required to do so (26). Further, Nantima et al. (20) note that smallholders are unable to comply with biosecurity measures given the nature of their production system and mentions that adoption of biosecurity is only feasible for pigs that are confined (either housed or tethered) as opposed to those allowed to roam freely. While medium and large-scale farmers may have the capacity to invest in biosecurity measures, this is often not the case especially for small-scale farmers who prefer to keep few pigs at a time and may not confine them. The objective of our paper is to document and discuss the feasibility of biosecurity measures in smallholder pig systems in low income countries and provide recommendations how ASF can sustainably be controlled for the time being.

METHODOLOGY FOR THE REVIEW

The authors present a desk-based study. At the start of the study, a framework highlighting the factors associated with ASF virus spread was developed (**Figure 1**). It included key factors such as input supplies, farm level practices, marketing, processing, policy, as well as the impacts that ASF can have, especially in developing countries (trade, food security, and livelihoods). Gender was specifically considered as a cross-cutting elements given the roles women play in pig management and marketing. The discussion is framed around these key areas with an emphasis on biosecurity and what can be considered as bottlenecks in its implementation.

DESCRIPTION OF REVIEW FINDINGS

Epidemiology of African Swine Fever

ASF is a contagious and highly lethal hemorrhagic disease of pigs and is considered the greatest obstacle to development of the industry in SSA (18, 27). ASF was first reported in East Africa but then spread to many other countries (28, 30), including Europe, South East Asia and the Caribbean region (28). Smallholder pig production in the African region is well described in previous studies (29, 31–37).

The causative agent, the African swine fever virus (ASFV), is a large, enveloped, double-stranded DNA virus (38). Epizootic outbreaks can arise in a number of ways. ASFV can be transmitted through direct contact with infected pigs (by the oral-nasal route or through skin abrasions) (39). The virus spreads effectively by contact via aerosol droplets and blood, feces and other virus-infected tissues (18). Wild suids in Africa can be persistently infected and develop few if any clinical signs and little or no viremia (39). In Europe, the wild boar suffers an acute disease similar to the domestic pig (38). Young warthogs develop a transient viremia that is sufficient to infect *Ornithodoros* moubata ticks when they feed on them. The *Ornithodoros* tick vector is thought to play an important role in virus transmission between warthog hosts (39). The sylvatic cycle involves warthogs and soft ticks. In Africa, transmission from warthogs, *Ornithodoros moubata* ticks or bush pigs, to domestic pigs is relatively infrequent and limited to village farms especially those in areas close to the wildlife reservoirs (40).

The incubation period in domestic pigs ranges from 5 to 15 days, and in clinical cases, there is fever (41–42°C for about 4 days), diarrhea, inappetence, incoordination, prostration, coma, and death (27). Vomiting, nasal and conjunctival discharge, dyspnea, anal and nasal hemorrhages can also be observed in some animals. Abortion is common in affected sows. In regions where ASF is absent, mortality rates often reach 100% (27), making it a highly dreaded disease. ASF cases can also be predominantly subclinical especially in endemic areas (41). Although early detection and laboratory diagnosis are essential for the control and management of the disease, resemblance with other hemorrhagic diseases of pigs including

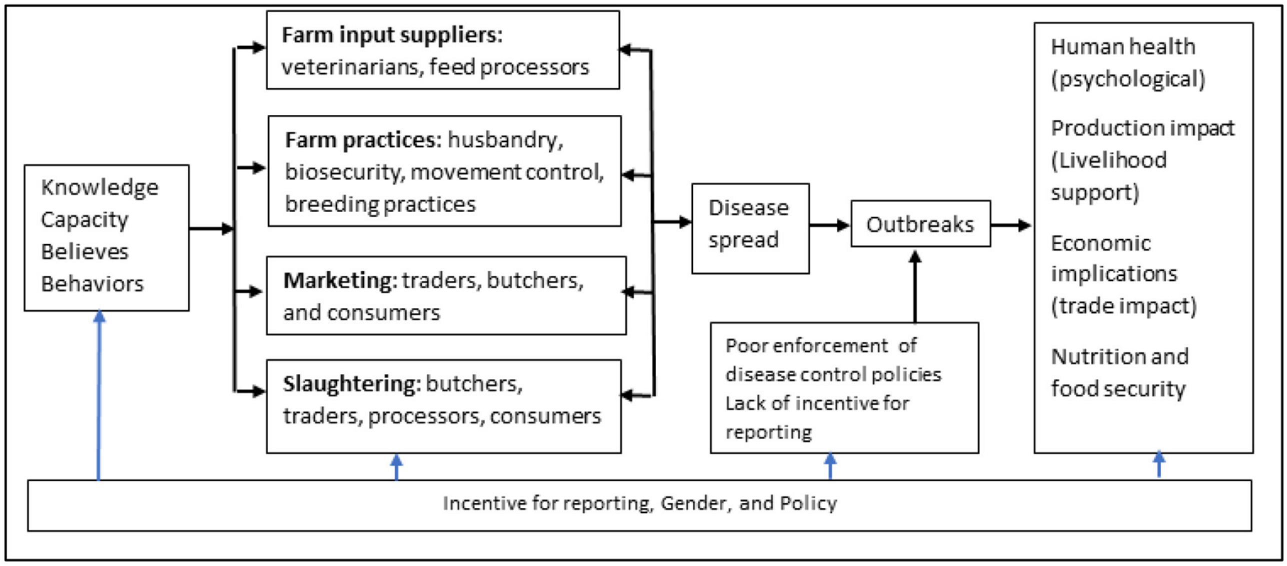


FIGURE 1 | Framework used in the desk-based study.

porcine reproductive and respiratory disease, erysipelas, and salmonellosis need to be considered (42, 43).

It has been noted that previous efforts to develop an ASF vaccine have not been successful (44). Vaccine development has been hindered by the limited knowledge regarding the disease and the virus strain variation (45). There is also no treatment for the disease. Suggested control measures include investing in quarantine facilities, banning free range pig systems, implementation of enhanced biosecurity, a ban on illegal import of pork and pork products, and the introduction of an improved surveillance system. In Europe, the main preventive measures are the use of animal identification and tracing systems, the enforcement of swill feeding bans, and containment of pigs to ensure they do not come into contact with pigs from other farms, feral pigs, wild boar, or their products (46). Livestock identification and traceability systems are virtually non-existent in many smallholder pig systems in Africa (47) and cannot be relied upon to reduce disease spread. Swill feeding can introduce disease in healthy populations (48). It is impossible to monitor its use at the household level although farmers can be requested to boil the swill before feeding it to their pigs, for about 30 min (49). Asking smallholders to confine their pigs will face some resistance as this imposes feeding obligations which they may not be ready to undertake (48). As such, a national policy which includes identifying sources of feedstuffs that are readily available and affordable, should be put in place (49). Stamping out is another approach but this also is not feasible especially in settings where ASF is endemic (as is the case in SSA). It involves (1) early detection, (2) enabling legislation for declaring national emergencies, (3) zoning of the country into infected zones, surveillance zones and free zones, (4) inspection and quarantine, (5) immediate slaughter of infected animals, (5) epidemiological surveillance, (6) safe burial of carcasses, (7) cleaning and disinfection of carcasses and (8) keeping previously infected premises and villages free of pigs (49). It has been observed that eradication of the disease from SSA is not an option given the involvement of African wild suids and ticks of the *Ornithodoros moubata* complex, in the epidemiology of the disease (48). It has also been noted that, in Africa, the domestic pig cycle is driven by poverty (30) hence the need to consider the role of other factors when designing interventions to control diseases involving pigs.

Biosecurity Control Measures

Biosecurity is key in ensuring disease free farms, regions, and countries. Its adoption will not only reduce the risk of disease introduction significantly, but will also reduce the magnitude of the financial losses that may occur following introduction of the disease in susceptible pig populations (50). Biosecurity has been defined as the management of the risk of pests and diseases entering, emerging, establishing, or spreading and causing harm to animals, plants, human health, the economy, the environment, or the community (51). In an agricultural context, "biosecurity" refers to practices that control the spread of disease both into and within the farm (52). As observed by Villarroel et al. (53) and Laanen et al. (54), a key component of farm-level biosecurity is biocontainment or internal biosecurity, which has been described as the series of management practices that prevent the spread of infectious agents between animal groups in a farm or the management practices designed to prevent the infectious agent from leaving the farm.

There are three main levels of biosecurity (55): (1) segregation, the creation and maintenance of barriers to limit entry of infected animals and contaminated materials to a non-infected site. Segregation measures include controlling the entry of pigs from outside farms, markets or villages, implementing quarantine for newly purchased animals, limiting the number of sources of replacement stocks, fencing farm areas and controlling access for people, as well as that of birds, bats, rodents, cats and dogs, maintaining adequate distances between farms, providing footwear and clothing to be worn only on the farm, and using an all-in-all-out management system (56); (2) cleaning of materials, including vehicles and equipment that enter or leave a site, aiming to remove all visible dirt. It is expected that the cleaning will remove most of the contaminants; and (3) disinfection which, when properly applied, will inactivate any pathogen present on materials that have already been cleaned. Cleaning and disinfection measures may involve the use of high-pressure and low-pressure washers, targeting buildings on the premises, but also vehicles, equipment, clothing and footwear. Cleaning and disinfection procedures are thought to be fundamental for pathogen inactivation, to prevent disease spread, and to facilitate repopulation after an outbreak (56). Indeed, cleaning represents one of the most important steps in the cleaning and disinfection process (57). It removes over 90% of microorganisms when properly performed and improves the disinfection efficacy (58). Other biosecurity concerns that Chenais et al. (59) highlight include slaughtering of pigs that showed signs of the disease and gaps in handling of the waste, high turnover of staff causing biosecurity routines to be lost and the handling of waste water. Compliance with biosecurity protocols in smallholder pig systems is challenging, possibly more so in a country like Uganda where ASF is endemic, even for farms that are fenced off and may confine their pigs (59).

Impact of African Swine Fever in Smallholder Pig Systems

African swine fever is a highly fatal disease of pigs. It has significant impacts on food security, income, and development. Because of a lack of epidemiological data, the impact of ASF is not well-understood, especially in SSA. The negative impacts are more significant in smallholder settings where pigs are traditionally raised and biosecurity systems are weak (60). According to Chenais et al. (61) assessing the economic impact of ASF in such systems is complicated, as the pigs are mostly reared as what could be seen as passive investments rather than being an active working capital.

Costs associated with ASF outbreaks are dependent on the nature of the virus and the degree to which susceptible populations are exposed (62). Sick pigs, as well as those that have been exposed to the virus, are often culled to reduce spread (63) and mitigate financial loss. Also, because of the uncertainty created following outbreaks, producers may be reluctant to increase their pig numbers (64). The result is a reduction in the amount of pork on the market and subsequently, an increase in price. In China, it is reported that the retail prices in the country rose by 78% heavily impacting consumers (65). It also has been observed that consumers are also likely to substitute pork with relatively cheaper products (66) further destabilizing the market. ASF has been circulating in domestic pig populations in Tanzania (67). A study involving 1085 households reported a mortality rate of 84% (range 46–97) (68). The authors found the average number of pigs lost per household to be 4 and this translated to a loss of Tsh 160.632 million (equivalent of USD 92,583 at a conversion rate of 1 USD = TSH 1,735, estimate for 2014 when the study was undertaken).

It has been reported that, by the end of 2019, due to ASF-outbreaks, the national pig herd in China was reduced by half (65). A study involving several countries in Europe found new ASF-events in the period between 2010 and 2019 to have reduced pork exports by almost 15% in the year after the cases had occurred (69). The feed sector was also affected, given the reduced demand. China's total consumption of animal feeds is said to have dropped by 17% in 2019 (65). Given the high mortality in pigs, and as an indirect result of the disease, staff employed in pig enterprises risk losing their jobs when outbreaks occur (59). The situation may be exacerbated if farmers decide to withdraw from production, especially in settings where pig production contributes significantly to local livelihoods.

Another concern is that producers in countries where the disease is endemic may not report all outbreaks to authorities (70) and sick pigs may be traded to reduce any losses due to ASF thereby increasing the spread of the disease. This was observed in Uganda where households that reported ASF outbreaks were found to consume meat more times per month compared to those that did not report any outbreaks (61).

Farm and Value Chain Management Practices That Influence Occurrence of African Swine Fever

Pig Husbandry Practices

Pig production in many sub-Saharan countries is characterized by backyard farming of small number of animals, managed semi-intensively, seasonal confinement, free-roaming or tethering (**Figures 2–4**). As minimal health care is afforded to pigs in these systems, the burden of infections, especially in relation to helminthiasis (71) and respiratory diseases (36), is very high. Such systems are prone to ASF incursions with epidemic peaks observed throughout the year. In terms of confinement, it is the pigs in peri-urban and urban settings that are more likely to be confined (15, 33, 72–74). The confined pigs receive better care including medication as, and when required, and commercial feeds since the production is more market oriented.

Pig Feeding Systems

Field experiences show that pigs reared in extensive or semi-extensive systems are mostly fed on crop residues or forages, while those in peri-urban or urban areas have access to swill (i.e., the leftover food from owners and restaurants, which do not undergo any processing). Richer farmers may purchase commercially formulated feeds or raw materials such as maize, rice bran, etc. which they can use to formulate rations for their pigs. Feeding strategies change depending on availability of feed resources, which also follow a seasonal pattern (9, 34, 75). It is worth noting that ASF can be perpetuated among permanently confined pigs through swill feeding (76). The virus can survive in chilled meat or carcasses for up to 6 months, and at 4°C

FIGURE 2 | Tethered sow with piglets in Uganda (picture credit: Michel Dione, ILRI).

FIGURE 3 | Housed sow with piglets in Uganda (picture credit: Michel Dione, ILRI).

FIGURE 4 | Free-ranging pig in Uganda (picture credit: Michel Dione, ILRI).

for two years. It has been shown to remain infective in smoked and salted pork. ASFV is highly resistant to putrefaction and can remain in feces for at least 11 days and in decomposed serum for 15 weeks (77). During an outbreak investigation in the central region in Uganda, ASFV was isolated from tissues of pigs that had died from ASF (78), suggesting that feeding pigs with contaminated materials or undercooked pork can predispose the animals to the disease. However, practices like processing swill by heating can kill the virus and consequently decrease the risk of virus transmission to healthy pigs. Niederwerder et al. (79) demonstrate that ASFV can easily be transmitted orally (although higher doses will be required for infection to occur through plant-based feed). In 2014, the introduction and spread of ASFV in Latvia was associated with failure to use simple biosecurity measures notably the feeding of virus-contaminated fresh grass or crops to naive pigs (80). It has also been demonstrated that ASFV can survive in feed ingredients (under simulated transboundary shipping models) (81) suggesting that ASFV spread might be attributed to less-recognized transmission routes such as feed or water (79). In smallholder systems, pig feeding strategies generally depend on availability of the feed resources and the ability of farmers to buy ingredients, which often are expensive. Financial constraints can lead to sub-optimal feeding practices, hence the risk for ASF can increase.

Movements of Pigs and Products

ASF has proved difficult to eradicate due to the movement of infected pigs and pig products (14, 82). Especially in East Africa, pig movements, due to trade and restocking, are the most common risk factors associated with the spread of ASF in small-holder systems (26, 83). In Uganda, movements of pigs and pork products were responsible for the vast majority of outbreaks (83). Animal loan practices for breeding purposes, such as sharing of boars and purchases can be a factor contributing to the transmission of ASF virus between farms, through direct pig-to-pig contact (84). Transboundary movements of pigs have also been associated with outbreaks at the borders of Uganda with 20.6% of reported outbreaks between 2001 and 2012 taking place in areas adjacent to international borders (14). Advanced genomic studies involving ASFV strains from Uganda, from outbreaks in 2007, identified 22 different tetrameric amino acid units, which were identical to the sequence of 6 isolates responsible for the second wave of infections that occurred in Western and Central Kenya from October 2006 to January 2007, suggesting that ASFV virus exchange between the two countries might have occurred on more than one occasion (78). Therefore, movements of pigs, through trade, does play an important role in spreading ASFV beyond national borders.

Animal movement control in many countries is not fully regulated, and although there are policies in place, they lack enforcement. Informal trade of livestock is a concern in many countries, and there are several factors driving it (economical, social, political) (85). There are no physical markets for live pigs in most countries, especially in East Africa, a measure aimed at disease control. In Kenya and Uganda, buyers, mainly traders and middlemen, visit villages and farms in order to source pigs for further sale (29, 86). There are also opportunities for farmers to contact traders when they have a need to sell a pig, increasingly now relying on mobile phone technology. Pigs may be purchased daily and, when bought, are transported from the farm directly to the slaughter slab, either by herding or using other available means (bicycles, motorcycles, etc.) (73, 86, 87). Within East Africa, the marketing of pigs faces a number of challenges including non-compliance with regulations regarding movement control of animals and animal by-products, and poor transport infrastructure. This situation constitutes a high risk to the spread of ASF, given that in some cases suspected outbreaks of ASF are not revealed by farmers and traders in order to avoid losses, and to escape enforced restrictions by government authorities (19, 23). Other risky practices include the panic sale of sick pigs, the movement of traders and butchers from farm to farm without taking any biosecurity precautions, as they search for cheap animals, and the illegal transportation of animals between villages or districts without movement permits. In Uganda, pig traders were identified by value chain actors as the highest risk for ASF spread (26).

Pig Slaughtering and Processing

In SSA, pig slaughtering practices in most smallholder pig systems are generally poor, mainly due to lack of proper slaughter facilities. In some of the countries, there is usually no formal slaughtering place for pigs, and routine meat inspection by veterinary officers is rarely undertaken. In Uganda, for example, most of the time, pigs are slaughtered at the backyard and meat is either sold to the butchers or consumed at home to some extent (9). Several practices, related to informal slaughter of pigs, potentially contribute to spread of ASFV, including improper disposal of offals, often in the immediate environment (bush) and the use of slaughter waste for the feeding of live pigs and/or dogs (26, 88). The risk of ASFV being spread by butchers was compounded by use of poorly constructed slaughter slabs/sites with open drainage, ineffective or non-existent meat inspection services, lack of biosecurity measures, and sale of pork to customers who often are not aware of the risks of ASFV-infected pork (89).

Factors Likely to Influence the Uptake of Biosecurity Measures

Lack of Knowledge and Lack of Awareness by Value Chain Actors

The implementation of biosecurity is key to successful pig production in an ASF-endemic environment (90). However, knowledge of the key principles of biosecurity is fundamental if farmers and other value chain actors such as traders, butchers and transporters want to substantially change their perception of disease risks, and consequently increase their level of awareness of the importance of biosecurity measures. In Uganda, several studies have recommended training of pig farmers on strict biosecurity measures as a means of mitigating ASF (16, 19). In Nigeria, the need for extension officers or livestock experts to educate less experienced farmers on pig production and provision of extension services aimed at raising technical knowledge on effective productivity and profitability was reported (91). Another study found that efficiency of pig production could be increased by 14% through farmer education and improving farming skills (92). A study in Chad highlighted the importance of providing knowledge to pig producers (93). In Uganda, participatory training can significantly improve farmer's knowledge of biosecurity (94). According to Young et al. (95), behavior change toward adopting improved biosecurity is likely to have positive benefits and impacts on the smallholder and public health at large. However, positively influencing the development of the smallholder farming system through uptake and adoption of sustainable interventions or change remains a major challenge, particularly with respect to improving the management of disease risks (96).

Financial Limitations of Smallholders in Sub-saharan Africa

In a specific smallholder pig sector such as Nigeria, according to Fasina et al. (90) additional workforce, costs and complexities of application of biosecurity, availability of funds are key barriers to adopt better practices. A study in Uganda concluded that pig farmers may be unwilling to adopt biosecurity practices if implemented alone to control ASF outbreaks unless there were financial incentives to compensate for higher costs (97). In Uganda, limited access of farmers to markets and the high cost of pig feed ingredients were among the major constraints of pigs farmers that interfere with the control of ASF (9). This situation may explain the reason why Costard et al. (98) advocate for market-based approaches or certification approaches to tackle ASF. However, according to Chenais et al. (61), causality of social and economic impact of ASF outbreaks in smallholder systems is complex. In the current pig systems context, farmers may rely on cheap biosecurity and animal management measures to sustain their pig enterprise; these practices are often not sufficient to prevent or control ASF. Profitability remains the principal driver for involvement in pig rearing, hence the understanding of this factor and its use in the introduction and maintenance of principles of biosecurity at farm level becomes important for controlling ASF in small- to medium-scale piggeries and farming communities (90). The assumption for promoting biosecurity is that compliance will lead to better performance and consequently higher financial returns; so that farmers can invest back in improving biosecurity in their farms and increase their pig production.

Socio-Cultural Factors

Knowledge levels, capacity, and incentives to adopt biosecurity measures at farm level are shaped by differences between men and women arising mainly from their socio-cultural backgrounds, responsibilities, and societal expectations. Pig farm tasks of men differ from those of women, depending on settings. Also, men and women have different knowledge, skills, experiences as well as needs and constraints (99). Decision making patterns in households are not homogenous, but cultural norms seem to influence certain patterns across most communities (100). In Uganda, women play a critical role in pig husbandry and biosecurity as they deal with most of the management activities (99, 101). Typical gender roles and the perceptions of men and women toward biosecurity undermine effective implementation of biosecurity measures in smallholder pig systems in Uganda. In most smallholder systems, given the crucial role women play in pig husbandry and disease control and the overall purpose of improving the livelihoods of smallholder pig keepers, interventions must address underlying gender inequalities and women's workload, which inhibit improved ASF control and prevention (102).

In Uganda, women reported facing constraints mostly related to labor demands that are time-consuming and also related to exposure to disease during the implementation of biosecurity. On the other hand, constraints faced by men are mostly periodic/occasional and related to social or community standing. On-farm constraints reported include lack of capital to construct pigsties and the purchase of farm tools/equipment, which is attributed to the low incomes of households, absence of alternative sources of revenue, and lack of labor to implement some biosecurity measures (e.g., for digging pits to bury dead pigs) (102). Addressing these issues would contribute toward creating an enabling environment for men and women to implement biosecurity measures. Engaging both female and male pig producers in ASF disease prevention and control can promote more sustainable livelihoods along the pig value chain and beyond. Through the provision of training for men and women relating to pig husbandry and disease control and through gender sensitization, gains can be made to increase the participation of men in taking on tasks that are, in the context of this setting, considered to be tasks of women (102). Training on biosecurity should explicitly target both men and women in households, reflect on the division of labor, open opportunities for women in emerging labor markets, and build on gender role changes that have already occurred rather than revert back to the traditional roles of women.

ASF Control and Policy Implications

African swine fever was first detected in Kenya in 1910 but has since spread across the globe (30). Human behavior, livestock management, and inadequate biosecurity measures are the main factors driving its occurrence (103). In East Africa, the greatest risk is brought about by operations of traders, brokers and pig butchers (26). The challenge then is to identify practical, sustainable farmer-based and situation-specific solutions, and developing risk mitigation strategies along pig and pork- product value chains that will positively impact on the sector (30).

ASF is a transboundary animal disease (TAD) and building strong collaborations at national, regional and international levels is critical to its control. Disease spread to neighboring countries is mainly due to cross-border trade, either involving live pigs or pork products, formally and informally (104). The vast majority of TADs are highly contagious and usually have serious socio-economic impacts. Regional harmonization of ASF interventions is needed for the effective control of ASF (105). A global ASF strategy covering the period between 2020 and 2025 exists (103). This strategy considers the Global Framework for the Progressive Control of Transboundary Animal Diseases (GF-TADs) as a tool with the potential to fight transboundary animal diseases. GF-TADs is a joint initiative of FAO and OIE, with the expected participation of WHO for diseases with zoonotic potential, to achieve the prevention, detection and control of TADs (106). The Terrestrial animal health code requires importing countries to only accept animals that have been subjected to a health examination and which are accompanied by an international veterinary certificate (107).

A regional strategy for ASF control in SSA exists (105). It includes review and enforcement of existing disease control legislation and policies while promoting formulation, harmonization, and implementation where gaps are identified. The strategy proposes risk-based solutions that are feasible for outbreak control (105). Africa can learn a lot from approaches used to contain the disease in other countries. China issued several policies and regulations to prevent and control ASF outbreaks (64). This included establishing more stringent surveillance programs and the need to meet legal requirements relating to biosecurity. The Chinese Animal Husbandry and Veterinary Bureau formulated the animal vaccine regulation to counter the problem of fake veterinary vaccines on the market, that among other expectations requires those producing veterinary vaccines illegally to be fined 5 times the product value or RMB 200,000 in the case where the amount cannot be fixed (108). The EU adopted a directive that lays down community measures for the control of African swine fever. Measures required for reporting and follow up actions are very well-detailed. Member states were required to establish laws, regulations and administrative provisions necessary to comply with the relevant Directive (109).

Especially for Africa, institutional and legal elements that governments should consider when preparing for, and reacting to outbreaks of ASF, are already defined (110); some of which need to be in place before an outbreak occurs—for example existence of an emergency plan as an indication of preparedness, availability of funds, establishment of a legislative framework (assess current legislation and identify gaps), awareness creation (through the veterinary department, schools, the media etc.). Once an outbreak occurs, measures are put in place to check spread, legislation is enacted, and the public is sensitized. Being prepared for disease emergencies requires governments to set aside funds for this, including sampling of animals and laboratory confirmation of disease. Addressing the risk of ASF requires involvement and cooperation of all relevant stakeholders. This includes producers who are likely to comply with control measures if they are aware of the benefits that may result from such efforts (104). In a study by Dione et al. (94), veterinarians in Uganda were found not to always observe proper biosecurity measures when visiting pig farms. Inadequate enforcement of rules and regulations, obsolete legal frameworks, and lack of appropriate compensation schemes are the main regulatory challenges (105).

It is the responsibility of the veterinary authorities to control ASF, although stakeholder efforts are also required (111), including farmers who need to comply with biosecurity measures. But many SSA countries face a number of challenges including lack of political support and existence of policies that do not effectively respond to the needs of the sector (103, 105). With limited funds, control operations cannot be fully implemented. A starting point could be to lobby for increased government support, perhaps starting with sensitization at the lowest levels of governance. For ASF, mitigation strategies have to be effective and practical (112). Traders may be aware of how the disease clinically manifests (37) but factors including poor access to resources and policy limitations remain a problem (26). Improving biosecurity will require pig farmers to invest more resources into their pig businesses (105), a challenge given that these are low input/ low output operations. Confirmation of ASF is not a problem given that reference laboratories exist, however, for SSA, the main challenge has been the time it takes to detect the disease in the field (113). Early warning of disease relies on functional surveillance systems, rapid reporting and epidemiological analysis of results (49, 111). For countries where ASF is emerging, and to confine outbreaks, surveillance requires a more comprehensive policy, laboratory support and rapid response procedures and adequate human resources (63). Given the experience from recent outbreaks in China, investments in animal health system infrastructure, capacity building, and policy are needed to reduce the likelihood and costs associated with disease outbreaks (62).

In Kenya, reporting of notifiable diseases is well-defined in section 4 of the Animal Diseases Act (114). The Meat Control Act (114) requires animals to be inspected before slaughter. Pigs showing temperatures of 41°C or higher are supposed to be condemned. High fever is one of the symptoms of Africa swine fever. According to the pig Industry Act, Chapter 361 (repealed in 2006), pig farmers are required to have a license. It states that *"....every pig kept by a pig producer shall, whenever kept in a building, be confined in a pig-proof building and whenever not in a building shall be confined in a pig-proof paddock"*(115). In Uganda, construction of pig houses is specified in the regulations (116). Allowing pigs to roam freely is a concern, not only for ASF but also for diseases of public health importance (e.g., pig cysticercosis). The health status of the original herd will be lost when pigs mix with other pigs in animal markets (111) and will spread the virus to their new destination.

Many countries have regulations on animal movements, but enforcement of the measures has always been a challenge, especially in developing countries where food value chains are informal. In Kenya for example, moving animals from one county to another requires one to obtain a permit that the person accompanying the animals will need to carry and present to authorities when asked to do so. Appropriate incentives need to be determined to encourage compliance by relevant stakeholders. Although important for animal health and food safety, Livestock Identification and Traceability systems (LITS) are lacking in many developing countries. Namibia is an example of a country that has made progress in that regard (117). LITS is useful for disease management, vaccination programmes, husbandry, zoning or compartmentalization, surveillance, early response and notification systems, animal movement controls, inspection, certification, etc. (118), all of which are important in ASF control.

CONCLUSIONS AND RECOMMENDATIONS

Pigs are an important source of income especially to smallholder communities, and, with an increasing human population, can potentially mitigate risks of food insecurity. ASF remains the greatest threat to the pig sector, globally, and outbreaks can be devastating, especially in small farms who may not have other income sources. Although significant progress has been made in vaccine development, there has not been any breakthrough to date. Several control measures have been proposed and improved, but many of these are not designed in the context of developing countries. Although application of biosecurity measures can make a difference in these setting, compliance with even the simplest measures has been, and continues to be, a challenge, especially for farmers and other actors in the pig value chain. Relevant stakeholders need to be educated about the disease and implementation of biosecurity measures in an effort to mitigate the risks. However, farmers require options that are feasible and cheap to implement. Further research is needed to develop, validate, and sensitize farmers about these solutions, even as more research to develop vaccines continues. While stakeholder sensitization is an easy, short term investment, we recommend the development of a policy system that would ensure compliance with ASF control measures, while providing incentives to invest in the value chain. Interventions should be tailored to specific contexts and socio-economic environments if we want to boost adoption of biosecurity of smallholder pig value chain actors. In the context of COVID-19 epidemic, there is an opportunity to rethink the field of biosecurity taking into consideration a more integrated and holistic approach. This will encourage stakeholder engagement and also support smallholder producers.

AUTHOR CONTRIBUTIONS

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

REFERENCES

1. Neumann C, Harris DM, Rogers LM. Contribution of animal source foods in improving diet quality and function in children in the developing world. *Nutr Res.* (2002) 22:193–220. doi: 10.1016/S0271-5317(01)00374-8
2. Thornton PK. Livestock production: recent trends, future prospects. *Philos Trans R Soc B Biol Sci.* (2010) 365:2853–67. doi: 10.1098/rstb.2010.0134
3. Ampaire A, Rothschild MF. Pigs, goats and chickens for rural development: small holder farmer's experience in Uganda. *Livestock Res Rural Dev.* (2010) 22:102. Available online at: http://www.lrrd.org/lrrd22/6/ampa22102.htm
4. Phiri IK, Ngowi H, Afonso S, Matenga E, Boa M, Mukaratirwa S, et al. The emergence of Taenia solium cysticercosis in Eastern and Southern Africa as a serious agricultural problem and public health risk. *Acta Trop.* (2003) 87:13–23. doi: 10.1016/s0001-706x(03)00051-2
5. Delgado CL. Rising consumption of meat and milk in developing countries has created a new food revolution. *J Nutr.* (2003) 133(11 Suppl. 2):3907S–10S. doi: 10.1093/jn/133.11.3907S
6. FAO (2021). *Sources of Meat. Animal Production and Health*. Available online at: http://www.fao.org/ag/againfo/themes/en/meat/backgr_sources.html
7. FAOSTAT. *FAO Statistics Division*. Food and Agriculture Organization of the United Nations (2010).

8. FAO. *Mapping Supply and Demand for Animal-Source Foods to 2030. Animal Production and Health Working Paper No. 2*. Rome: FAO (2011).
9. Ouma E, Dione M, Lule PM, Pezo D, Marshall K, Roesel K, et al. *Smallholder pig value chain assessment in Uganda: results from producer focus group discussions and key informant interview*. ILRI, Nairobi, Kenya (2015).
10. Motsa'a JS, Defang HF, Keambou CT. Socio-economic and technical characteristics of pig (Sus scrofa domesticus) production system in the humid forest with monomodal rainfall agroecological zone of Cameroon. *Int J Biol Chem* Sci. (2018) 12 2318–27. doi: 10.4314/ijbcs.v12i5.31
11. Scheftelowitz M, Thrän D. Unlocking the energy potential of manure—an assessment of the biogas production potential at the farm level in Germany. *Agriculture*. (2016) 6:20. doi: 10.3390/agriculture6020020
12. Deka R, Thorpe WM, Lapar L, Kumar A. *Assam's pig sub-sector: current status, constraints and opportunities*. Assam: ILRI (2007).
13. Dietze K. *Pigs for Prosperity. Diversification Booklet Number 15*. Rome: Rural Infrastructure and Agro-Industries Division Food and Agriculture Organization of the United Nations Rome (2011).
14. Atuhaire DK, Ochwo S, Afayoa M, Mwiine FN, Kokas I, Arinaitwe E, et al. Epidemiological Overview of African Swine Fever in Uganda (2001–2012). *J Vet Med*. (2013). 2013:949638. doi: 10.1155/2013/949638
15. Muhanguzi D, Lutwama V, Mwiine FN. Factors that influence pig production in Central Uganda—case study of Nangabo Sub-County, Wakiso district. *Vet World*. (2012) 5:346–51. doi: 10.5455/vetworld.2012.346-351
16. Dione MM, Ouma EA, Roesel K, Kungu J, Lule P, Pezo D. Participatory assessment of animal health and husbandry practices in smallholder pig production systems in three high poverty districts in Uganda. *Prev Vet Med*. (2014) 117:565–76. doi: 10.1016/j.prevetmed.2014.10.012
17. Jolaoluwa Awosanya EJ, Olugasa B, Ogundipe G, Grohn YT. Sero-prevalence and risk factors associated with African swine fever on pig farms in southwest Nigeria. *BMC Vet Res*. (2015) 11:133. doi: 10.1186/s12917-015-0444-3
18. Foster JE. Chapter 8—Viruses as pathogens: animal viruses affecting wild and domesticated species. *Viruses*. Cambridge, MA: Academic Press. (2018). p. 189–216.
19. Dione MM, Akol J, Roesel K, Kungu J, Ouma EA, Wieland B, et al. Risk factors for african swine fever in smallholder pig production systems in Uganda. *Transbound Emerg Dis*. (2015) 64:872–82. doi: 10.1111/tbed.12452
20. Nantima N, Ocaido M, Ouma E, Davies J, Dione M, Okoth E, et al. Risk factors associated with occurrence of African swine fever outbreaks in smallholder pig farms in four districts along the Uganda-Kenya border. *Trop Anim Health Prod*. (2015) 47:589–95. doi: 10.1007/s11250-015-0768-9
21. Thomas LF, Bishop RP, Onzere C, McIntosh MT, Lemire KA, de Glanville WA, et al. Evidence for the presence of African swine fever virus in an endemic region of Western Kenya in the absence of any reported outbreak. *BMC Vet Res*. (2016) 12:192. doi: 10.1186/s12917-016-0830-5
22. Okoth EA, Onzere C, Amimo JO, Riitho V, Mwangi W, Davies J, et al. Detection of African swine fever virus in the tissues of asymptomatic pigs in smallholder farming systems along the Kenya–Uganda border: implications for transmission in endemic areas and ASF surveillance in East Africa. J Gen Virol. (2017) 98:1806–14. doi: 10.1099/jgv.0.000848
23. Nantima N, Davies J, Dione M, Ocaido M, Okoth E, Mugisha A, et al. Enhancing knowledge and awareness of biosecurity practices for control of African swine fever among smallholder pig farmers in four districts along the Kenya-Uganda border. *Trop Anim Health Prod*. (2016) 48:727–34. doi: 10.1007/s11250-016-1015-8
24. Dione M, Nantima N, Mayega L, Amia W, Wieland B, Ouma E. *Enhancing biosecurity along Uganda's pig value chains to control and prevent African swine fever. Livestock Brief 1*. Nairobi: ILRI (2017).
25. Barongo MB, Bishop RP, Fèvre EM, Knobel DL, Ssematimba A. A mathematical model that simulates control options for african swine fever virus (ASFV). PLoS ONE. (2016) 11:e0158658. doi: 10.1371/journal.pone.0158658
26. Dione M, Ouma E, Opio F, Kawuma B, Pezo D. Qualitative analysis of the risks and practices associated with the spread of African swine fever within the smallholder pig value chains in Uganda. *Prev Vet Med*. (2016) 135:102–12. doi: 10.1016/j.prevetmed.2016.11.001
27. Penrith ML. African swine fever. *Onderstepoort J Vet Res*. (2009) 76:91–5. doi: 10.4102/ojvr.v76i1.70
28. Revilla Y, Pérez-Núñez D, Richt JA. African swine fever virus biology and vaccine approaches. *Adv Virus Res*. (2018) 100:41–74. doi: 10.1016/bs.aivir.2017.10.002
29. Mutua FK, Dewey CE, Arimi SM, Ogara WO, Githigia SM, Levy M, et al. Indigenous pig management practices in rural villages of Western Kenya. *Livestock Res Rural Dev*. (2011) 23:144. Available online at: http://www.lrrd.org/lrrd23/7/mutu23144.htm
30. Penrith ML. Current status of African swine fever. *CABI Agric Biosci*. (2020) 1:11. doi: 10.1186/s43170-020-00011-w
31. Wabacha JK, Maribei JM, Mulei CM, Kyule MN, Zessin KH, Oluoch-Kosura W. Characterisation of smallholder pig production in Kikuyu Division, central Kenya. *Prev Vet Med*. (2004) 63:183–95. doi: 10.1016/j.prevetmed.2004.02.007
32. Karimuribo ED, Chenyambuga SW, Makene VW, Mathias S. Livestock research for rural development. Characteristics and production constraints of rural-based small-scale pig farming in Iringa region, Tanzania. *Livestock Res Rural Dev*. (2011) 23:2011 23.
33. Kimbi E, Lekule F, Mlangwa J, Mejer H, Thamsborg S. Smallholder pigs production systems in Tanzania. J Agric Sci Technol A. (2015) 5:47–60. doi: 10.17265/2161-6256/2015.01A.007
34. Nantima N, Ocaido M, Davies J, Dione M, Okoth E, Mugisha A, et al. Characterization of smallholder pig production systems in four districts along the Uganda-Kenya border. *Livestock Res Rural Dev*. (2015) 27:166.
35. Mbuza F, Majyambere D, Ayabagabao JDD, Dutuze AF. Inventory of pig production systems in Rwanda. *Int J Livestock Prod*. (2016) 7:41–7. doi: 10.5897/IJLP2016.0299
36. Dione M, Masembe C, Akol J, Amia W, Kungu J, Lee HS, et al. The importance of on-farm biosecurity: sero-prevalence and risk factors of bacterial and viral pathogens in smallholder pig systems in Uganda. *Acta Trop*. (2018) 187:214–21. doi: 10.1016/j.actatropica.2018.06.025
37. Atherstone C, Galiwango RG, Grace D, Alonso S, Dhand NK, Ward MP, et al. Analysis of pig trading networks and practices in Uganda. *Trop Anim Health Prod*. (2019) 51:137–47. doi: 10.1007/s11250-018-1668-6
38. Galindo I, Alonso C. African swine fever virus: a review. *Viruses*. (2017) 9:103. doi: 10.3390/v9050103
39. Dixon LK, Sun H, Roberts H. African swine fever. *Antiviral Res*. (2019) 165:34–41. doi: 10.1016/j.antiviral.2019.02.018
40. Jori F, Vial L, Penrith ML, Pérez-Sánchez R, Etter E, Albina E, et al. Review of the sylvatic cycle of African swine fever in sub-Saharan Africa and the Indian ocean. *Virus Res*. (2013) 173:212–27. doi: 10.1016/j.virusres.2012.10.005
41. Murcia P, Donachie W, Palmarini M. Viral pathogens of domestic animals and their impact on biology, medicine and agriculture. *Encyclopedia of Microbiol*. (2009). p. 805–19.
42. Sánchez-Vizcaíno JM, Mur L. African swine fever diagnosis update. *Dev Biol*. (2013) 135:159–65. doi: 10.1159/000189240
43. Bastos ADS, Fasina FO, King DP. African swine fever (Chapter 50). In: Liu D, editor. *Manual of Security Sensitive Microbes and Toxins*. Taylor and Francis CRC Press (2014). p. 579–87.
44. Bastos ADS, Fasina FO, King DP. African swine fever (Chapter 50). In: Liu D, editor. Manual of Security Sensitive Microbes and Toxins. Taylor and Francis; *CRC Press*, (2014). p. 579–87.
45. Rock DL. Challenges for African swine fever vaccine development—"… perhaps the end of the beginning.". Vet Microbiol. (2017) 206:52–8. doi: 10.1016/j.vetmic.2016.10.003
46. Jurado C, Martínez-Avilés M, De La Torre A, Štukelj M, de Carvalho Ferreira HC, Cerioli M, et al. Relevant measures to prevent the spread of african swine fever in the european union domestic pig sector. *Front Vet Sci*. (2018) 5:77. doi: 10.3389/fvets.2018.00077
47. Mutua F, Lindahl J, Randolph D. Possibilities of establishing a smallholder pig identification and traceability system in Kenya. *Trop Anim Health Prod*. (2020) 52:859–70. doi: 10.1007/s11250-019-02077-9
48. Beltrán-Alcrudo D, Arias M, Gallardo C, Kramer S, Penrith ML. *African swine fever: detection and diagnosis—a manual for veterinarians. FAO Animal Production and Health Manual No. 19*. Rome: Food and Agriculture Organization of the United Nations (FAO) (2017). p. 88.

49. FAO. Preparation of African swine fever contingency plans. Penrith ML, Guberti V, Depner K, Lubroth J, editor. *FAO Animal Production and Health Manual No. 8*. Rome: FAO (2009).
50. Nespeca R, Vaillancourt JP, Morrow WE. Validation of a poultry biosecurity survey. *Prev Vet* Med. (1997) 31:73–86. doi: 10.1016/S0167-5877(96)01122-1
51. Carr J, Howells M. Biosecurity on pig and poultry farms: principles for the veterinary profession. *In Pract.* (2018) 40:238–48. doi: 10.1136/inp.k2593
52. Dargatz DA, Garry FB, Traub-Dargatz JL. An introduction to biosecurity of cattle operations. Vet Clin North Am Food Anim Pract. (2002) 18:1–5. doi: 10.1016/S0749-0720(02)00002-6
53. Villarroel A, Dargatz DA, Lane VM, McCluskey BJ, Salman MD. Suggested outline of potential critical control points for biosecurity and biocontainment on large dairy farms. *J Am Vet Med Assoc.* (2007) 6:808–19. doi: 10.2460/javma.230.6.808
54. Laanen M, Persoons D, Ribbens S, De Jong E, Callens B, Strubbe M, et al. Relationship between biosecurity and production/antimicrobial treatment characteristics in pig herds. Vet J. (2013) 198:508–12. doi: 10.1016/j.tvjl.2013.08.029
55. FAO, OIE, WB. Good practices for biosecurity in the pig sector—issues and options in developing and transition countries. *FAO Animal Production and Health Paper No. 169*. Rome: FAO (2010).
56. Ford WB. Disinfection procedures for personnel and vehicles entering and leaving contaminated premises. Rev Sci Tech Off Int Epizoot. (1995) 14:393–401. doi: 10.20506/rst.14.2.847
57. De Lorenzi G, Borella L, Alborali GL, Prodanov-Radulović J, Štukelj M, Bellini S. African swine fever: a review of cleaning and disinfection procedures in commercial pig holdings. Res Vet Sci. (2020) 132:262–7. doi: 10.1016/j.rvsc.2020.06.009
58. PREP, F. *NAHEMS Guidelines: Cleaning and Disinfection*. Ames, IA, MD: The Foreign Animal Disease Preparedness and Response Plan/National Animal Health Emergency Management System. (2014).
59. Chenais E, Sternberg-Lewerin S, Boqvist S, Liu L, LeBlanc N, Aliro T, et al. African swine fever outbreak on a medium-sized farm in Uganda: biosecurity breaches and within-farm virus contamination. *Trop Anim Health Prod.* (2017) 49:337–46. doi: 10.1007/s11250-016-1197-0
60. Mulumba-Mfumu LK, Saegerman C, Dixon LK, Madimba KC, Kazadi E, Mukalakata NT, et al. African swine fever: Update on Eastern, Central and Southern Africa. *Transbound Emerg Dis.* (2019) 66:1462–80. doi: 10.1111/tbed.13187
61. Chenais E, Boqvist S, Emanuelson U, von Bromssen C, Ouma E, Aliro T, et al. Quantitative assessment of social and economic impact of African swine fever outbreaks in northern Uganda. *Prev Vet Med.* (2017) 144:134–48. doi: 10.1016/j.prevetmed.2017.06.002
62. Weaver TRD, Habib N. Evaluating Losses Associated with African Swine Fever in the People's Republic of China and Neighboring Countries. *ADB East Asia Working Paper Series No.* (2020) 27:38. doi: 10.22617/WPS200263-2
63. Woonwong Y, Do Tien D, Thanawongnuwech R. The future of the pig industry after the introduction of african swine fever into Asia. *Anim Front.* (2020) 10:30–7. doi: 10.1093/af/vfaa037
64. Tao D, Sun D, Liu Y, Wei S, Yang Z, An T, et al. One year of African swine fever outbreak in China. *Acta Trop.* (2020) 211:105602. doi: 10.1016/j.actatropica.2020.105602
65. Berthe F. *The Global Economic Impact of ASF*. Paris: OIE; Bulletin Panorama (2020).
66. Mason-D'Croz D, Bogard JR, Herrero M, Robinson S, Sulser TB, Wiebe K, et al. Modelling the global economic consequences of a major African swine fever outbreak in China. Nat Food. (2020) 1:221–8. doi: 10.1038/s43016-020-0057-2
67. Yona CM, Vanhee M, Simulundu E, Makange M, Nauwynck HJ, Misinzo G. Persistent domestic circulation of African swine fever virus in Tanzania, 2015–2017. *BMC Vet Res.* (2020) 16:369. doi: 10.1186/s12917-020-02588-w
68. Swai ES, Lyimo CJ. Impact of African Swine fever epidemics in smallholder pig production units in Rombo district of Kilimanjaro, Tanzania. *Livestock Res Rural Dev.* (2014) 26:32. Available online at: http://www.lrrd.org/lrrd26/2/SWAI26032.html
69. Niemi JK. Impacts of African swine fever on pigmeat markets in Europe. *Front Vet Sci.* (2020) 7:634. doi: 10.3389/fvets.2020.00634
70. Costard S, Zagmutt FJ, Porphyre T, Pfeiffer DU. Small-scale pig farmers' behavior, silent release of African swine fever virus and consequences for disease spread. *Sci Rep.* (2015) 5:17074. doi: 10.1038/srep17074
71. Roesel K, Dohoo I, Baumann M, Dione M, Grace D, Clausen PH. Prevalence and risk factors for gastrointestinal parasites in small-scale pig enterprises in Central and Eastern Uganda. *Parasitol Res.* (2017) 116:335–45. doi: 10.1007/s00436-016-5296-7
72. Rutebarika C, Ademun AR. African swine fever Diagnostics, surveillance, epidemiology and control in Uganda. In: *Identification of Researchable Issues Targeted to the Endemic Areas Within Sub-Saharan Africa*. Nairobi: Fairview Hotel (2011).
73. Ouma EA, Dione MM, Lule PM, Roesel K, Pezo D. Characterization of smallholder pig production systems in Uganda: constraints and opportunities for engaging with market systems. Livestock Res Rural Dev. (2014) 26:56. Available online at: http://www.lrrd.org/lrrd26/3/ouma26056.htm
74. Adjei OD, Osei-Amponsah R, Ahunu BK. Characterization of local pig production systems in Ghana. *Bull Anim Health Prod Africa.* (2015) 63:337–42.
75. Mutua FK, Dewey C, Arimi S, Ogara W, Levy M, Schelling E. A description of local pig feeding systems in village smallholder farms of Western Kenya. *Trop Anim Health Prod.* (2012) 44:1157–62. doi: 10.1007/s11250-011-0052-6
76. Bellini S, Casadei G, De Lorenzi G, Tamba M. A review of risk factors of african swine fever incursion in pig farming within the european union scenario. *Pathogens.* (2021) 10:84. doi: 10.3390/pathogens10010084
77. Perith ML, Guberti G, Lubroth J. *Preparation of African Swine fever contingency plan*. Rome: FAO (2009).
78. Gallardo C, Ademun AR, Nieto N, Nantima N, Arias M, Martín E, et al. Genotyping of African swine fever virus (ASFV) isolates associated with disease outbreaks in Uganda in 2007. *Afr J Biotechnol.* (2011) 10:3488–97. doi: 10.5897/AJB10.1439
79. Niederwerder MC, Stoian AMM, Rowland RRR, Dritz SS, Petrovan V, Constance LA, et al. Infectious dose of African swine fever virus when consumed naturally in liquid or feed. *Emerg Infect Dis.* (2019) 25:891–7. doi: 10.3201/eid2505.181495
80. Olševskis E, Guberti V, SerŽants M, Westergaard J, Gallardo C, Rodze I, et al. African swine fever virus introduction into the EU in 2014: Experience of Latvia. *Res Vet Sci.* (2016) 105 28–30. doi: 10.1016/j.rvsc.2016.01.006
81. Dee SA, Bauermann FV, Niederwerder MC, Singrey A, Clement T, de Lima M, et al. Survival of viral pathogens in animal feed ingredients under transboundary shipping models. *PLoS ONE.* (2018) 13:e0194509. doi: 10.1371/journal.pone.0194509
82. Costard S, Mur L, Lubroth J, Sanchez-Vizcaino JM, Pfeiffer DU. Epidemiology of African swine fever virus. *Virus Res.* (2012)173:1–7. doi: 10.1016/j.virusres.2012.10.030
83. Tejler E. *Outbreaks of African swine fever in domestic pigs in Gulu district, Uganda* (Examensarbete). Swedish University of Agricultural Sciences, Examensarbete inom veterinärprogrammet, Uppsala. (2012).
84. Okoth E, Gallardo C, Macharia JM, Omore A, Pelayo V, Bulimo DW, et al. Comparison of African swine fever virus prevalence and risk in two contrasting pig-farming systems in South-west and Central Kenya. *Prev Vet Med.* (2013) 110:198–205. doi: 10.1016/j.prevetmed.2012.11.012
85. Grace D, Little P. Informal trade in livestock and livestock products. *Rev Sci Tech Off Int* Epiz. (2020) 39:183–92. doi: 10.20506/rst.39.1.3071
86. Mtimet N, Baker D, Ouma E. Analysing pig traders in Uganda: sampling issues, marketing activities, and constraint analysis. *Dev Pract.* (2018) 28:107–24. doi: 10.1080/09614524.2017.1363873
87. Levy M, Dewey C, Weersink A, Mutua F, Poljak Z. Pig marketing and factors associated with prices and margins in Western Kenya. *J Agric Econ Dev.* (2013) 2:371–83.
88. Muhangi D, Masembe C, Berg M, Ståhl K, Ocaido M. Practices in the pig value chain in Uganda; implications to African swine fever transmission. *Livestock Res Rural Dev.* (2014) 26:94. Available online at: https://www.lrrd.cipav.org.co/lrrd26/5/muha26094.htm
89. Lichoti JK, Davies J, Maru Y, Kitala PM, Githigia SM, Okoth E, et al. Pig traders' networks on the Kenya-Uganda border highlight potential for mitigation of African swine fever virus transmission and

improved ASF disease risk management. *Prev Vet Med.* (2017) 140:87–96. doi: 10.1016/j.prevetmed.2017.03.005

90. Fasina FO, Lazarus DD, Spencer BT, Makinde AA, Bastos AD. Cost implications of African swine fever in smallholder farrow-to-finish units: economic benefits of disease prevention through biosecurity. *Transbound Emerg Dis.* (2012) 59:244–55. doi: 10.1111/j.1865-1682.2011.01261.x
91. Umeh JC, Ogbanje C, Adejo MA. Technical efficiency analysis of pig production: a sustainable animal protein augmentation for Nigerians. *J Adv Agric Technol.* (2015) 2:19–24. doi: 10.12720/joaat.2.1.19-24
92. Obayelu AE, Ogunmola OO, Sowande OK. Economic analysis and the determinants of pig production in ogun state, Nigeria. *Agricultura Tropica et Tubtropica.* (2017) 50/2:61–70. doi: 10.1515/ats-2017-0007
93. Youssouf ML, Zeuh V, Adoum IY, Kabore CY. Production practices and constraints in pig farming in N'Djamena area, Tchad. *Int J Livestock Prod.* (2014) 5:196–203.
94. Dione M, Dohoo I, Ndiwa N, Poole J, Ouma E, Amia W, et al. Impact of participatory training on farmers' knowledge, attitude and practices of biosecurity measures for the control of African swine fever in Uganda. *Transbound Emerg Dis.* (2020) 67:1–12. doi: 10.1111/tbed.13587
95. Young JR, Suon S, Andrews CJ, Henry LA, Windsor PA. Assessment of financial impact of FMD on smallholder cattle farmers in southern Cambodia. *Transbound Emerg Dis*. (2013) 60:166–74. doi: 10.1111/j.1865-1682.2012.01330.x
96. Young JR, Evans-Kocinski S, Bush RD, Windsor PA. Improving smallholder farmer biosecurity in the mekong region through change management. *Transbound Emerg Dis.* (2015) 62:491–504. doi: 10.1111/tbed.12181
97. Ouma E, Dione M, Birungi R, Lule P, Lawrence M, Dizyee K. African swine fever control and market integration in Ugandan peri-urban smallholder pig value chains: An ex-ante impact assessment of interventions and their interaction. *Prev Vet Med.* (2018) 151:29–39. doi: 10.1016/j.prevetmed.2017.12.010
98. Costard S, Zagmutt F, Porphyre T, Roger F, Pfeiffer DU. Small-scale pig farmers, behaviour, silent release of African swine fever and consequences for persistence. In: *International Symposia on Veterinary, Epidemiology, and Economics 2012*; Maastricht, Netherlands: ISVEE; (2012).
99. Ouma E, Ochago R, Dione M, Birungi R, Lule P. Gender equitable pig business hubs. In: Rhiannon P, Eerdewijk A, editors. *A Different Kettle of Fish? Gender Integration in Livestock and Fish Research*. Volendam: LM Publishers (2016).
100. FAO. FAO corporate document repository. Meat processing technology for small- to medium-scale producers. Rome. (2013). Avaialble online at: http://www.fao.org/3/ai407e/ai407e.pdf (accessed December 30, 2013).
101. Dione M, Ochago R, Ouma E, Lule P, Birungi B. The gender dimensions of a pig disease: African swine fever in Uganda. In: Rhiannon P, Eerdewijk A, editors. *A Different Kettle of Fish? Gender Integration in Livestock and Fish Research*. Volendam: LM Publishers (2016).
102. Dione M, Ochago R, Ouma E, Lule P, Kakinda MJ, Nyapendi R, et al. Gender perspective of pig husbandry and disease control among smallholder pig farmers in Uganda. *AgriGender*. (2020) 5:13–26. doi: 10.19268/JGAFS.522020.2
103. FAO, OIE. Global control of African swine fever: A GF-TADs initiative. 2020–2025. Paris (2020). Available online at: https://www.oie.int/fileadmin/Home/eng/Animal_Health_in_the_World/docs/pdf/ASF/ASF_GlobalInitiative_web.pdf doi: 10.20506/bull.2020.1.3116 (accessed March, 2021).
104. Costard S, Wieland B, de Glanville W, Jori F, Rowlands R, Vosloo W, et al. African swine fever: how can global spread be prevented? *Philos Trans R Soc Lond B Biol Sci.* (2009) 364:2683–96. doi: 10.1098/rstb.2009.0098
105. FAO, AU-IBAR, ILRI. Regional strategy for the control of african swine fever in Africa (2017). Available online at: https://rr-africa.oie.int/wp-content/uploads/2020/01/au_strategy_asf_en.pdf (accessed March, 2021).
106. FAO. *Global Framework for the Progressive Control of Transboundary Animal Diseases* (GF-TADs). Rome: FAO (2021). Available online at: http://www.gf-tads.org/about/en/
107. OIE. *Terrestrial Animal Health Code*. vol I. 20th ed. Paris: OIE (2011).
108. Ding Y, Wang Y. Big government: The fight against the African Swine Fever in China. *J Biosafe Biosecur.* (2020) 2:44–9. doi: 10.1016/j.jobb.2020.04.001
109. EU. *Council Directive 2002/60/EC of 27 June 2002 laying down specific provisions for the control of African swine fever and amending Directive 92/119/EEC as regards Teschen disease and African swine fever (Text with EEA relevance).* (2002). Available online at: https://eur-lex.europa.eu/eli/dir/2002/60/oj (accessed March, 2021).
110. FAO *Institutional And Legal Measures To Combat African Swine Fever.* (1999). Available online at: http://www.fao.org/3/bb036e/bb036e.pdf (accessed March, 2021).
111. Bellini S, Rutili D, Guberti V. Preventive measures aimed at minimizing the risk of African swine fever virus spread in pig farming systems. *Acta Vet Scand.* (2016) 58:82–82. doi: 10.1186/s13028-016-0264-x
112. Guinat C, Gogin A, Blome S, Keil G, Pollin R, Pfeiffer DU, et al. Transmission routes of African swine fever virus to domestic pigs: current knowledge and future research directions. *Vet Rec.* (2016) 178:262–7. doi: 10.1136/vr.103593
113. Sánchez-Vizcaíno JM. Early detection and contingency plans for African swine fever. In: *Conf.* Paris: OIE. (2010).
114. GOK. *Meat Control (Local Slaughterhouse) Regulations, 2010 Arrangement of Regulations.* (2012). Available online at: http://extwprlegs1.fao.org/docs/pdf/ken101239.pdf (accessed March, 2021).
115. GOK. *Animal Diseases Act Chapter 364*. (1989). *National Council for Law Reporting with the Authority of the Attorney-General* (2012). Available online at: http://extwprlegs1.fao.org/docs/pdf/ken63506.pdf
116. Go U. The Animal Diseases Act (2015). Statutory Instrument 38−4. The Animal Diseases Rules. Arrangement of Rules. Available online at: https://ugandatrades.go.ug/media/136_1Animal_Diseases_Rules_(S.I._38_4).pdf (accessed March, 2021).
117. Prinsloo T, de Villiers C. A framework to define the impact of sustainable ICT for agriculture projects: the Namibian livestock traceability system. *EJISDC.* (2017) 86:1–22. doi: 10.1002/j.1681-4835.2017.tb00606.x
118. OIE. *General principles on identification and traceability of live animals.* Terrestrial Animal Health Code - 28/06/2019 (2019). Available online at: https://www.oie.int/fileadmin/home/eng/health_standards/tahc/current/chapitre_ident_traceability.pdf (accessed March, 2021).

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

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

Copyright © 2021 Mutua and Dione. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.

frontiers in Veterinary Science

ORIGINAL RESEARCH
published: 24 August 2021
doi: 10.3389/fvets.2021.723375

Risk Factors of African Swine Fever in Domestic Pigs of the Samara Region, Russian Federation

Anastasia A. Glazunova[1]*, Fedor I. Korennoy[2,3], Timofey A. Sevskikh[4], Daria A. Lunina[1], Olga I. Zakharova[3], Andrei A. Blokhin[3], Anton K. Karaulov[2] and Andrey E. Gogin[4]

[1] Federal Research Center for Virology and Microbiology, Branch in Samara, Samara, Russia, [2] Federal Center for Animal Health (FGBI ARRIAH), Vladimir, Russia, [3] Federal Research Center for Virology and Microbiology, Branch in Nizhny Novgorod, Nizhny Novgorod, Russia, [4] Federal Research Center for Virology and Microbiology, Pokrov, Russia

African swine fever (ASF) is an incurable viral disease of domestic and wild pigs. A large-scale spread of ASF began in Eurasia in 2007 and has affected territories from Belgium to the Far East, occurring as both local- and regional-level epidemics. In 2020, a massive ASF epidemic emerged in the southeastern region of European Russia in the Samara Oblast and included 41 outbreaks of ASF in domestic pigs and 40 cases in wild boar. The Samara Oblast is characterized by a relatively low density of wild boar (0.04–0.05 head/km^2) and domestic pigs (1.1–1.3 head/km^2), with a high prevalence of small-scale productions (household farms). This study aims to understand the driving forces of the disease and perform a risk assessment for this region using complex epidemiological analyses. The socioeconomic and environmental factors of the ASF outbreak were explored using Generalized Linear Logistic Regression, where ASF infection status of the Samara Oblast districts was treated as a response variable. Presence of the virus in a district was found to be most significantly ($p < 0.05$) associated with the importation of live pigs from ASF-affected regions of Russia (OR = 371.52; 95% CI: 1.58–87290.57), less significantly ($p < 0.1$) associated with the density of smallholder farms (OR = 2.94; 0.82–10.59), volume of pork products' importation from ASF-affected regions of Russia (OR = 1.01; 1.00–1.02), summary pig population (OR = 1.01; 0.99–1.02), and insignificantly ($p > 0.1$) associated with presence of a common border with an ASF-affected region (OR = 89.2; 0.07–11208.64). No associations were found with the densities of pig and wild boar populations. The colocation analysis revealed no significant concentration of outbreaks in domestic pigs near cases in wild boar or vice versa. These results suggest that outbreaks notified in low biosecurity household farms were mainly associated with the transportation and trade of pigs and pork products from ASF-affected regions of Russia. The findings underline the importance of taking into account animal transportation data while conducting future studies to develop a risk map for the region and the rest of European Russia.

Keywords: African swine fever, Russian Federation, Samara region, logistic regression, low-biosecurity farms, colocation analysis, animal movement

OPEN ACCESS

Edited by:
Klaus Depner,
Friedrich-Loeffler-Institute, Germany

Reviewed by:
Nicolai G. W. Denzin,
Friedrich Loeffler Institute, Germany
Marina Stukelj,
University of Ljubljana, Slovenia

***Correspondence:**
Anastasia A. Glazunova
timon883@outlook.com

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

Received: *10 June 2021*
Accepted: *02 August 2021*
Published: *24 August 2021*

Citation:
Glazunova AA, Korennoy FI, Sevskikh TA, Lunina DA, Zakharova OI, Blokhin AA, Karaulov AK and Gogin AE (2021) Risk Factors of African Swine Fever in Domestic Pigs of the Samara Region, Russian Federation. Front. Vet. Sci. 8:723375. doi: 10.3389/fvets.2021.723375

INTRODUCTION

African swine fever (ASF) is one of the most dangerous transboundary diseases of domestic and wild suids and is characterized by high lethality and serious socio-economic consequences due to the lack of a vaccine (1). The largest epidemic of ASF in the history of Eurasia caused by a highly virulent virus of the II p72 genotype began 15 years ago in South Caucasus and since then has spread without the involvement of natural hosts or biological vectors. The pandemic has spread to Middle Eastern countries, North Caucasus, East and West Europe, the Russian Far East, China, and southeastern Asian and Oceanian countries.

The spread of ASF in Eurasia has continued since 2007, resulting in local and large-scale epidemics in domestic pig and wild boar populations. ASF has gradually and continuously spread throughout the southern regions of the Russian Federation and has sporadically jumped to regions distant from ASF-affected zones. In 2011, the number of ASF notifications increased significantly in the central regions of the European part of Russia. In 2017, sporadic cases of ASF were reported in the Asian part of Russia, and in 2019, ASF became endemic in the Russian Far East (**Figure 1A**).

Throughout the Russian Federation, the majority of ASF outbreaks were registered in domestic pigs. As of the end of 2020, 1,074 outbreaks in domestic pigs and 737 cases in wild boar were reported to the World Organization for Animal Health (OIE). A similar pattern was observed in Eastern Europe and Asian countries, especially in countries in which small pig productions are more common than commercial pig farms.

The ASF virus (ASFV) is spread and maintained outside Africa in the absence of the classic sylvatic cycle without (or with limited) participation of pig-associated *Ornithodoros* tick species involving wild boar and domestic pigs as reservoirs of virus (2). For this reason, the epidemiology of ASF outside Africa is complex and varies depending on the availability and type of factors of transmission and the epidemiological reservoirs. Circulation of the virus in Eurasia is maintained via the domestic cycle (when the virus circulates in domestic pigs and pig-derived products) and the wild boar-habitat cycle (when the virus circulates in wildlife without the involvement of ticks). These cycles are not isolated and can overlap, allowing the virus to survive for a long time and spread over long distances (3). The circulation of the virus in the domestic pig sector involves human activity and biosecurity, as it occurs within pig farms. The tendency for ASF to become endemic is common in countries with small-scale pig production units with inadequate biosecurity (4).

The functioning of the cycles of the virus, their interactions, and the establishment of endemicity are dependent on several factors such as the biological properties of both the virus and host and abiotic factors (including environmental and natural conditions and social and economic circumstances). According to previous investigations of ASF epidemics in the Russian Federation, susceptible animals typically become infected after contact with infected animals or contaminated fomites, feed, vehicles, or clothing (5). A matched case-control study conducted in Romania revealed that in addition to proximity to outbreaks in domestic farms, the abundance of wild boar and a short distance between the farm and infected wild boar were significant risk factors for the spread of ASF in commercial and small-scale pig farms (6).

Studying the features of an epidemic and ASF epidemiology in a specific region may improve the understanding of its driving forces, risk factors, and transmission routes, especially when the virus is present in both domestic and wild boar populations. Often, epidemiological investigations do not provide information regarding the exact source and risk factors of introduction of virus and whether the domestic pigs or the wild boar plays the primary role in sustaining and spreading of the ASFV. A better understanding of these factors will help provide an effective solution for the prevention and eradication of ASF.

The Samara Oblast is a region where the virus has rapidly spread within a year affecting large areas, and caused at least 41 outbreaks in domestic pigs and 40 cases in wild boar, which accounted for nearly one-third of all ASF outbreaks in the Russian Federation during 2020 (**Figure 1B**). Therefore, this region can be used as a model to investigate the role of various epidemic drivers shaping the observed disease spread. In this study, for the first time we use the national surveillance data on animal movements among other potential risk factors, to explain the observed pattern of ASF outbreaks' distribution in domestic pigs and to provide a basis for the further development of an ASF risk model at both national and regional level.

MATERIALS AND METHODS

Data

Study Area

The Samara Oblast, a region located in southeast European Russia bordering Kazakhstan in the south, is one of 59 ASF affected regions of the Russian Federation.

The average human population density in the region is ∼60 people/km^2. The human population is concentrated around the administrative center and significantly decreased in the peripheral districts. The Samara Oblast has an advantageous economic-geographical location, as two international transport corridors (North-South and West-East) intersect in this region. The central part of the region and large cities have the highest density of roads. The main agricultural areas are situated in the periphery of the region.

Second-level administrative units termed districts (n = 37) were used as spatial units for the assessment of the epidemiological parameters and potential risk factors in this study. Two large cities were excluded as they were statistical outliers for human population density and have no pig husbandry areas. Four districts that have no pig population according to official statistics were also excluded. Therefore, the spatial analysis included 31 districts of the Samara Oblast.

River networks are poorly developed in the southern areas of the Samara Oblast. The main waterbody is the Volga River, which delimits the western part of the region. Forests cover 14% (760,000 ha) of the Samara Oblast, including 25–40% of the central part of the region, 3% of the southern part of the region,

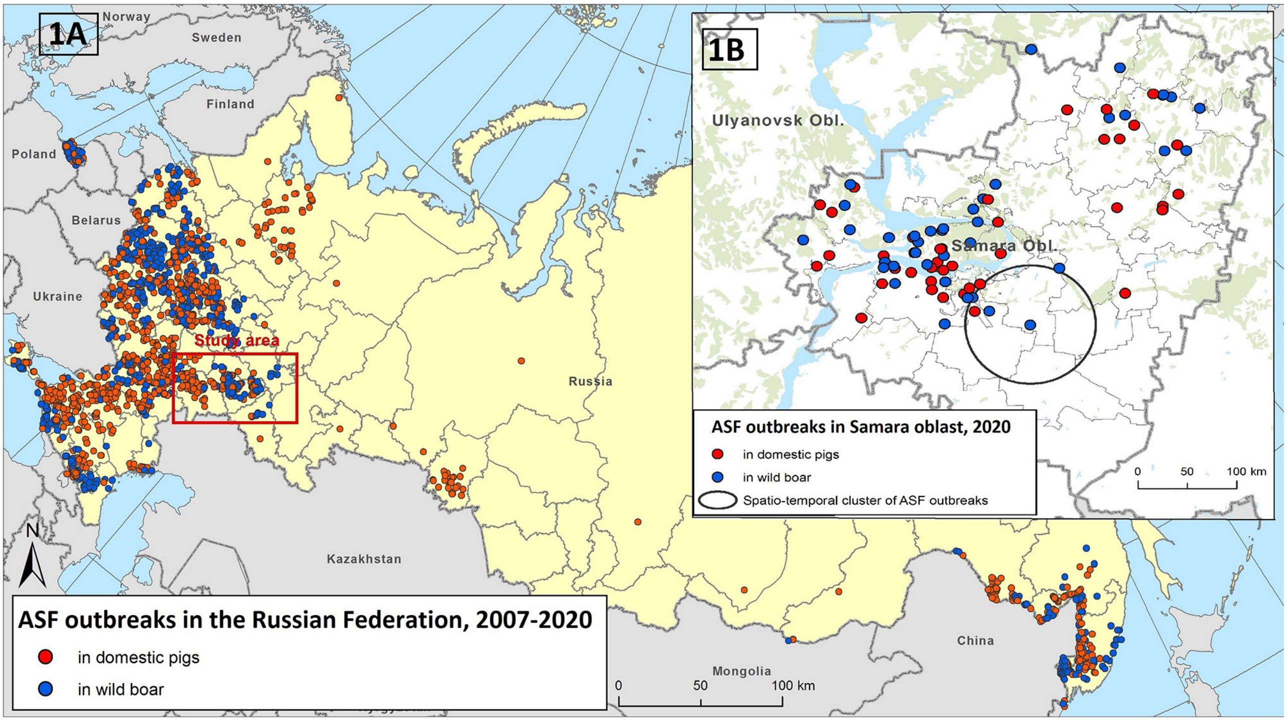


FIGURE 1 | The epidemiological overview of African swine fever (ASF) in the Russian Federation in 2007–2020 **(A)**. The ASF outbreaks in the Samara Oblast in 2020 and revealed spatial-temporal cluster of outbreaks **(B)**.

and 14% of the northern part of the region. There are 217 wildlife nature reserves and national parks in the region where wild boar hunting is prohibited. Sown areas, reserves, and wildlife parks have lakes and rivers that provide a good habitat for wild boar. At the beginning of 2020, the estimated total number of wild boar in the Samara Oblast was 2,345, and the northern and central parts of the region had the highest densities of wild boar (0.78–1.31 ind. per 1,000 hectares). The areas of the Samara Oblast border the Saratov and Ulyanovsk Oblasts, which were already affected by ASF in 2019.

Domestic Pig Sector Characteristics

The agricultural sector of the Samara Oblast is focused mainly on crop production. Most of the meat produced in the region is poultry (60%), while pork accounts for 24% of the meat produced in the region (7). The density of the pig population is relatively low in this region, with most pigs kept in small-scale farms. At the end of 2019, the total number of ASF-susceptible animals was 187,185 pigs, including 84,075 heads in small-scale farms (backyards, for self-consumption), 9,954 in non-specialized commercial farms (from 3 to 3,695 pigs per holding), and 56,342 in large-scale specialized commercial pig farms. In August 2020, the total number of pigs was ∼192,000.

A significant proportion of the domestic pigs in this region were contained in holdings with a low level of biosecurity, where restrictive and safety measures were implemented only in emergency situations. At the end of 2020, only 32 pig husbandries had official biosecurity statuses. Overall, 68.75% of households were unprotected, 6.25% had low-level biosecurity, 12.5% had average levels of biosecurity, and 12.5% had high levels of biosecurity.

ASF Data

This study used ASF outbreaks data notified by the Russian Federation to OIE (8). According to these data, 41 outbreaks occurred in domestic pigs and 40 cases registered in wild boar in the Samara Oblast in February—December 2020. The exact geographical coordinates, disease start date, and numbers of susceptible and infected animals were reported for each outbreak.

Explanatory Factors

Human and pig population data were acquired from the Federal Service of Governmental statistics (9). Data regarding wild boar population were obtained from the Department of Hunting and Fishing (10). Data regarding settlements and smallholder farm distribution were acquired from the official registry of supervised objects and compartments (11). Data regarding the legal movements of pigs and pork products between the Samara Oblast and the regions of Russia that were affected by ASF in 2019 and 2020 were acquired from "Mercury" database—the state information system of Rosselkhoznadzor (12). This system is designed to trace cargo that is monitored by state veterinary services. Data regarding road networks were acquired from the official website of the Samara Oblast Government (13). Data regarding forest areas were extracted from the raster dataset generated from Earth remote sensing system Proba-V from 2000 to 2018 with an original spatial resolution of 100 × 100 m (14).

Table 1 includes the geospatial variables used for the analyses. **Supplementary Figures 1–14** (see **Supplementary Material**) present the distribution maps of these variables in the Samara Oblast. To avoid multicollinearity, all variables in this study were previously tested using the Spearman rank correlation test. The further modeling used only variables with correlation levels $|r_s| \leq 0.7$.

Descriptive Spatial Analysis

To explore the potential relationship between the ASF outbreaks in domestic pigs and wild boar, we used colocation analysis, a geographic information system (GIS) technique (15–17). This technique measures local patterns of spatial association between two categories of point features using colocation quotient statistics. In this study, the local colocation quotient (LCQ) expressed the local proportion of wild boar ASF cases' locations within a defined neighborhood of domestic pig outbreaks' locations. The analyzed locations were then randomly permuted within the entire study area to estimate whether the observed distribution differs from a random distribution and to calculate the *p*-value of the pattern (9,999 permutations were used in our study to achieve the minimum *p*-value of 0.0002). If the local proportion was higher than the global proportion, the LCQ was > 1. As the colocation analysis is not symmetric, the relationships between domestic pig and wild boar outbreaks and wild boar and domestic pig outbreaks were both explored. Neighborhoods for the LCQ calculations were defined as a circle with a radius equal to the mean neighboring distance for the set of ASF outbreaks, calculated using the Average Nearest Neighbor GIS tool. The colocation was analyzed using a time window accounting of 14 days (i) and 45 days (ii) before and after the analyzed outbreaks to add epidemiological meaning to the relationship between ASF outbreaks. Those time periods correspond to an average and maximum duration of infectious period in domestic swine and wild boar as reported elsewhere (18, 19). It was assumed that ASF outbreaks may be epidemiologically related (for example, an outbreak in domestic pigs might be associated with an infected wild boar from a close neighborhood or a wild boar outbreak might be associated with contaminated waste or the improper disposal of domestic pigs' carcasses). Except for the local colocation quotient, a global colocation was also evaluated (GCQ), which expresses a measure of spatial association between both categories of locations across the entire study area.

Regression Analysis

To identify the ≪susceptibility≫ of districts to ASF outbreaks in domestic pigs, a Generalized Linear Logistic Regression (GLLR) analysis was used (20, 21), where the presence or absence of ASF outbreaks in domestic pigs was considered as a response variable. Several socioeconomic and environmental explanatory variables were used in this analysis, as listed in **Table 1**. To remove redundant variables, a preliminary analysis for Variance Inflation Factor (VIF) was conducted for the model using a threshold VIF of 5, so that all variables with VIF > 5 were excluded from further modeling.

The model was fitted using stepwise exclusion of the insignificant variables to achieve lowest Akaike information criterion (AIC) value with stepAIC procedure in R programming environment. The significance of variables was evaluated using the Student's *t*-test. The goodness of the logistic regression model fit was evaluated using the proportion of the explained variation in the response variable, and joint Wald statistics, which evaluate the efficacy of independent variables based on a null hypothesis assuming their inefficacy. A Hosmer–Lemeshow test was applied to evaluate an overall goodness of the model's fit by indicating of whether the differences between the expected and observed proportions are significant. The spatial distribution of both response variable and model residuals was evaluated using Moran's I spatial autocorrelation test, which demonstrates compliance of the observed spatial distribution of the analyzed variable to a hypothetical random distribution (null hypothesis). Values of Moran's I coefficient close to zero corresponding to low z-scores with $p > 0.05$ indicate normality of the studied distribution. A presence of spatial autocorrelation in both response variable and residuals would indicate an unexplained clustering of studied phenomenon non adjusted by explanatory variables.

Space-Time Cluster Analysis

A space-time cluster analysis was conducted using Kulldorff scan statistics (22), which allows for the identification of clusters in the studied area, where disease events (outbreaks) were grouped more densely than could be expected according to the null hypothesis assuming their random distribution. The analysis uses a cylindric moving scan window, where the vertical dimension represents time. A space-time permutations model used in our analysis only evaluates the presence of space-time clustering of the studied features regardless of any background denominator scores (such as population density etc.). The maximum scanning window sizes were chosen as 50% of the size of the study area and 50% of the study period.

Software

Cleansing, validation, and preliminary evaluation of the data were conducted with Microsoft Office Excel (Microsoft Corporation, Redmond, Washington, U.S.). Preliminary VIF analysis and model fitting were conducted in R programming environment (23) with MASS (24), car (25), and plyr (26) packages. Data were converted into shapefiles for analysis and visualization using GIS-technologies. The spatial and regression analyses were performed using the geographical informational systems ArcGIS Desktop version 10.8.1 and ArcGIS Pro version 2.7 (Esri, Redlands, California, U.S.). SaTScan software (27) was used for the cluster analysis.

RESULTS

Descriptive Epidemiological Analysis

The first cases of ASF in the Samara Oblast were reported in the middle of January 2020 in the area bordering the already affected Ulyanovsk Oblast. Despite all disease control measures, the risk of further spreading of the ASF virus in neighboring

TABLE 1 | Geospatial variables.

	Unit	Variable type (as used in regression analysis)	Median (minimum–maximum)	VIF
Primary road length	km	Continuous	306.6 (23.3–650.8)	4.06
Road density	km^{-1}	Continuous	0.63 (0.32–17.3)	>5
Human population density	Persons/km^2	Continuous	12.7 (5.7–1428.7)	Excluded as highly correlated
Density of smallholder farms	Holdings/km^2	Continuous	0.5 (0–5.3)	1.41
Domestic pig density	Head/km^2	Continuous	0.90 (0.18–7.89)	1.18
Average number of pigs per a smallholder farm	Head	Continuous	1.2 (0–616)	>5
Total volume of live pigs' movements from ASF-affected regions of Russia	Head or yes/no	Continuous or categorical (yes/no)	75 (0–1319)	3.05
Total volume of pig products movements from ASF-affected regions of Russia	kg	Continuous	120 422 (0–7 126 257)	1.35
ASF-affected region bordering with ASF-affected region of Russia	Yes/no	Categorical (yes/no)	0–1	1.54
Proportion of rural population in the total population of the district	%	Continuous	0.8 (0–1)	>5
Forest/total area proportion	%	Continuous	9.8 (0 – 29.7)	>5
Number of ASF cases in wild boar	Number or yes/no	Continuous or categorical (yes/no)	1 (0–7)	>5

regions was high. In the Samara Oblast, 41 outbreaks of ASF in domestic pigs and 40 cases in wild boar were reported in 2020 (**Figure 1B**). Ninety-five percent of the ASF outbreaks in domestic pigs occurred on smallholder farms with the number of susceptible animals ranging from 1 to 140 (median: 16 pigs). The average morbidity rate in these farms was 0.72 ± 0.34, with a mortality rate of 0.57 ± 0.38. The total mortality rate was 0.56 $\pm$ 0.38. Outbreaks on two large industrial pig farms with 38,960 and 3,391 susceptible animals resulted in 404 and 538 infected animals, respectively. In wild boar, the incidence ranged from 1 to 30 infected animals, with a median of two.

ASF outbreaks were more frequent during the summer months (July and August) (**Figure 2**). ASF cases in wild boar were reported from January to March and from June to December, with a peak in July and August. ASF infections in domestic pigs were reported from June to October, with a peak in August.

Spatial and Space-Time Analysis

Results of colocation analysis are presented in **Table 2**. Overall, no evidence of significant global colocation between ASF outbreaks in domestic pigs and wild boar were revealed. At both time windows analyzed, outbreaks in domestic pigs were found to be globally insignificantly collocated with cases in wild boar, while the reverse relationships were found to be insignificantly isolated. No cases in wild boar were found to be significantly concentrated near outbreaks in domestic pigs, neither isolated (**Figure 3**, left). Similarly, no significant clustering of outbreaks in domestic pigs around cases in wild boar were identified. One and two cases in wild boar (4 and 8%, respectively) were significantly collocated with outbreaks in domestic pigs at 14 and 45 days periods respectively, while one case in wild boar was significantly isolated at 45 days period (**Figure 3**, right).

The preliminary data analysis revealed significant correlations between the population density and road density ($r_s = 0.88$), and the human population density and proportion of rural population ($r_s = -0.74$). Therefore, population density was excluded from the regression analysis. Further calculation of VIF for the model left the following predictors with VIF ≤ 5 (**Table 1**):

a. wild boar density,
b. summary pig population,
c. pig population density,
d. smallholder farms density,
e. summary road length,
f. volume of pork products' importation from ASF-affected regions of Russia,
g. importation of live pigs from ASF-affected regions of Russia,
h. presence of a common border with an ASF-affected region.

The final GLLR model includes: importation of live pigs from ASF-affected regions of Russia as the most significant variable ($p < 0.05$), volume of pork products' importation from ASF-affected regions of Russia, density of smallholder farms and total pig population of the district as less significant factors ($p < 0.1$), while presence of common border with ASF-affected region was found to be insignificantly associated with ASF infection status of the district ($p > 0.1$). This model had the lowest AIC,

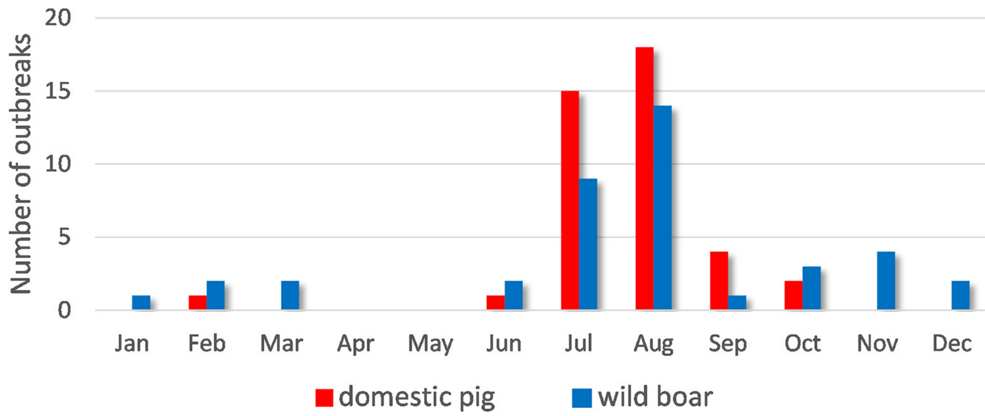


FIGURE 2 | Temporal distribution of African swine fever cases in domestic pigs and wild boar in the Samara Oblast in 2020.

TABLE 2 | Colocation analysis results*.

	Domestic Pigs to Wild Boar		**Wild Boar to Domestic Pigs**	
Time span	14 days	45 days	14 days	45 days
Significantly collocated ($p \leq 0.05$)	–	–	1	2
Insignificantly collocated ($p > 0.05$)	13	14	10	7
Significantly isolated ($p \leq 0.05$)	–	–	–	1
Insignificantly isolated ($p > 0.05$)	17	16	12	13
Global colocation	Insignificantly collocated (GCQ = 1.05, $p = 0.63$)	Insignificantly collocated (GCQ = 1.14, $p = 0.22$)	Insignificantly isolated (GCQ = 0.93, $p = 0.64$)	Insignificantly isolated (GCQ = 0.94, $p = 0.61$)

**those locations having no neighbors within the defined neighborhood radius were removed from the analysis.*

statistically significant Wald test ($p < 0.0001$), and acceptable share of explained variation of 0.67. A Hosmer-Lemeshow test returned $\chi^2 = 6.11$ with $p = 0.63$, thus suggesting an overall model significance. The distribution of the predicted probability of having ASF outbreaks in domestic pigs is shown in **Figure 4** (left). **Table 3** presents the regression metrics for the model. The test for spatial autocorrelation of the response variable returned a Moran's I index of −0.02 that corresponds to z-score of 0.06, p =0.94. For the model residuals, Moran's I index was estimated as −0.13, z-score = −0.73, $p = 0.46$. Hence, no spatial autocorrelation was found in response variable, neither in residuals (**Figure 4**, right). This suggest no spatial dependencies existed in the data distribution that would not be unexplained by the model.

The only statistically significant ($p < 0.001$) cluster of ASF outbreaks was identified in the southern part of the region (including the Neftegorsky, Krasnoarmeysky, Bolsheglushitsky, and Volzhsky districts) (**Figure 1B**). Four outbreaks of ASF were reported from September 18 to October 8 in this area with a radius of 40 km. The first outbreak involved domestic pigs while the rest of cases were in wild boar.

DISCUSSION

This study presents an epidemiological analysis of ASF outbreaks in domestic pigs and wild boar in the Samara Oblast using spatial and colocation analyses. A regression model was used to evaluate the influence of socioeconomic factors on the occurrence of ASF in domestic pigs. Despite the fact that the supposed dependent variable (number of ASF outbreaks notified in domestic pigs) represents count data, its distribution was zero-inflated with comparatively low variation (var = 4), and the number of outbreaks may have been underreported due to attempts by householders to disguise ASF cases in their farms (28–31). Therefore, a logistic model that interprets the dependent variable as the presence or absence of outbreaks was used.

No evidence of significant spatio-temporal associations between outbreaks in domestic pigs and those in wild boar were identified in this study. These results do not allow us to accept a hypothesis of direct epidemiological correlation between nearby outbreaks in wild boar and domestic pigs, and suggest that in this epidemic a close contact between susceptible wild and domestic pigs could hardly play a predominant role in ASF transmission. A similar conclusion is supported by the fact that there was no tendency revealed for ASF outbreaks to cluster in a major part of the region, though the results of colocation and spatio-temporal cluster analyses may be influenced by the underestimation of the number of cases in wild boar due to underreporting. However, an overlap between the dynamics of ASF outbreaks in wild and domestic suids was observed (**Figure 2**). This overlap demonstrates the indirect influence of the populations on one another. ASF cases in wild boar can

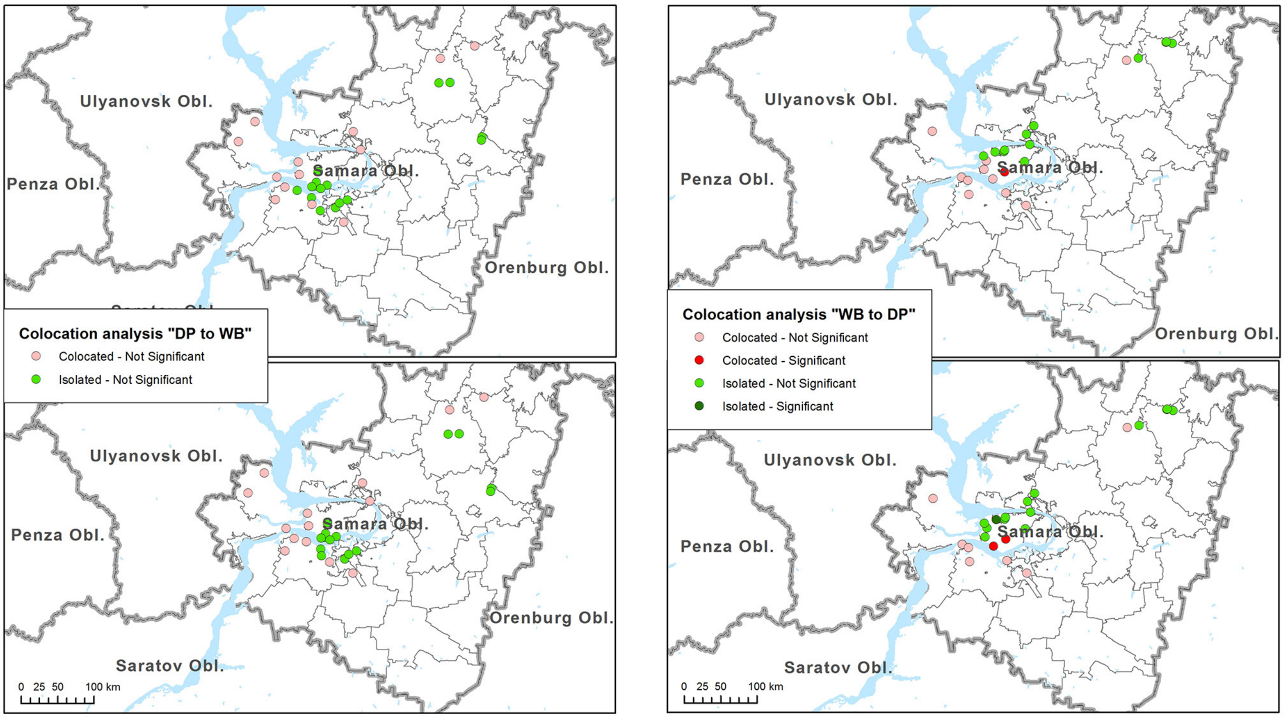


FIGURE 3 | Results of the colocation analysis of African swine fever (ASF) cases in wild boar (WB) near outbreaks in domestic pigs (DP) (left). Colocation of outbreaks in DP near cases in WB (right). Top maps indicate the results for the analysis time span of 14 days, while bottom maps indicated the results for 45-days' time span.

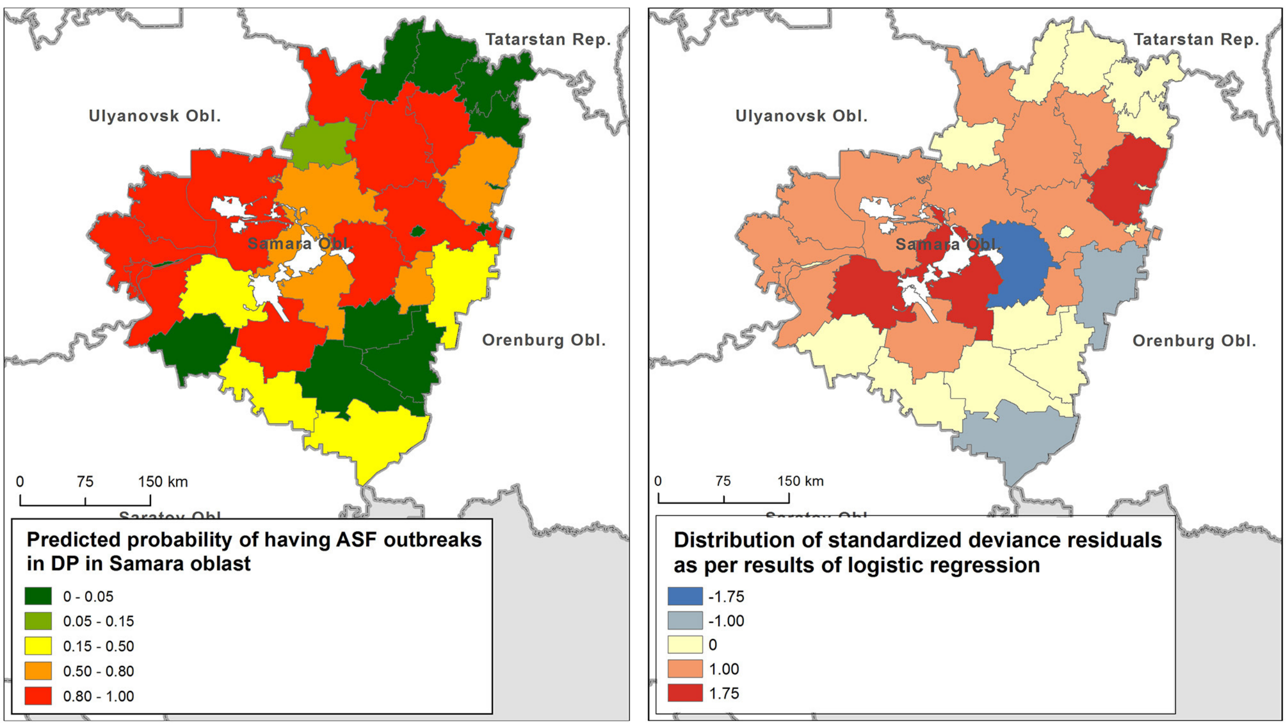


FIGURE 4 | Predicted probability of having an African swine fever (ASF) outbreak in domestic pigs (DP) in the Samara oblast (left), and the distribution of deviance residuals (right).

TABLE 3 | Logistic regression metrics.

Independent variable	Logistic regression coefficient	Standard error	*p*-value	OR	OR 95% CI
Intercept	–8,71	4,48	0,05	0,0001	0.0000–1.0832
Live pig movements from ASF affected RF regions	5.917	2.785	0.03	371.52	1.58–87290.57
Volume of pork products' movements from ASF-affected regions	4E-6	2E-6	0.06	1.001	1.000–1.002
Summary pig population	0.002	0.001	0.09	1.002	0.999–1.004
Density of smallholder farms	1.078	0.653	0.09	2.941	0.817–10.585
Shared border with ASF affected region	4.49	3.64	0.21	89.18	0.07–11,208.64

OR, odds ratio; CI, Confidence Interval.

be related to the end of hunting seasons and breeding periods. The prevalence of outbreaks in domestic populations is likely related to human activities (agricultural activities, trade, and economic relations) and human visits to wild boar habitats and feeding grounds (such as mushroom gathering or berry picking). Though, the results of spatio-temporal analysis should be interpreted carefully because they are subject of reporting accuracy, while underreporting of cases in wild boar may be assumed. Thus, it is believed that as maximum as 10 percent of wild boar carcasses are normally found (32).

The main factors related to the occurrence of ASF outbreaks in domestic pigs identified in this study include the transportation of pigs and pork products from previously infected regions, summary pig population, density of smallholder farms, and sharing borders with ASF-affected regions. These results are consistent with previous studies of risk factors for livestock infections in smallholder farms and studies regarding factors contributing to intraregional infection transmission. The introduction of ASFV via the shipment of pigs was found to be the most significant risk factor for ASF transmission in other studies (33, 34). Sharing a border with a previously-infected region increases the risk of infection during the local movement of people and domestic pigs and the migration of wild boar (35), though it was found to be statistically insignificant in our study. The summary pig population and density of smallholder farms were also identified as significant factors associated with the ASF presence in a district providing an indication of a local pig farming system density that promotes between-holdings contacts and facilitates the ASF transmission (36, 37).

The results of this study indicate that human-mediated activities, and the intensity of smallholder pig operations may be the main driving force of the ASF epidemic in the Samara Oblast independent of the density of wild boar. More studies are required to identify additional risk factors and to clarify a mutual influence of wild boar and domestic pigs populations in order to develop a risk map as a basis of a prognostic model of ASF spread in regions of the Russian Federation and other countries with high proportion of rural inhabitants that are currently free from ASF. A colocation analysis presents an interesting GIS technique that enables studying the space-time relationships between ASF cases in domestic and wild pigs, and provides further opportunities for deeper understanding of observed epidemiological patterns of the disease local spread.

This study is limited by the incomplete assessment of factors associated with a lack of statistical data. For example, the contribution of the illegal sale and movement of pigs and pork products to the spread of ASF cannot be assessed. Data regarding movements between districts within the Samara Oblast are also missing.

In conclusion, this study identifies the spatio-temporal patterns and epidemiological associations of ASF outbreaks in the Samara Region of the Russian Federation in 2020. No obvious associations between outbreaks in domestic pigs and wild boar were identified. ASF-infected districts were associated with the transportation of live pigs from ASF-affected regions of Russia, suggesting socioeconomic links as the main factor of disease spread within the region. The results clearly underline the importance of considering animal transportation data as an explanatory factor in further modeling efforts.

DATA AVAILABILITY STATEMENT

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

AUTHOR CONTRIBUTIONS

AGl, DL, and AGo: conceptualization. FK, OZ, AB, and AGo: methodology. AGl, FK, DL, and OZ: formal analysis. TS, AB, and AGo: validation. AGl, FK, DL, and AK: data curation. FK, AGl, DL, and TS: writing-original draft preparation. FK, TS, OZ, AB, and AGo: writing-review and editing. AGl and DL: visualization. AB and AGo: project administration. All authors have read and agree to the published version of the manuscript.

ACKNOWLEDGMENTS

This work was supported by the Federal Research Center for Virology and Microbiology for government assignments.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fvets.2021.723375/full#supplementary-material

REFERENCES

1. Wu K, Liu J, Wang L, Fan S, Li Z, Li Y, et al. Current state of global african swine fever vaccine development under the prevalence and transmission of ASF in China. *Vaccines.* (2020) 8:1–26. doi: 10.3390/vaccines8030531
2. Dixon LK, Stahl K, Jori F, Vial L, Pfeiffer DiU. African swine fever epidemiology and control. *Annu Rev Anim Biosci.* (2020) 8:221–46. doi: 10.1146/annurev-animal-021419-083741
3. Chenais E, Depner K, Guberti V, Dietze K, Viltrop A, Ståhl K. Epidemiological considerations on African swine fever in Europe 2014–2018. *Porcine Health Management BioMed Central Ltd.* (2019) 5:6. doi: 10.1186/s40813-018-0109-2
4. Penrith ML. Current status of African swine fever. *CABI Agric Biosci [Internet].* (2020) 1:11. doi: 10.1186/s43170-020-00011-w
5. Belyanin S. Dynamic of spreading and monitoring of epizootological process of african swine fever in Russian Federation. (2013). Available online at: http://vniivvim.ru/dissertation/advert/
6. Boklund A, Dhollander S, Chesnoiu Vasile T, Abrahantes JC, Bøtner A, Gogin A, et al. Risk factors for African swine fever incursion in Romanian domestic farms during 2019. *Sci Rep.* (2020) 10:10215. doi: 10.1038/s41598-020-66381-3
7. Main indicators of agricultural sector in Samara Oblast [Internet]. Available online at: https://samarastat.gks.ru/news/document/97001
8. OIE-WAHIS (2021). *Animal disease events. [Internet].* (2021). Available online at: https://wahis.oie.int/#/analytics
9. Federal Service of governmental statistics, Samara Oblast. [Internet]. (2020). Available online at: https://samarastat.gks.ru/population
10. Department of hunting and fishery in Samara Oblast. *Database of governmental hunting farms statistics. [Internet].* (2020). Available online at: https://dor.samregion.ru/category/deyatelnost/monitoring-i-reestry/dannye-gosudarstvennogo-ohothozyajstvennogo-reestra/
11. Cerberus. Registry on supervised structures. *Compartment. [Internet].* (2021). Available online at: https://cerberus.vetrf.ru/cerberus/compartment/pub
12. Governmental informational system of veterinary service. [Internet]. (2020). Available online at: https://mercury.vetrf.ru/
13. Government of Samara Oblast. *Statistics of road system. [Internet].* (2020). Available online at: https://www.samregion.ru/economy/infrastructure/roads/
14. Egorov VA, Bartalev SA, Kolbudaev PA, Plotnikov DE, Khvostikov SA. Land cover map of Russia derived from Proba-V satellite data. *Sovrem Probl Distantsionnogo Zo Zemli iz Kosmosa.* (2018) 15:282–6. doi: 10.21046/2070-7401-2018-15-2-282-286
15. Leslie TF, Kronenfeld BJ. The Co-location quotient: a new measurement of spatial correlation between categories. *Geogr Anal.* (2011) 43:306–26. doi: 10.1111/j.1538-4632.2011.00821.x
16. Wang F, Hu Y, Wang S, Li X. Local indicator of colocation quotient with a statistical significance test: examining spatial association of crime and facilities. *Prof Geogr.* (2017) 69:22–31. doi: 10.1080/00330124.2016.1157498
17. How Colocation Analysis works. [Internet]. (2021). Available online at: https://pro.arcgis.com/en/pro-app/latest/tool-reference/spatial-statistics/learnmorecolocationanalysis.htm
18. de Carvalho Ferreira HC, Backer JA, Weesendorp E, Klinkenberg D, Stegeman JA, Loeffen WLA. Transmission rate of African swine fever virus under experimental conditions. *Vet Microbiol.* (2013) 165:296–304. doi: 10.1016/j.vetmic.2013.03.026
19. African swine fever. OIE Technical Disease cards (2019). Available online at: https://www.oie.int/app/uploads/2021/03/african-swine-fever.pdf (accessed Jun 24, 2021)
20. Menard, S. Applied logistic regression analysis. *Sage.* (2002) 106. doi: 10.4135/9781412983433
21. How Generalized Linear Regression works. [Internet]. (2021). Available online at: https://pro.arcgis.com/en/pro-app/latest/tool-reference/spatial-statistics/how-glr-works.htm
22. Kulldorff M, Heffernan R, Hartman J, Assunção R, Mostashari F, A. space-time permutation scan statistic for disease outbreak detection. *PLoS Med.* (2005) 2:0216–24. doi: 10.1371/journal.pmed.0020059
23. R Core Team. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. (2020) Available online at: https://www.R-project.org/.
24. Venables WN, Ripley BD. Modern Applied Statistics with S, Fourth edition. New York: Springer. (2002). Available online at: https://www.stats.ox.ac.uk/pub/MASS4/.
25. Fox J, Weisberg S. *An R Companion to Applied Regression, Third edition.* Thousand Oaks CA: Sage. (2019) Available online at: https://socialsciences.mcmaster.ca/jfox/Books/Companion/
26. Wickham H. "The Split-Apply-Combine Strategy for Data Analysis." *J Statistical Software.* (2011) Available online at: 40:1–29. http://www.jstatsoft.org/v40/i01/
27. Kulldorff M. and Information Management Services, Inc. SaTScanTM v80: Software for the spatial and space-time scan statistics. (2009) Available online at http://wwwsatscanorg/
28. Vergne T, Guinat C, Petkova P, Gogin A, Kolbasov D, Blome S, et al. 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. *Transbound Emerg Dis.* (2014) 1:6. doi: 10.1111/tbed.12254
29. Costard S, Zagmutt FJ, Porphyre T, Pfeiffer DU. Small-scale pig farmers' behavior, silent release of African swine fever virus and consequences for disease spread. *Sci Rep.* (2015) 27:5. doi: 10.1038/srep17074
30. Dione M, Ouma E, Opio F, Kawuma B, Pezo D. Qualitative analysis of the risks and practices associated with the spread of African swine fever within the smallholder pig value chains in Uganda. *Prev Vet Med.* (2016) 135:102–12. doi: 10.1016/j.prevetmed.2016.11.001
31. Chenais E, Boqvist S, Sternberg-Lewerin S, Emanuelson U, Ouma E, Dione M, et al. Knowledge, Attitudes and practices related to African swine fever within smallholder pig production in Northern Uganda. *Transbound Emerg Dis.* (2017) 64:101–15. doi: 10.1111/tbed.12347
32. Guberti V, Khomenko S, Masiulis M, Kerba S. African swine fever in wild boar ecology and biosecurity. *FAO Animal Production and Health Manual No. 22.* Rome: FAO, OIE and EC. (2019).
33. Mur L, Boadella M, Martínez-López B, Gallardo C, Gortazar C, Sánchez-Vizcaíno JM. monitoring of African swine fever in the wild boar population of the most recent endemic area of Spain. *Transbound Emerg Dis.* (2012) 59:526–31. doi: 10.1111/j.1865-1682.2012.01308.x
34. Mur L, Martínez-López B, Costard S. de la Torre A, Jones BA, Martínez M, et al. Modular framework to assess the risk of African swine fever virus entry into the European Union. *BMC Vet Res.* (2014) 10:1–13. doi: 10.1186/1746-6148-10-145
35. Schettino DN, Abdrakhmanov SK, Beisembayev KK, Korennoy FI, Sultanov AA, Mukhanbetkaliyev YY, et al. Risk for African swine fever introduction Into Kazakhstan. *Front Vet Sci.* (2021) 8. doi: 10.3389/fvets.2021.605910
36. Korennoy FI, Gulenkin VM, Malone JB, Mores CN, Dudnikov SA, Stevenson MA. Spatio-temporal modeling of the African swine fever epidemic in the Russian Federation, 2007-2012. *Spat Spatiotemporal Epidemiol.* (2014) 11:135–41. doi: 10.1016/j.sste.2014.04.002
37. Vergne T, Korennoy F, Combelles L, Gogin A, Pfeiffer DU. Modelling African swine fever presence and reported abundance in the Russian Federation using national surveillance data from 2007 to 2014. *Spat Spatiotemporal Epidemiol.* (2016) 19:70–7. doi: 10.1016/j.sste.2016.06.002

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

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

Copyright © 2021 Glazunova, Korennoy, Sevskikh, Lunina, Zakharova, Blokhin, Karaulov and Gogin. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.

frontiers in Veterinary Science

ORIGINAL RESEARCH
published: 23 September 2021
doi: 10.3389/fvets.2021.689377

Spatial-Temporal Movements of Free Ranging Pigs at the Wildlife-Livestock Interface of Murchison Falls National Park, Uganda: Potential of Disease Control at a Local Scale

Ariane Payne[1*†], *Peter Ogweng*[1], *Karl Ståhl*[2], *Charles Masembe*[1] *and Ferran Jori*[3,4,5]

[1] *Department of Zoology, Entomology and Fisheries Sciences, Makerere University, Kampala, Uganda,* [2] *National Veterinary Institute, SVA, Uppsala, Sweden,* [3] *CIRAD, UMR Animal, Santé, Territoires, Risque et Ecosystèmes (ASTRE), Montpellier, France,* [4] *UMR ASTRE, University of Montpellier, CIRAD, INRAE, Montpellier, France,* [5] *Department of Zoology and Entomology, University of Pretoria, Pretoria, South Africa*

OPEN ACCESS

Edited by:
Roswitha Merle,
Freie Universität Berlin, Germany

Reviewed by:
Anke Wiethoelter,
The University of Melbourne, Australia
Claire Guinat,
ETH Zürich, Switzerland

***Correspondence:**
Ariane Payne
ariane.payne@ofb.gouv.fr

†Present address:
Ariane Payne,
French Agency for Biodiversity (OFB),
Orléans, France

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

Received: *31 March 2021*
Accepted: *21 July 2021*
Published: *23 September 2021*

Citation:
Payne A, Ogweng P, Ståhl K, Masembe C and Jori F (2021) Spatial-Temporal Movements of Free Ranging Pigs at the Wildlife-Livestock Interface of Murchison Falls National Park, Uganda: Potential of Disease Control at a Local Scale. Front. Vet. Sci. 8:689377. doi: 10.3389/fvets.2021.689377

In many Ugandan rural communities, pigs are generally kept under traditional smallholder systems without basic biosecurity measures in place. In some instances, these systems are at the livestock-wildlife interface, as it is the case in Nwoya district, which is bordered by Murchison Falls National Park (MFNP). This pig system has potential for the maintenance and transmission of pathogens like African swine fever (ASF) between different herds, and also with wild pigs (warthogs and bushpigs). In this paper, we describe the spatial and temporal pattern of the movements of free ranging domestic pigs in a rural setting in Northern Uganda where ASF is endemic. We also determine their use of habitat to highlight the potential interaction hotspots between domestic pigs and between domestic and wild pig populations. We fitted 10 free-ranging domestic pigs owned by different homesteads with GPS harnesses during rainy and dry seasons. The pig home range, daily distance, activity pattern and habitat use were calculated. Our results show that the maximum area covered (MCP 100%) by the pigs varied between 35,965 and 475,077 m^2. The core area varied from 1,317 to 50,769 m^2.The pigs' home ranges were significantly bigger during the dry season than during the rainy season (Wilcoxon test, $W = 22$, $p = 0.04$). The mean full day (24 h) distance was longer in the dry season than in the rainy season (Student test, $t = 2.7$, $p = 0.03$). The pigs were mostly located within their own homestead, but they also used other homesteads, grass and crop fields. This study highlights that free-ranging domestic pigs may cover a wide area, especially during the dry season. Interestingly, the home range of pigs from different herds may overlap with areas used by wild pigs which share crops and other resources in this area. This study provides insights into a better understanding of the potential for spread of diseases such as ASF at small-scale and can be used to raise awareness of such risks and to better target implementation of preventive measures.

Keywords: pig farming, pig diseases, GPS harness, home range, homestead, biosecurity, African swine fever

INTRODUCTION

In East Africa, pig production has almost doubled in the last 10 years reaching over 12.5 million heads in 2014 (1). It has become a source of income for resource-poor farmers as pigs can be reared with low investments but have a high and fast productivity and a high feed conversion efficiency (2). Pigs are kept under a wide variety of farming systems, ranging from large-scale intensive and integrated systems to traditional smallholder systems where pigs are reared in free-ranging conditions, tethered or confined in locally built pigsties (2–5). This is the case in Uganda, where traditional farming systems prevails and where the development of the pig sector has been increasing since early 2000 (6, 7). The pig population in Uganda by 2016 stood at 4 million, according to Uganda Bureau of Statistics (8).

Under the free-ranging rearing system, pigs roam freely searching for food waste, scavenging or feeding on crops residues, reducing the cost and the labor of feeding and housing. This practice is often restricted to the dry season when crops have been harvested, whereas pigs are tethered or confined in small pens during the rainy season to prevent them from damaging the growing crops. However, this system albeit more affordable, hardly enables to meet nutritional requirements for pig growth and results in a low profitability. Furthermore, it exposes pigs to accidents, predation, theft and disease transmission since basic biosecurity measures are rarely implemented. Disease transmission may occur through direct or indirect contact with other wild or domestic animals or through contact with contaminated products or fomites. Some of the pathogens infecting pigs may raise public health issues and are considered by farmers as a main production constraint (2–6, 9, 10).

African swine fever (ASF), an infectious disease caused by ASF virus (ASFV), is considered a major limiting factor for the development of the pig farming in Africa (5, 11). This haemorrhagic, contagious and typically very lethal disease of pigs and Eurasian wild boar has neither treatment nor vaccine. In the East African context, ASFV can infect both domestic pigs and different species of wild suids such as warthogs (*Phacochoerus spp)* and bushpigs (*Potamocheorus spp*.) and soft ticks within the genus *Ornithodoros*. However, in Africa, only domestic pigs show clinical symptoms. Depending on the presence and overlap between these different hosts, the virus can circulate within a domestic cycle, involving domestic pigs and, in some cases, soft ticks and/or within a sylvatic cycle, involving warthogs, soft ticks and potentially bushpigs. The transmission can occur through direct or indirect contact, via infected carcasses, swill or fomites or tick bites. It is acknowledged that direct contact between pigs and movement of infected pigs and pig products represents the main way of dissemination of the virus (12–14). Nevertheless, in presence of an interface where wild and domestic hosts may interact, the domestic and sylvatic cycles can be connected and wild pigs may be a source of infection for domestic pigs, although the route of transmission remains poorly understood (12, 15).

ASF is endemic in Uganda and is considered the most fatal disease in pigs. The surveillance process starts with the farmer, who upon suspecting ASF, reports to nearest animal health worker or local authority. This is followed by a reporting chain going from the district veterinary officer to the commissioner of animal health (CAH) who dispatches a team from National Animal Disease Diagnostic and Epidemiological Center to undertake disease investigation and confirm or infirm the outbreak. Upon confirmation of the disease, CAH then informs OIE (World Organization for Animal Health). Outbreaks occur regularly with a peak often described during the dry season (5, 11, 16, 17). For instance, using report-driven investigations in 43 villages located in Gulu district, 211 outbreaks (the unit being the household) were reported between 2011 and 2014 (18). The occurrence of the sylvatic cycle has also been confirmed in Uganda, although the current importance is unknown (13, 19). Furthermore, in some areas, free-ranging domestic pigs coexist with warthogs and bushpigs, giving opportunity for the virus to circulate among and between the three species (16). Previous studies carried out in Uganda found that ASF outbreaks were associated with free-ranging pigs, small-scale farms, presence of warthogs burrows in the vicinity and the dry season (5, 16, 20–22). Moreover, the estimation of the basic reproduction number (R_0) of ASF in small holder free-range pig production system in northern Uganda ranged between 1.58 and 3.24, depending on the method (23), indicating that free-ranging system prompt maintenance and between herd transmission of ASFV. These results suggest that, in Uganda, free-ranging pigs might be exposed to ASFV through contact with pigs from other herds and with infected material and potentially through interaction with wild hosts. Previous studies by our research in the same study area group suggest that indirect interactions between domestic pigs and wild pigs are frequent, and that they may pose an opportunity for disease transmission, particularly during the dry season and at water sources or crop fields (22, 24).

However, fine-scale studies describing how free-ranging pigs may interact with other free-ranging pigs and with wild pigs have been lacking. Improving the knowledge on the spatial behavior of the free-ranging pigs is thus needed to assess more precisely how this husbandry practice may contribute to the spread of ASF at a local scale in an area where ASFV is circulating. Moreover, such knowledge can help to better target preventive measures aimed at mitigating the spread of diseases such as ASF in traditional pig farming systems lacking basic biosecurity. In this paper, we describe the spatial and temporal pattern of the movements of free ranging domestic pigs and determine their use of habitat. Our results aimed to provide an idea of the average home range and activity covered by domestic pigs living in proximity of the boundaries of Murchison Falls National Park (MFNP). This information, combined with results from previous studies implemented in the area and documenting wild pigs incursion into farmland (22, 24), provide insight into the potential interactions occurring between domestic pigs and wild pigs at the interface of a large protected area in Northern Uganda.

MATERIALS AND METHODS

Study Site

The study area was located in North Western Uganda, in Nwoya district (total human population: 138,500; area: 4,736 km²),

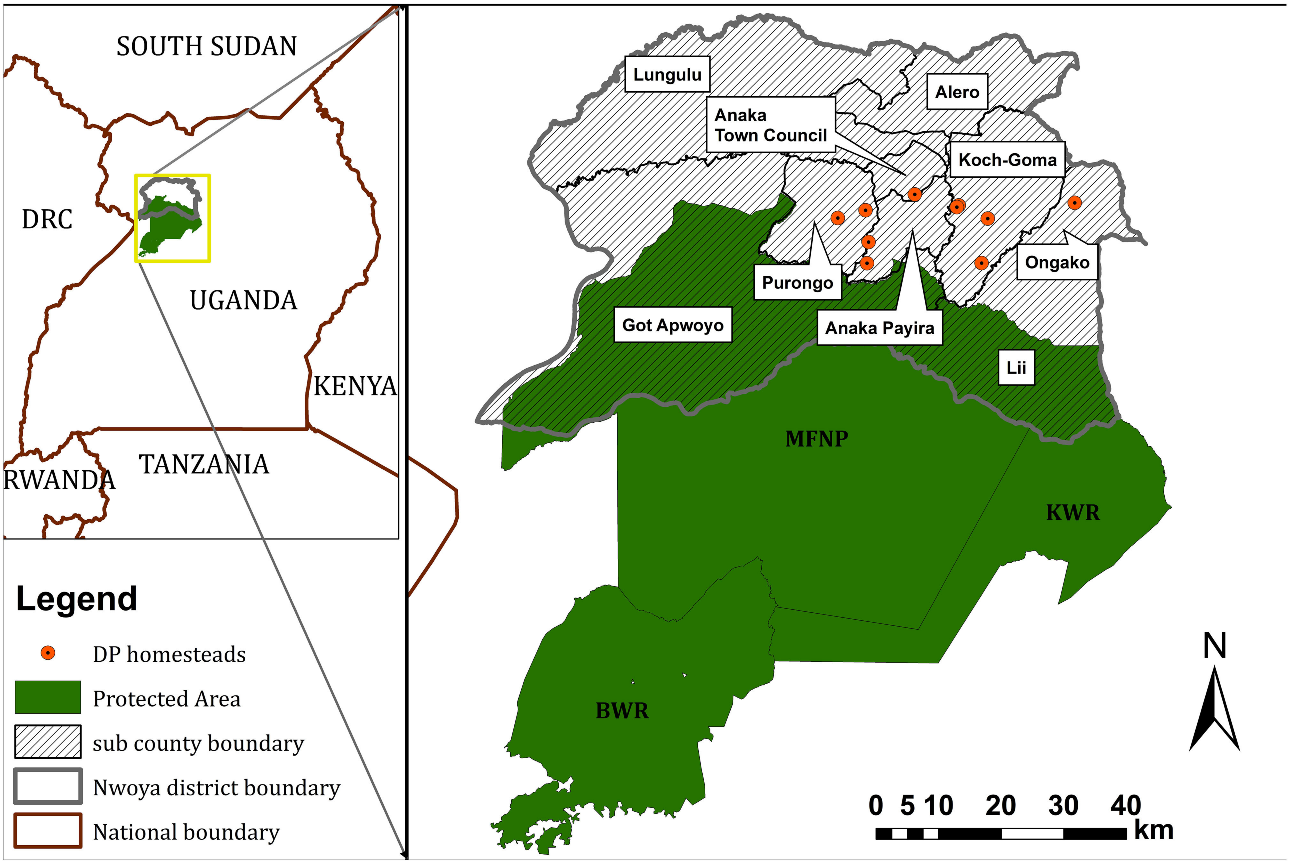


FIGURE 1 | Location of the study site showing the homesteads from which domestic pigs (DP) were collared within Nwoya district and the Murchison Falls Conservation area composed of Murchison Falls National Park (MFNP), Karuma Falls Wildlife Reserve (KFWR) and Bugungu Wildlife Reserve (BWR).

an administrative unit in the Acholi subregion (**Figure 1**). It comprised the northern boundary of MFNP and the adjacent rural communities at a maximum distance of 25 km from the park boundary. The vegetation consists of mostly savannah and the region is covered by a mixture of grassland and farmland interspersed by small woods. The major crops cultivated in Nwoya district are groundnuts, beans, maize, rice, cassava and sesame (24, 25). The major livestock species in Nwoya district are cattle, goats, sheep and pigs (22). The population of pigs in Nwoya stands at 12,800 as of 2019 according to the official figures of the Nwoya District Production office. Most farmers are smallholders, keeping between 1 and 4 pigs on free range during the dry season and most often tethering during the wet season with the local and cross breeds most preferred although few farmers also keep exotic breeds (especially Camborough and Large white). The climate is tropical with a rainy season from April through November and a dry season from December to March. Warthogs and bushpigs are widespread in the unfenced national park that borders the study area but they are also seen up to 25 km from such border into the farmland area. Based on farmers sightings reports in the same district, Kukielka et al. (22) assessed a density of individuals/km^2 ranging from 0 to 10 for warthogs and from 0 to 5 for bushpigs.

Selection of the Pigs, Collaring, and Data Collection

Within the study site (i.e., within farmland within a distance of 25 km from the MFNP boundary, see **Figure 1**), we selected 14 domestic pigs meeting the following criteria: they were kept free-range, their body size was large enough to fit with the harness adjustment (i.e., above 4 months) and they were owned by different families who agreed to the study. The number was also dictated by the number of GPS collars available. In addition, we planned to have a balanced sample between males and females, rainy and dry seasons and looked for a subsample of neighboring pigs (belonging to adjacent homesteads). We excluded sows being in the last trimester of pregnancy or those nursing piglets. Pigs that were due to be slaughtered in the next week were also excluded. Permission to carry out the study was granted by the Uganda National Council for Science and Technology under the reference number A497. A written consent from the District veterinary officer was obtained prior to the start of any activity in the area. At the time of the study, participants were informed

FIGURE 2 | Domestic pig fitted with a GPS-GSM harness (Savannah Tracking, Ltd., Nairobi, Kenya).

that the study was voluntary, confidential, and that they had the choice of ending their participation at any time. An informed consent was given by all participants prior to the implementation of the study.

The pigs were manually restrained and fitted with a GPS unit mounted on a harness (Savannah Tracking, Ltd., Nairobi, Kenya). The harnesses were made of straps which were not extensible (**Figure 2**). Elastic material could be more adapted to rapid growth of the body but it is also more fragile, that is why it was not used by the collar manufacturer. We used 7 GPS GSM and 7 GPS Iridium collars. Data were uploaded daily to a server through either GSM or iridium satellite transmission, depending on the type of collar used. Prior to deployment, the accuracy of the GPS was tested in a stationary position, under different vegetation covers with the program that was planned to be set when deployed on pigs. The maximum margin of error on the GPS locations provided by the collars was assessed to be 5 m and did not differ between the two transmission systems.

Collars were programmed to take one location every 30 min and were deployed for 2 weeks on each selected pig. We considered this schedule as the best compromise between precision, saving of battery power (some of the collars were to be deployed again or had already been deployed) and duration of the monitoring (i.e., we considered that 2 weeks of tracking were representative of the usual activity of the pig). To study the effect of the season, we monitored 6 pigs during the dry season and 4 pigs during the rainy season (**Table 1**).

Home Range, Daily Distance, and Activity Pattern

To maximize the precision of the estimate, each home range was generated from all the available locations for each animal (26, 27). We obtained the home range and the core area using the fixed kernel method (28) taking into account 90% and 50% of the locations respectively, as it is commonly used in ecological studies (27, 29, 30). The smoothing parameter value was estimated by using the reference bandwidth method since the least-squares cross-validation method did not converge for most of the pigs (31, 32). The home range was additionally estimated by using the minimum convex polygon, taking into account 100% of the locations (100% MCP) in order to determine the maximum area the pigs were able to cover. These treatments were performed

TABLE 1 | Characteristics of the collared pigs.

Pig ID	Sex	Tracking duration (days)	Number of days used in the analysis	Number of nights used in the analysis	Number of locations	Months of tracking	Season
1	M	13	12	13	306	March 2016	Dry
2	M	13	12	13	599	March-April 2016	Dry
3	F	17	13	11	544	April-May 2016	Rainy
4	M	7	6	5	226	June 2016	Rainy
5	F	5	4	5	207	October 2016	Rainy
6	F	9	9	9	416	October-November 2016	Rainy
7	F	14	12	13	578	January 2017	Dry
8	M	9	8	8	369	January 2017	Dry
9	M	11	10	11	504	March 2017	Dry
10	F	11	10	11	501	March-April 2017	Dry

using the adehabitat R package (33). The areas of the home ranges and core areas were then calculated by using QGis 2.18 (34).

The full day distance for each pig was calculated by connecting the consecutive locations belonging to the same day, from 1 am to midnight (i.e., during 24 h). The first and last days of monitoring as well as the days with more than 10% of missing data (i.e., at least 5 missed locations) were excluded from the analysis. This was followed by computing the minimum, maximum and mean distances for each animal.

To determine the activity pattern, we split each full monitoring day into daytime (i.e., from 7 a.m. to 7 p.m.) (daily distance) and night time (i.e., from 7 p.m. to 7 a.m.) (nightly distance) and computed the minimum, maximum and mean distances for these 2 periods for each pig.

The maximum and mean distance from the individual homestead were calculated. To do this, the perimeter of the homestead, being that area utilized by the house for domestic activity (therefore excluding crop fields), was tracked by walking along the boundary using a handheld GPS unit (Garmin GPS Map 60Cx). Then, a polygon layer based on this perimeter corresponding to the homestead was generated with a buffer of 5 m to take into account the accuracy of the GPS units used. The centroid of this polygon was then created. We calculated the maximum, mean and standard deviation of the distance between this centroid and all the recorded locations except the ones falling under the homestead layer. All these distance calculations were made using QGis 2.18 (29).

We checked whether the home ranges (yielded by the kernel 90% and the MCP 100%), the full day, daily and nightly distances had a normal distribution using the Shapiro-Wilks test of normality. We then performed univariate analysis to check if these variables differed between the sex of the pigs, the season (dry vs. rainy) and the size of the herd (less or equal to 4 pigs vs. more than 4 pigs) using a Student test when the variables had a normal distribution and a Wilcoxon rank test in the other cases. We also compared the daily and nightly distances made by the pigs. These statistical analyses were performed with R version 3.4.2 (35).

Use of Habitat

Once the pig tracking was completed and all the GPS locations retrieved, the GPS coordinates were plotted on a map and a landscape item was assigned to every location. This was done by going physically to the locations: for each location the GPS coordinates were entered in a handheld GPS unit (Garmin GPS Map 60Cx) enabling the operator to reach the locations uploaded from the pig's collar. The corresponding landscape was recorded according to one of these 5 categories: 1) homestead, 2) crop, 3) grassland (including also bush and forest), 4) waterpoint (river, borehole, pond, swamp or spring) and 5) road. When "homestead" was assigned, it was noted whether it was the one to which the pig belonged, or another one. The number of "other homesteads" was recorded.

For each pig, we used the same dataset as for the full day distances (see paragraph 2.3) i.e., where days with more than 10% of missing data were excluded. We calculated the use of each habitat item by the ratio: number of locations falling into the habitat item i to the total number of locations n.

As previous studies carried out in the same study sites pointed out that waterpoints and crops may be items at risk for interactions between domestic and wild pigs (22, 24), we focused on these two items by checking if their use was different between day and night and between the rainy and the dry seasons. We kept the definition of daytime and night time and used the same tests and software as for the activity pattern (see paragraph Home Range, Daily Distance, and Activity Pattern).

RESULTS

Data Collected

Fourteen pigs were collared between March 2016 and April 2017. Among these 14, two lost their collars 2 days after deployment and two reported for only 1 or 2 days. For these reasons, data from these 4 pigs were excluded from the analysis.

Out of the 10 remaining pigs, five were females and five were males. Six were tracked during the dry season and four during the rainy season (**Table 1** and **Supplementary Material**). Their age

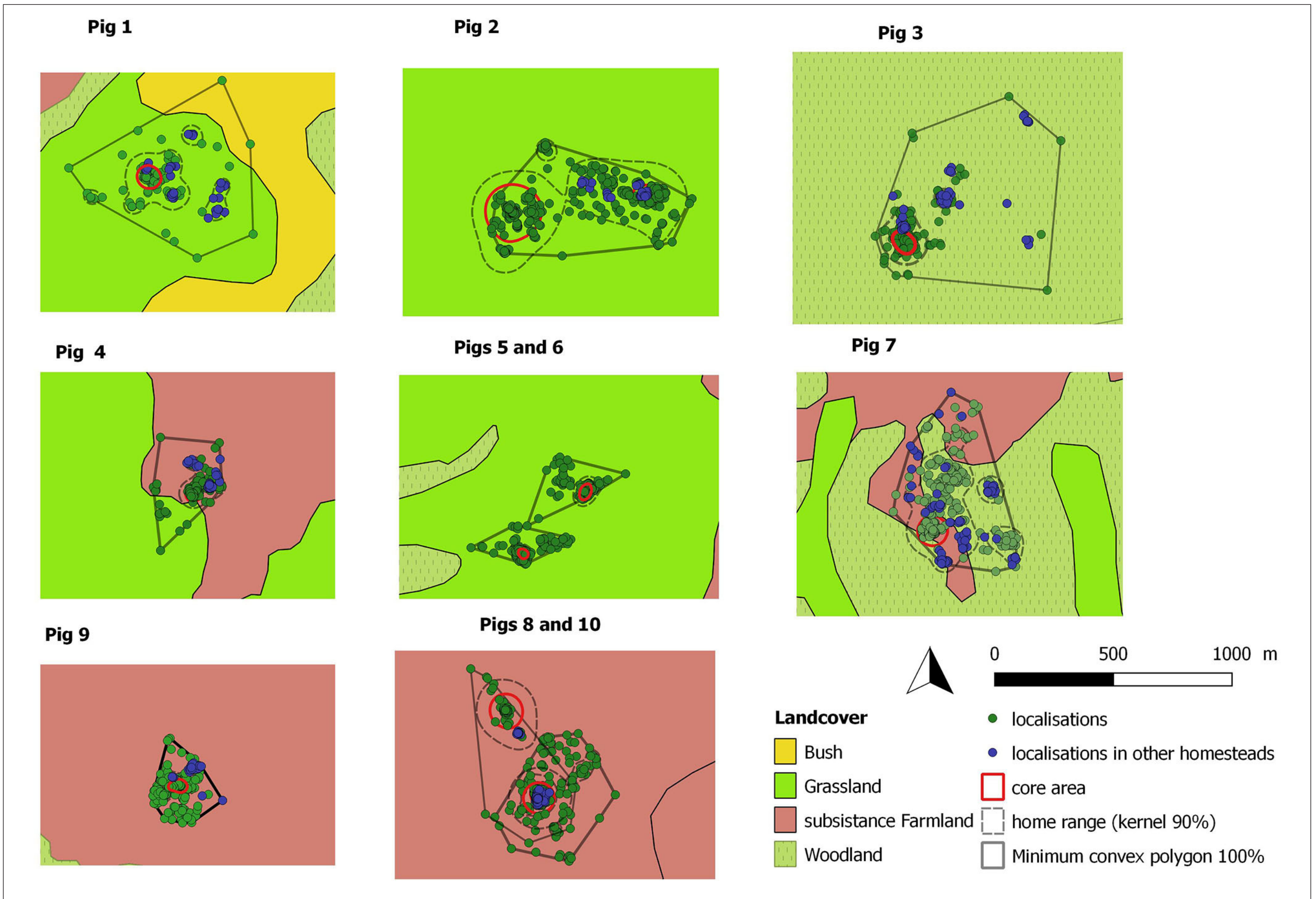


FIGURE 3 | Collected locations, home ranges and core areas used by the 10 monitored pigs plotted on the different landcover types. Pigs 1, 2, 7, 8, 9, 10 were monitored during the dry season and pigs 3, 4, 5, 6 during the rainy season. The use of habitat was not studied for pig 10. The blue dots localized in his home range corresponds to pig 8's locations.

ranged between 5 and 9 months. The data regarding the use of habitat could not be collected for one pig (ID 10) within the time frame of the study. As a consequence, all the analysis regarding the use of habitat was performed on nine pigs.

The mean duration of the tracking was 10.7 days (range: 5–17 days). The deployment had to be shortened for several pigs, due to either a fast growth of the body size, leading to remove the collar earlier than planned to prevent injury (4 pigs), or a stop in the reporting (2 pigs) or the tethering of the pig (1 pig; despite the fact that the pig's owner agreed to take part in the study and leave his pig roaming freely, he had to tether the pig because it damaged lots of crops).The number of days and nights as well as the number of locations used for the analysis are shown in **Table 1**.

Home Range, Daily Distance, and Activity Pattern

The pig home ranges varied between 8,078 and 253,327 m^2, with an average of 74,113 m^2. The maximum area covered by the monitored pigs, yielded by the MCP 100% varied between 35,965 and 475,077 m^2. The size of the core area varied from 1,317 to 50,769 m^2 (**Figure 3** and **Table 2**). For every pig, the core area included the homestead where the pig belonged to and for two pigs, it also included another homestead (**Figure 3**).

Home ranges were significantly bigger during the dry season than during the rainy season (Wilcoxon test, $W = 22$, $p = 0.04$; **Figure 4**). The mean full day distance ranged from 420 to 1,677 m and was statistically longer in the dry season than in the rainy season (Student test, $t = 2.7$, $p = 0.03$; **Figure 4**). Mean values between the distances traveled during daytime and night time by each pig were higher for diurnal (1,002 m) than for nocturnal measures (758 m) but these differences were not significant. The monitored pigs roamed away from their homestead at a mean distance ranging from 64 to 338 m (**Table 2**). No significant difference was found for any of the measured indicators, neither between males and females nor according to the size of the herd.

Use of Habitat

The monitored pigs used mainly their own homestead except the pigs 2 and 8, which used mostly grassland and other homesteads, respectively. The mean use of other homesteads was 13.3% and the number of other homesteads visited by the pigs varied from

TABLE 2 | Details of the movements of the ten collared pigs.

Pig ID	MCP 100% (m^2)	Home range (m^2)	Core area (m^2)	Full day distance (m) [min-max], mean	Daily distance (m) [min-max], mean	Nightly distance (m) [min-max], mean	Distance to homestead (m) max mean
1	342,703	76,570	7,647	[1,407–3,237], 2,168	[265–2,336], 1,198	[111–1,236], 553	512 94
2	280,395	253,327	50,769	[1,614–3,646] 2,574	[560–1,407], 872	[1,124–2,463], 1,570	760 300
3	475,077	38,014	6,669	[1,392–2,780], 1,899	[675–1,520], 1,089	[352–1,479], 726	787 131
4	93,771	28,644	4,935	[995–2,624], 1,843	[288–1,667], 932	[267–1,065], 563	311 87
5	50,884	15,452	2,540	[1,084–1,507], 1,339	[524–933], 816	[319–439], 396	297 71
6	35,965	8,078	1,317	[1,092–1,949], 1,461	[307–1,482], 975	[181–487],293	219 64
7	252,994	144,621	12,295	[2,106–3,246], 2,425	[207–603], 420	[1,520–26,83], 2,070	577 199
8	180,444	111,410	28,927	[272–3,153], 1,675	[130–2,453], 1,008	[142–791], 316	552 338
9	62,798	24,821	3,393	[1,839–2,937], 2,232	[1,312–1,949], 1,677	[171–653], 390	206 86
10	173,164	40,189	3,826	[1,353–2,647], 1,960	[692–1,350], 1,031	[432–1,107], 702	NA
Mean	194,820	74,113	12,232	1,958	1,002	758	152

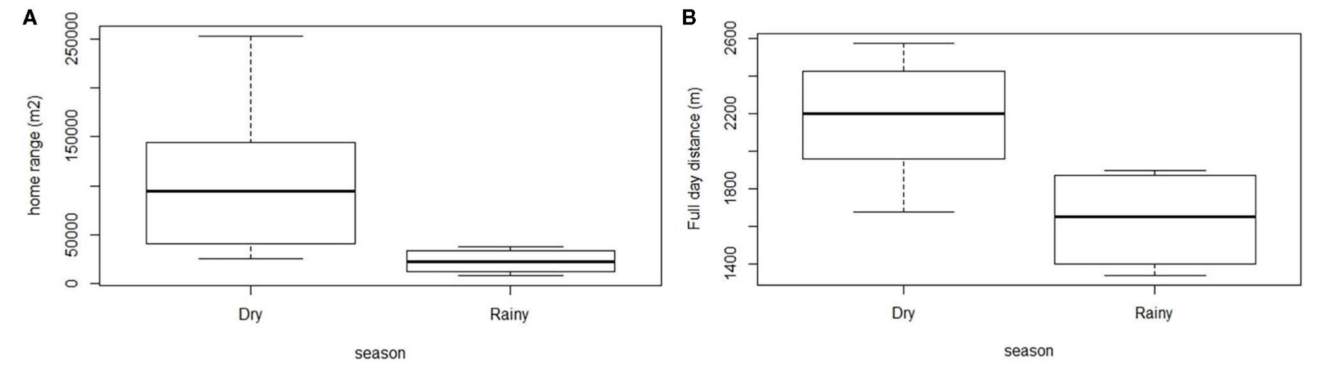


FIGURE 4 | Distribution of the home range **(A)** and the mean 24 h distance **(B)** of the 10 monitored pigs according to the season. Intervals defining boxes represent the interquartile range (IQR), while intervals out of the boxes (whiskers) show the highest and lowest values within 1.5 × IQR.

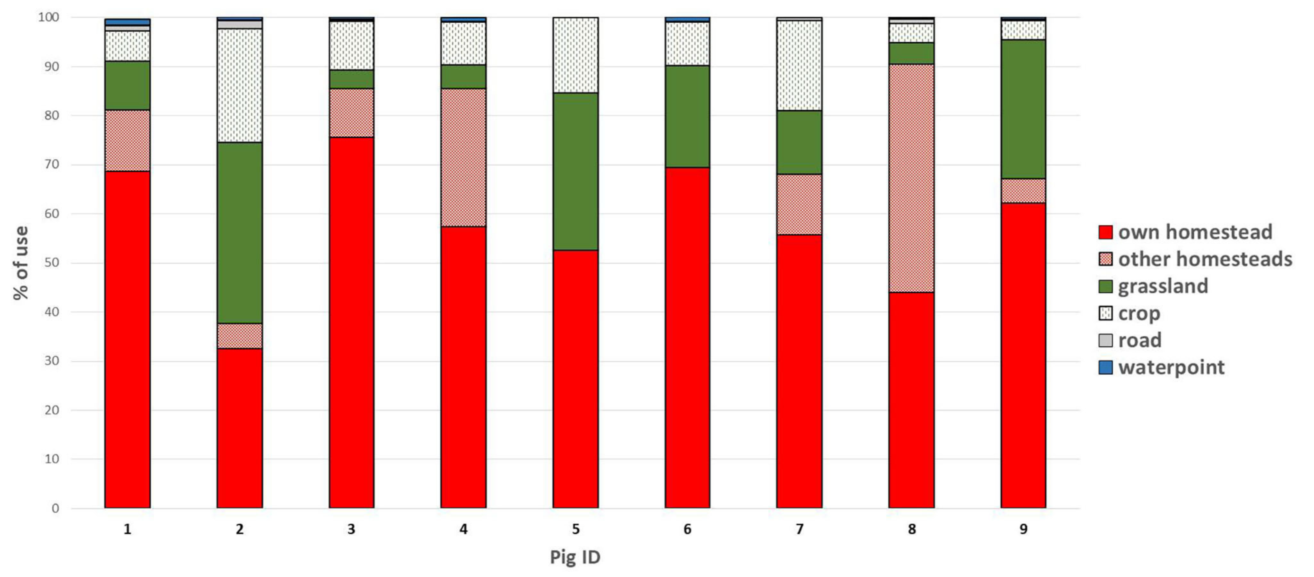


FIGURE 5 | Use of the 6 habitats of interest by the 9 monitored domestic pigs, expressed in proportion of the total recorded locations.

1 to 18 with an average of 6. The water points were the least used habitat accounting for a mean use of 0.5% and ranging between 0 and 1.3% (**Figure 5**). As the use of water points was very limited and equal to 0 for two pigs, we did not perform any test regarding this item. The use of crops ranged between 3.8 and 23.1% with an average of 10.9%. Cassava and maize fields were the most visited crops. No statistical difference was found between the two seasons and between day time and night time.

DISCUSSION

The use of spatial-temporal analysis in veterinary medicine has proven vital in understanding the epidemiology of animal and transboundary diseases across Africa, especially when dealing with free-ranging domestic and wild animals (36–38). In the context of Uganda where ASF is highly prevalent and the free-ranging pig farming system is highly widespread in rural areas, analyzing the spatiotemporal patterns of such pig systems is important to better understand the potential risks of disease exposure, transmission and possible consequences such as pig losses and reduced productivity.

Although ecological studies documenting the spatial dimension of domestic pig movements are scarce in the African context, one study addressed this topic in Kenya (29). However, this is the first time that this approach is implemented in the context of an ASFV infected area at the interface of a wildlife national park where the presence of a warthog—tick sylvatic cycle and the sympatric presence of warthogs and bushpigs with domestic pigs is well described (22, 24). The small number of pigs we had in our study limits the robustness of our results. Increasing the sample size would have enabled to gain power in the analysis and would have smoothed the possible individual variability that might have interfered with the effect of the variables tested at a population level. In the study carried out in Kenya, Thomas et al. (38) also monitored 10 free-ranging pigs, five being tracked during the dry season and five others during the rainy seasons and they did not find any significant effect of the season on the pigs' movements. In this case, pigs seemed to move larger average daily distances than in our study site (for instance around 4,000 vs. 1,000 m in our study). This emphasizes that movement of free-ranging pigs can differ from one rural settings to another, depending on the specificity of husbandry practices and the availability of food and water resources. Consequently, the results obtained in the context of such small-scale studies should not be extrapolated to other areas.

Our study reveals that the free ranging domestic pig home ranges were significantly larger during the dry season than during the rainy season, with mean full day distances statistically longer in the dry season than in the rainy season. Coincidentally, this is also the season where the number of reported ASF cases is higher in the study area and considered as a risk factor for ASF outbreaks (11, 16, 22). The large home ranges used by pigs in the dry season, combined with higher number of pigs kept free-range rather than tethered or confined may increase contacts between infected domestic pigs, fomites or carcasses from different infected farms.

Incursions into other homesteads were quite frequent in our study (representing 13% of the habitat use), though variable among pigs (seven pigs were frequenting an average of six other homesteads). Considering that the infectious period can last between 5 and 14 days (39) and even beyond in the case of pigs which have survived the acute phase of the disease [25 days, (40)], the probability of excreting ASF virus and thus representing a source of infection for other domestic and wild pigs is non-negligible.

As a result, these movements could potentially contribute to ASF transmission between households in case of an outbreak. In addition, the dry season is the most productive season in terms of wild pig hunting (22), which makes potential exposure to wild pig hunting leftovers more likely than during the rainy season. Finally, yet importantly, the dry season is likely to attract wild and domestic pigs around water points, as suggested by interviews with farmers in a previous study (22). However, surprisingly, our results showed a very limited dependence of domestic pig movements on water points. A possible explanation could be that water is found within the homesteads or in puddles which we did not assign as water point. We did not record wether pigs were provided with water or/and with feed, which could also have influenced the dependence of the pigs on water points and possibly to crops. Crops represented more than 10% of the habitat used by the domestic pigs, most of them being cassava and maize. This result is not surprising given that these cereals are very palatable for pigs, which are free to feed in cultivated land and are often underfed by their owners. Payne et al. (24) reported that cassava is particularly sought after during the night by the bushpigs in this area. In our study, we found that domestic pigs moved also during the night making this type of habitat a potential hotspot for interactions between this two sympatric species and therefore, for ASF transmission.

Regardless of the season, an additional permanent source of virus in the context of the study area is the probability for a free roaming domestic pig to become exposed to an ASF infected soft tick (*Ornithodoros moubata* complex) bite. Despite the fact that there are no data on the rate of infestation of warthog burrows with ASF-infected *O.moubata* in the study area, soft ticks infected with ASFV have been found and the occurrence of a sylvatic cycle in MFNP has been confirmed (unpublished results). Therefore, the likelihood of exposure to this permanent source of virus in this environment cannot be ignored. At the interface of MFNP, sightings of warthogs have been reported up to 25 km from the park boundary (22) into the domestic homesteads. The same study reports that almost ¼ of the farmers interviewed in our study area had observed active warthog burrows in proximity and in 60% of cases at <3 km from their homesteads. This confirms that domestic pigs kept in this area, like the ones we selected in our study, are sharing the space and resources with warthogs and their ticks. Coincidentally, a recent study assessing potential wild-domestic pig interactions at the interface of wildlife game reserve in South Africa, also reported that local pig farmers reported wild pig sightings up to 25 km from the boundary of the reserve (41). This measure of the potential home range of wild pigs outside of natural reserves is only based on interviews and should be confirmed by more precise ecological study methods. Nevertheless, it provides a similar indication of the spatial overlap between wild and domestic pigs at the wildlife-livestock interface of two different protected areas in East and Southern Africa.

Seven out of nine pigs makes 78% of pigs visiting other homesteads in our sample. Assuming this percentage is right, and considering there are a total of 12,800 pigs estimated in the area, there would be nearly 10,000 pigs visiting other homesteads per year. In case of an outbreak of ASF, the impact of these movements in disease dissemination is far from being negligible. Similarly, wild and domestic pigs in tropical areas can carry several infectious and parasitic diseases such as cysticercosis, trichinellosis, toxoplasmosis, porcine circovirus or *Actinobacillus pleuropneumoniae* (2, 3, 9, 29, 42). In this context, the potential high contact rate between pigs from different herds, exposes them to higher probabilities of disease exposure and transmission to other susceptible individuals.

This study provides additional evidence of the high risk faced by pig farming lacking basic biosecurity measures at the interface of a protected area in East Africa. Further studies should target at quantifying that risk by assessing wild and domestic pig densities and identifying potential contacts in hotspot interaction locations. Contact networks could be drawn from our data, enabling to better assess the connectivity between domestic pigs from different homesteads and map the risk of transmission of diseases such as ASF at fine-scale (43). Our findings could further be used to target effective preventive measures aiming to mitigate disease transmission risks in low biosecurity farming systems. As an alternative, pig farming with simple and affordable but efficient measures of higher biosecurity should be promoted in the area with the goal to inform on the advantages that could be found in terms of higher productivity and profit. For example, community-based animal health workers could be involved in designing local scale homestead disease prevention strategies. However, awareness on the availability of biosecurity and control measures does not guarantee their implementation (11). Indeed, the adoption of disease prevention and biosecurity measures among small scale farmers in poor resource settings such as the interface of MFNP, is far from complete, mainly due to financial constraints, despite acknowledging the capacity of biosecurity to protect pigs from ASF (44) and other diseases. While the vaccine is still awaited, another interesting alternative unexplored to date, could be exploitation of innate resistance to the virus, which is fully effective in wild African suids and has been observed in some domestic pig populations in areas of prolonged endemicity (14).

DATA AVAILABILITY STATEMENT

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

ETHICS STATEMENT

The animal study was reviewed and approved by Uganda National Council for Science and Technology under the reference number A497. A written consent from the District veterinary officer was obtained prior to the start of any activity in the area. Written informed consent was obtained from the owners for the participation of their animals in this study.

AUTHOR CONTRIBUTIONS

AP and PO collected the data. AP performed the analysis. AP, KS, CM, and FJ conceptualized the thrust and focus of the manuscript. All authors participated in drafting the manuscript or revising it critically for content. All authors were involved in the study design.

FUNDING

This study was financed by APHIS (US Department of Agriculture, Animal and Plant Health Inspection Service, APHIS Agreement No. 13-7440-0989-GR) Wellcome trust (Grant 105684/Z/14/Z) and French Embassy in Uganda (Convention de subvention 10/10/2016. Appui CIRAD 185UGA0079).

ACKNOWLEDGMENTS

We are grateful to Alfred Ojok who was the local facilitator and made that work possible. We acknowledge all the pig owners who allowed us to fit their pigs with GPS equipment. We thank Henrik Rasmussen, for assisting us with the GPS equipment functioning and for having designed the harnesses. We warmly thank Raymond Ssekadde who drove us and took part into the field work, and the team in Lutuk who help with the logistics. Finally, we thank Gordon Yofesi Mwesigwa and Edward Rubongoya for helping us with the mapping of the study site.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fvets.2021.689377/full#supplementary-material

Supplementary Table 1 | GPS data file.

REFERENCES

1. FAOSTAT. (2018). Available online at: http://faostat3.fao.org/faostat-gateway/go/to/home/E (accessed March 25, 2021).
2. Lekule FP, Kyvsgaard NC. Improving pig husbandry in tropical resource-poor communities and its potential to reduce risk of porcine cysticercosis. *Acta Trop*. (2003) 87:111–7. doi: 10.1016/S0001-706X(03)00026-3
3. Phiri IK, Ngowi H, Afonso S, Matenga E, Boa M, Mukaratirwa S, et al. The emergence of Taenia solium cysticercosis in Eastern and Southern Africa as a serious agricultural problem and public health risk. *Acta Trop*. (2003) 87:13–23. doi: 10.1016/S0001-706X(03)00051-2
4. Kagira JM, Kanyari PWN, Maingi N, Githigia SM, Ng'ang'a JC, Karuga JW. Characteristics of the smallholder free-range pig production

system in western Kenya. *Trop Anim Health Prod.* (2010) 42:865–73. doi: 10.1007/s11250-009-9500-y

5. Dione MM, Ouma EA, Roesel K, Kungu J, Lule P, Pezo D. Participatory assessment of animal health and husbandry practices in smallholder pig production systems in three high poverty districts in Uganda. *Prev Vet Med.* (2014) 117:565–76. doi: 10.1016/j.prevetmed.2014.10.012
6. Ouma E, Dione M, Lule P, Rosel K, Pezo D. Characterization of smallholder pig production systems in Uganda: constraints and opportunities for engaging with market systems. *Livest Res Rural Dev*. (2014) 26. doi: 10.22004/ag.econ.160677
7. FAO. *FAO.* (2019). Available online at: http://www.fao.org/faostat/en/#data (accessed March 22, 2021).
8. Uganda Bureau of Statistics. *The National Population and Housing Census 2014-Main Report*. Ministry of Agriculture, Animal Industry & Fisheries, Entebbe, Uganda and Uganda Bureau of Statistics, Kampala, Uganda (2016).
9. Dione M, Masembe C, Akol J, Amia W, Kungu J, Lee HS, et al. The importance of on-farm biosecurity: sero-prevalence and risk factors of bacterial and viral pathogens in smallholder pig systems in Uganda. *Acta Trop.* (2018) 187:214–21. doi: 10.1016/j.actatropica.2018.06.025
10. Atherstone C, Smith E, Ochungo P, Roesel K, Grace D. Assessing the potential role of pigs in the epidemiology of ebola virus in Uganda. *Transbound Emerg Dis.* (2017) 64:333–43. doi: 10.1111/tbed.12394
11. Chenais E, Boqvist S, Sternberg-Lewerin S, Emanuelson U, Ouma E, Dione M, et al. Knowledge, attitudes and practices related to african swine fever within smallholder pig production in Northern Uganda. *Transbound Emerg Dis.* (2015) 64:101–15. doi: 10.1111/tbed.12347
12. Costard S, Mur L, Lubroth J, Sanchez-Vizcaino JM, Pfeiffer DU. Epidemiology of African swine fever virus. *Virus Res.* (2013) 173:191–19. doi: 10.1016/j.virusres.2012.10.030
13. Penrith ML, Vosloo W, Jori F, Bastos ADS. African swine fever virus eradication in Africa. *Virus Res.* (2013) 173:228–46. doi: 10.1016/j.virusres.2012.10.011
14. Penrith M-L, Bastos A, Chenais E. With or without a vaccine—a review of complementary and alternative approaches to managing african swine fever in resource-constrained smallholder settings. *Vaccines.* (2021) 9:116. doi: 10.3390/vaccines9020116
15. Jori F, Bastos ADS. Role of wild suids in the epidemiology of african swine fever. *Ecohealth.* (2009) 6:296–310. doi: 10.1007/s10393-009-0248-7
16. Atuhaire D, Ochwo S, Afayoa M, Mwiine FN, Kokas I, Arinaitwe E, et al. Epidemiological overview of african swine fever in Uganda (2001–2012). *J Vet Med.* (2013) 2013:1–9. doi: 10.1155/2013/949638
17. Nantima N, Ocaido M, Davies J, Dione M, Okoth E, Mugisha A, et al. Characterization of smallholder pig production systems in four districts along the Uganda-Kenya border. *Livest Res Rural Dev.* (2015) 27.
18. Chenais E, Sternberg-Lewerin S, Boqvist S, Emanuelson U, Aliro T, Tejler E, et al. African swine fever in uganda: qualitative evaluation of three surveillance methods with implications for other resource-poor settings. *Front Vet Sci.* (2015) 2:2–11. doi: 10.3389/fvets.2015.00051
19. Jori F, Vial L, Penrith ML, Pérez-Sánchez R, Etter E, Albina E, et al. Review of the sylvatic cycle of African swine fever in sub-Saharan Africa and the Indian ocean. *Virus Res.* (2013) 173:212–27. doi: 10.1016/j.virusres.2012.10.005
20. Muhanguzi D, Lutwama V, Mwiine FN. Factors that influence pig production in central Uganda - case study of Nangabo sub-county, wakiso district. *Vet World.* (2012) 5:346–51. doi: 10.5455/vetworld.2012.346-351
21. Muhangi D, Masembe C, Emanuelson U, Boqvist S, Mayega L, Ademun RO, et al. A longitudinal survey of African swine fever in Uganda reveals high apparent disease incidence rates in domestic pigs, but absence of detectable persistent virus infections in blood and serum. *BMC Vet Res.* (2015) 11:1–106. doi: 10.1186/s12917-015-0426-5
22. Kukielka EA, Jori F, Martínez-López B, Chenais E, Masembe C, Chavernac D, et al. Wild and domestic pig interactions at the wildlife–livestock interface of murchison falls national park, Uganda, and the potential association with African swine fever outbreaks. *Front Vet Sci.* (2016) 3:31. doi: 10.3389/fvets.2016.00031
23. Barongo MB, Ståhl K, Bett B, Bishop RP, Fèvre EM, Aliro T, et al. Estimating the basic reproductive number (R0) for African Swine Fever Virus (ASFV) transmission between pig herds in Uganda. *PLoS ONE.* (2015) 10:e0125842. doi: 10.1371/journal.pone.0125842
24. Payne A, Ogweng P, Ojok A, Etter E, Gilot-Fromont E, Masembe C, et al. Comparison of three methods to assess the potential for bushpig-domestic pig interactions at the wildlife-livestock interface in Uganda. *Front Vet Sci.* (2018) 5:295. doi: 10.3389/fvets.2018.00295
25. Mwongera C, Shikuku K, Twyman J, Winowiecki L. *Rapid rural appraisal report of Northern Uganda*. (2014). Available online at: https://cgspace.cgiar.org/handle/10568/35639
26. De solla S, Bonduriansky R, Brooks R. Eliminating autocorrelation reduces biological relevance of home range estimates. *J Anim Ecol.* (1999) 68:221–34. doi: 10.1046/j.1365-2656.1999.00279.x
27. Pellerin M, Saïd S, Gaillard J. Roe deer Capreolus capreolus home-range sizes estimated from VHF and GPS data. *Wildlife Biol.* (2008) 14:101–10. doi: 10.2981/0909-6396 (2008) 14[101:RDCCHS]2.0.CO;2
28. Worton BJ. Using Monte Carlo simulation to evaluate Kernel-based home range estimators. *J Wildl Dis.* (1995) 59:1995. doi: 10.2307/3801959
29. Thomas LF, De Glanville WA, Cook EA, Fèvre EM. The spatial ecology of free-ranging domestic pigs (Sus scrofa) in western Kenya. *BMC Vet Res.* (2013) 9:46. doi: 10.1186/1746-6148-9-46
30. Börger L, Franconi N, De Michele G, Gantz A, Meschi F, Manica A, et al. Effects of sampling regime on the mean and variance of home range size estimates. *J Anim Ecol.* (2006) 75:1393–405. doi: 10.1111/j.1365-2656.2006.01164.x
31. Seaman DE, Millspaugh JJ, Kernohan BJ, Brundige GC, Raedeke KJ, Gitzen RA. Effects of sample size on kernel home range estimates. *J Wildl Manage.* (1999) 63:1999. doi: 10.2307/3802664
32. Hemson G, Johnson P, South A, Kenward R, Ripley R, Mcdonald D. Are kernels the mustard? Data from global positioning system (GPS) collars suggests problems for kernel home-range analyses with least-squares cross-validation. *J Anim Ecol.* (2005) 74:455–463. doi: 10.1111/j.1365-2656.2005.00944.x
33. Calenge C. The package "adehabitat" for the R software: a tool for the analysis of space and habitat use by animals." *Ecol Modell.* (2006) 197:516–9. doi: 10.1016/j.ecolmodel.2006.03.017
34. QGIS Development Team. *QGIS Geographic Information System. Open Source Geospatial Foundation.* (2018). Available online at: http://qgis.org
35. R Development Core Team. R 3.4.2. *A Language and Environment for Statistical Computing*. Vienna: R Development Core Team (2017).
36. Miguel E, Grosbois V, Caron A, Boulinier T, Fritz H, Cornelis D, et al., Tshabalala PT, De Garine-Wichatitsky M. Contacts and foot and mouth disease transmission from wild to domestic bovines in Africa. *Ecosphere.* (2013) 4:1–32. doi: 10.1890/ES12-00239.1
37. de Glanville WA, Vial L, Costard S, Wieland B, Pfeiffer DU. Spatial multi-criteria decision analysis to predict suitability for African swine fever endemicity in Africa. *BMC Vet Res.* (2014) 10:9. doi: 10.1186/1746-6148-10-9
38. Fasina FO, Mokoele JM, Spencer BT, Van Leengoed LAML, Bevis Y, Booysen I. Spatio-temporal patterns and movement analysis of pigs from smallholder farms and implications for African swine fever spread, Limpopo province, South Africa. *Onderstepoort J Vet Res.* (2015) 82:795. doi: 10.4102/ojvr.v82i1.795
39. Guinat C, Gubbins S, Vergne T, Gonzales JL, Dixon L, Pfeiffer DU. Experimental pig-to-pig transmission dynamics for African swine fever virus, Georgia 2007/1 strain. *Epidemiol Infect.* (2016) 144:25–34. doi: 10.1017/S0950268815000862
40. Eblé PL, Hagenaars TJ, Weesendorp E, Quak S, Moonen-Leusen HW, Loeffen WLA. Transmission of African swine fever virus via carrier (survivor) pigs does occur. *Vet Microbiol.* (2019) 237:108345. doi: 10.1016/j.vetmic.2019.06.018
41. Mapendere C, Jori F, Etter E, Ferguson JH. Do wild suids from Ndumo Game Reserve, South Africa, play a role in the maintenance and transmission of African Swine Fever to domestic pigs? *Transbound Emerg Dis.* doi: 10.1111/tbed.14090
42. Jori F, Payne A, Ståhl K, Nava A, Rossi S. Wild feral pigs: disease transmission at the interface between wild domestic pig species in the Old the New World. In: Melletti M, Meijaard E, editors. *Ecology*, *Evolution Management of Wild Pigs Peccaries*. *Implications for Conservation* Cambridge: Cambridge University Press. p. 388–403.

43. Miguel E, Grosbois V, Fritz H, Caron A, de Garine-Wichatitsky M, Nicod F, et al. Drivers of foot-and-mouth disease in cattle at wild/domestic interface: Insights from farmers, buffalo and lions. *Divers Distrib.* (2017) 23:1018–30. doi: 10.1111/ddi.12585
44. Chenais E, Lewerin SS, Boqvist S, Ståhl K, Alike S, Nokorach B, et al. Smallholders' perceptions on biosecurity and disease control in relation to African swine fever in an endemically infected area in Northern Uganda. *BMC Vet Res.* (2019) 15:279. doi: 10.1186/s12917-019-2005-7

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

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

Copyright © 2021 Payne, Ogweng, Ståhl, Masembe and Jori. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.

frontiers in Veterinary Science

ORIGINAL RESEARCH
published: 25 October 2021
doi: 10.3389/fvets.2021.686038

An Assessment of the Economic Impacts of the 2019 African Swine Fever Outbreaks in Vietnam

Thinh Nguyen-Thi[1], Linh Pham-Thi-Ngoc[2], Que Nguyen-Ngoc[2], Sinh Dang-Xuan[1], Hu Suk Lee[1], Hung Nguyen-Viet[3], Pawin Padungtod[4], Thuy Nguyen-Thu[5], Thuy Nguyen-Thi[2], Thang Tran-Cong[2] and Karl M. Rich[6]*

[1] International Livestock Research Institute, Regional Office for East and Southeast Asia, Hanoi, Vietnam, [2] Institute of Policy and Strategy for Agriculture and Rural Development, Hanoi, Vietnam, [3] International Livestock Research Institute, Nairobi, Kenya, [4] Food and Agriculture Organization of the United Nations, Hanoi, Vietnam, [5] Department of Animal Health, Ministry of Agriculture and Rural Development, Hanoi, Vietnam, [6] International Livestock Research Institute, Dakar, Senegal

OPEN ACCESS

Edited by:
Erika Chenais,
National Veterinary Institute, Sweden

Reviewed by:
Georgina Limon,
Pirbright Institute, United Kingdom
Karl Ståhl,
National Veterinary Institute, Sweden
Folorunso Oludayo Fasina,
University of Pretoria, South Africa

****Correspondence:***
Thinh Nguyen-Thi
t.t.nguyen@cgiar.org

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

Received: *26 March 2021*
Accepted: *23 September 2021*
Published: *25 October 2021*

Citation:
Nguyen-Thi T, Pham-Thi-Ngoc L, Nguyen-Ngoc Q, Dang-Xuan S, Lee HS, Nguyen-Viet H, Padungtod P, Nguyen-Thu T, Nguyen-Thi T, Tran-Cong T and Rich KM (2021) An Assessment of the Economic Impacts of the 2019 African Swine Fever Outbreaks in Vietnam. Front. Vet. Sci. 8:686038. doi: 10.3389/fvets.2021.686038

The 2019 African swine fever (ASF) outbreaks in Vietnam imposed considerable impacts on the pig sector in Vietnam, resulting in the death or culling of nearly six million pigs, or more than 20% of the country's pig population. In order to assess the magnitude of the outbreak at sector level (both on farm and at value chain level), on livelihoods, and on the broader national economy, a comprehensive impact assessment was conducted using a mixed methods approach that integrated a value chain assessment with the use of quantitative modeling tools at sector and national levels. The results showed that the outbreak caused severe direct and indirect economic losses among farmers, particularly medium- and large-farmers whose livelihoods are largely derived from pig production. The outbreaks also affected other value chain actors due to a halving in the volume of pigs traded. At sector level, the outbreaks posed adverse impacts on the domestic supply and demand for pork, especially in the traditional sector. Meanwhile, the modern sector with higher levels of biosecurity and high technology growth was less likely to be affected and even benefited from the outbreak, which was evidenced by increased supply and income throughout the simulation period in this sector. At national level, different model simulation scenarios showed a sharp reduction in total gross domestic product (GDP) and a substantial loss of jobs. Improvements in the system of ASF compensation scheme are needed, both in terms of its administration, but also in its targeting, with greater emphasis needed on developing improved risk-sharing and funding mechanisms across national and local levels.

Keywords: African swine fever, economic impact, multi-market model, social accounting matrix, value chain, Vietnam

INTRODUCTION

Incursions of African swine fever (ASF) can generate substantial economic losses on affected pig sectors, given its high mortality in pig populations and dislocations in pig markets (1). In East and Southeast Asia, the first ASF outbreak started in 2018 in China, home to half of the world's pig population, leading to the death and culling of 40% of its pig population (2). It has since swept across the whole region. ASF can cause up to 100% mortality in pigs and is difficult to control in the absence of an effective vaccine. As of August 2019, farmers in 51 countries have shouldered the burden of ASF, with approximately one fourth of the world's pigs killed or culled due to ASF (3).

Sharing a porous border with China, Vietnam was put on red alert as ASF had severely impacted pig farmers in China. ASF finally made its way into Vietnam with the first case reported in early February 2019. Necessary actions were implemented to prevent and control the spread of ASF in Vietnam, including a ban on the import of pigs and pork products from ASF affected countries and strict movement controls of pigs and pig products from infected provinces to the south of Vietnam. The government and relevant authorities also supported (i) early detection, culling, disinfection, and compensation, (ii) movement control, (iii) biosecurity application, (iv) risk communication and public awareness, (v) information sharing and updating, and (vi) international collaboration with donors and technical experts. Despite these strong efforts, the number of reported outbreaks and affected provinces increased rapidly. After only 5 months from the first case, ASF was found in all 62 provinces of the country, resulting in the death or culling of nearly six million pigs, or well over 20% of the country's pig population (4). More than 90% of outbreaks occurred in small- and medium-sized farms with poor biosecurity practices, which posed challenges for the prevention and control of ASF (5).

Pig production is a strategic sector of Vietnam's economy given its contribution to 60% of total livestock output (6). It is a source for the livelihoods of approximately three million households, of which 77% were smallholders (7, 8). Also, pork is the most important type of meat produced and consumed in Vietnam, representing 70% of total meat output. Therefore, the 2019 ASF outbreaks had considerable effects on the pig sector in Vietnam.

In order to assess the magnitude of economic impacts associated with the ASF outbreak at sector level (both on farm and in value chains), on livelihoods and the broader national economy, a comprehensive impact assessment was conducted. Findings from the study would allow the government and other actors to understand the scale of possible impacts and the types of investments needed to offset these negative effects. This would provide a basis for the design of necessary actions to make the response to disease and control efforts more efficient.

MATERIALS AND METHODS

A combination of qualitative and quantitative methods was used to address the multifaceted impacts of ASF in Vietnam. Details of these different methodologies are provided below.

Assessment of ASF Impacts Along the Pig Value Chain – A Case Study

First, a case study was conducted in Duc Thang commune, Tien Lu district, Hung Yen province—the first province confirming an outbreak of ASF. Between February and June 2019, Hung Yen registered 154 outbreaks in all 10 districts and the main city, with ∼135,000 pigs culled during the study period. The first ASF outbreak was detected in Tien Lu district on 12 March 2019 in one commune and then swiftly spread to all 15 communes leading to the culling of 13,920 pigs (or 24% of the district's pig population). Among the 15 communes of Tien Lu district, Duc Thang—the commune having the largest pig population—was considered to control the disease well with only 11% of its pig population being culled due to ASF.

TABLE 1 | List of participants of focus group discussion and key informant interviews.

Respondents	Number of respondents	Note
1. Focus group discussion (FGD)	6	
Farmers	4	Members of a cooperative (2) Independent farmers (2)
Animal feed supplier	1	
Slaughterhouse (also functioning as processor and retailer)	1	
2. Key informant interviews (KIIs)	19	
District staff	3	
Commune staff	2	
Farmers	4	Small scale (1) Medium scale (2) Large scale (1)
Broker	1	
Trader	1	
Slaughterhouse (also functioning as retailer)	2	
Slaughterhouse (also functioning as processor and retailer)	2	
Animal feed supplier	1	
Retailer	1	
Consumers	2	

The case study was conducted in June 2019 to assess the contextual drivers of ASF spread and control, and to determine proximate impacts among different types of value chain actors. In the case study, one focus group discussion (FGD) was organized and administered by a team of three enumerators (one facilitator, one note taker, and one board writer) to outline the pig value chain and identify potential impacts of ASF in the local context. The FGD consisted of six participants including two members of a cooperative, two independent farmers, one feed supplier, and one slaughterhouse owner who also acted as processor and retailer in the value chain. The FGD lasted 3 h. To deepen knowledge of ASF impacts on pig production and livelihoods of actors, we then carried out 19 key informant interviews (KIIs) with representatives of local authorities and the different value chain nodes. KIIs were carried out in 1 day by the same team of three members who facilitated the above FGD and each KII lasted for 30–45 min. Participants of FGD and KIIs were selected in close collaboration with the local authority and primarily based on their availability (**Table 1**). All participants belonged to the majority ethnic group in Vietnam (Kinh group), so the language used in FGD and KIIs was Vietnamese. Detailed interview guidelines for FGDs and KIIs were developed by staff of the International Livestock Research Institute (ILRI) and were conducted in collaboration with a team of the Vietnam National University of Agriculture (VNUA) (see **Supplementary Files 1, 2**). The guidelines captured information on characteristics of the actors, ways in which the ASF outbreaks affected their pig business and other farm/non-farm activities, and their reactions toward government's actions on ASF.

Data collected from FGDs and KIIs was employed to map the value chain, identify product flows, understand the linkages among actors, and measure the impacts of ASF on the chain. Due to the small sample size, care in interpretation of the results was noted. In particular, we highlighted in section Results specific data reported by individual respondents or, where there was consensus, an aggregate value or percentage change. These data should be considered as suggestive and perceptual to contextualize the more rigorous impact assessment at sector and national levels detailed in the following two subsections. The use of small size inference to guide hypothesize building and testing on impacts was employed in the value chain space (9) and in participatory research (10).

We reported specific details of the case study in **Supplementary File 3**. A summary of the case study findings can be found in section Assessment of ASF Impacts Along the Pig Value Chain—key case study findings.

Assessment of ASF Impacts at Sector Level

A variety of tools are available for measuring the impacts of animal disease at sector level (11). Multi-market partial equilibrium models, which capture the interactions of the livestock sector with related sectors (such as animal feed) are particularly useful, as they can distinguish between different production systems, while providing detailed, dynamic information on market and trade impacts of animal disease (12–14). For instance, Rich and Winter-Nelson (13) employed a multi-region, multi-species model of the livestock sector in the Southern Cone of South America to look at the impacts of different disease shocks and mitigation strategies associated with foot-and-mouth disease control.

In this part of the analysis, we deployed the Vietnam pig sector model (VPM[1]) to look at the regional and dynamic impacts of ASF at sector level and the returns to prospective intervention options based on secondary data collected from various sources (15, 16). VPM was developed in the tradition of previous spatial multimarket models of the agricultural (17) and livestock (13) sectors. VPM is a four-sector, eight-region, partial-equilibrium model that focuses primarily on the dynamics of different pig systems (traditional, commercial, and modern) and the use of maize for both human food and animal feed. Fresh pork sold in rural wet markets produced by traditional smallholder producers is categorized in the traditional sector. Fresh pork sold in urban/peri-urban wet markets produced by commercially oriented producers is categorized in the commercial sector, while processed pork sold in formal market outlets including supermarkets comprises the modern sector. The eight regions in VPM are the Northern Uplands, Red River Delta, North Central Coast, South Central Coast, Central Highlands, Southeast, Mekong River Delta, and the rest of the world. VPM simulates the evolution of the pig sector over a 13-year period starting from 2018 until 2030. Following Rich and Winter-Nelson (13), dynamics in the model over time are driven by changes in income, population, and technology, which in turn can influence the evolution of income elasticities that drive demand.

VPM was used to simulate the impact of ASF-related shocks in two scenarios: (i) a baseline scenario of income, price, and technology growth following current trends and (ii) a higher-income growth scenario. The different assumptions behind each scenario are summarized in **Table 2**. In all scenarios, we assumed that ASF-induced supply shocks were only applied to the traditional and commercial systems given their low levels of biosecurity. This assumption aligns with the progression of the outbreak in Vietnam in 2019, which overwhelmingly affected small- and medium-scale farms (5). Moreover, shocks to demand were differentiated by sector. We assumed a 10% rise in demand for products from the modern sector driven by consumer desires for perceived safer products. For products from the traditional and commercial sectors, we considered two levels of demand reduction, 5% and 20%, given uncertainties on how consumer demand responded to ASF outbreaks. The 5% demand shock is derived from an assumption that ASF does not significantly influence pork eating habits of Vietnamese consumers and their strong preference for fresh pork sold in wet markets. On the other hand, the 20% shock reflects consumer boycotts of pork products due to (unfounded) concerns over disease transmission

TABLE 2 | Summary of assumptions used in the base scenario and alternative scenarios simulated in VPM.

Scenario	Assumptions
Base scenario	Per capita income growth: 5% Population growth: 1.05% Nominal exchange rate growth[a]: 1.5%; Maize technology growth: 0.5% Traditional pig technology growth: 0% Commercial pig technology growth: 1% Modern pig technology growth: 1.5% World price growth for maize: 2.08% World price growth for pork: −1.32% Income elasticity of maize: 0.4 Income elasticity of traditional pork products: 1.25 Income elasticity of commercial pork products: 1.38 Income elasticity of modern pork products: 1.51 Own price elasticity of supply for traditional pig: 0.6 Own price elasticity of supply for commercial pig: 0.65 Own price elasticity of supply for modern pig: 0.75
Higher income growth	Same as base scenario except that per capita income growth is increased to 7.5%, and Income elasticity of traditional pork products: 0.6 Income elasticity of commercial and modern pork products: 2.3

Source: Authors' assumptions based on historic data, 2019.
[a]Nominal exchange rate growth averaged 3.15% in the period 1992–2002, 3.18% over 2002–2012, and 1.61% over 2012–2018. As there has been a downward trend in exchange rate depreciation, we chose 1.5% as our exchange rate projection for the simulation period.

[1]https://cgspace.cgiar.org/handle/10568/111133

from sick pigs to humans during the outbreak. We further differentiated shocks to supply and demand by region based on regional information obtained on the number of animals that were either culled or died from ASF. Finally, we imposed trade restrictions between the Northern Uplands and Red River Delta, and the Mekong River and Southeast, to simulate the effects of targeted movement restrictions that were implemented to slow the spread of ASF in the outbreak year (2019).

As a partial equilibrium model, the reported effects are limited to those in the pig and maize sectors, and so other impacts on agricultural and non-agricultural sectors are not reported. We address a result of the lack of data collected on these effects. However, expert consultations suggest the range of figures used in the analysis is plausible.

Assessment of ASF Impacts at National Level

While multimarket models are useful in determining sector-level impacts, broader effects on the wider economy require different types of analytical toolkits. Social accounting matrices, or SAMs, are a type of economywide database that can be utilized to quantify the impacts of ASF on other sectors of the economy (e.g., rice, maize, vegetable, animal feed, etc.), on GDP, and employment. They expand input-output models used in economic planning by disaggregating factor and household accounts, thus allowing the analyst to conduct a distributional assessment of economic shocks on different household groups (11). In a SAM, economic activities are characterized by a set of accounts, which receive income from other activities in the economy and which purchase goods and services from other accounts. Accounts can be classified in terms of specific economic sectors as well as factors of production (labor, capital, and land) and household groups that earn and spend income from different economic sectors. SAMs follow the principle of double-entry accounting in that an account's revenues must exactly equal its expenditures (18). SAMs and input-output models have been used in a number of animal health applications to quantify macro-level impacts of animal disease incursions (9, 19–22).

We used a SAM developed by the Vietnam Central Institute for Economic Management and United Nations University-World Institute for Development Economic Research (23)[2]. The CIEM-WIDER (23) SAM is one of the most comprehensive SAMs ever constructed in a developing world setting, comprising of a set of 164 sectors, ranging from agricultural production, food processing, industrial production, and a variety of different service industries. It also distinguishes between six types of labor categories (urban and rural, each with three different levels of skills based on education level [primary, secondary, or tertiary]), agricultural and non-agricultural capital, land, and capital for livestock and fisheries. The SAM further groups households into 20 different categories, 10 each in rural and urban areas. Each rural and urban household group is further subdivided as to whether they are engaged in farming or non-agricultural activities, with each of those groups subdivided into income quintiles. While the CIEM-WIDER SAM is calibrated to 2012 data, we posit that input-output coefficients between sectors should remain robust for assessment of later periods.

The CIEM-WIDER (23) SAM was used to stimulate three scenarios that decrease the value of the supply of pigs as a result of ASF: a 10% reduction (equivalent to the volume of pigs culled as of June 2019), 25% reduction, and a worst-case 50% reduction. We extrapolated results to 2018 values by increasing the values from the 2012 SAM by 57.1%, which represents the change in GDP between 2012 and 2018. This implicitly assumes that all groups' income grows by the same amount, which will overestimate some income classifications and underestimate others. Our analysis was based on the computation of SAM multipliers and their use in scenario analysis that follow standard techniques detailed in Rich et al. (18) and Breisinger et al. (24).

In animal health applications, the focus of SAM-based analyses has typically been on GDP or national output, but SAMs can also provide useful insights on employment (25). Following the techniques described in Miller and Blair (25) and ILO (26), employment multipliers were generated to compute the number of jobs lost from different-sized outbreaks. To compute this information, we used data for 2017 from GSO on the number of jobs in sector aggregate groupings and data from the 2012 SAM on the total wage bill per sector aggregate to compute an average annual wage per sector. This was used to allocate the wage bill in the SAM by each disaggregated activity and to compute employment levels and employment/output ratios. A caveat to this approach is that it assumes discrete employment activities per sector i.e., it does not allow for employment in multiple sectors, so the values here under-estimate sectoral employment. It also does not capture informal employment; thus, some employment impacts will be under-estimated.

Evaluation of Compensation Scheme

Finally, we analyzed the prevention and control policies by the Vietnamese government to cope with ASF in comparison with other disease outbreaks in animal, in particular highly pathogenic avian influenza (HPAI). The analysis emphasized on comparing compensation rates, eligible conditions, and financial resources for compensation based on a desk review of existing policies. We then further contextualized this analysis through our KIIs with value chain actors and an additional eight representatives of local authorities at different levels (e.g., national, provincial, district, and commune) using the KII guidelines. Our interviews helped to reveal any divergences that existed between official policy and actual implementation. The results could help policy makers understand relative performance, identify bottlenecks in their implementation, and therefore enhance improvements.

RESULTS

Assessment of ASF Impacts Along the Pig Value Chain—Key Case Study Findings

ASF had a multitude of impacts on surveyed actors in the pig value chain. At farm level, we observed that larger-scale farmers were more dependent on pigs for their livelihoods than smallholder farmers. Interviewed smallholders tended to be

[2]See https://www.wider.unu.edu/database/2012-social-accounting-matrix-viet-nam.

more diversified in their sources of income, with only 20–30% of their income derived from pig production. As a result, these farmers were likely to be more insulated from outbreaks of ASF due to their reliance on other agricultural and non-agricultural activities. On the other hand, interviewed medium- and large-scale farmers were found to derive 50–100% of their income from pigs, and the ASF outbreak had much more marked impacts on livelihoods, and in particular slowed their transition toward more modernized production practices. Given the reported large reduction in pig prices by respondents (from US$1.61/kg of live weight right after the first ASF outbreak and then to US$1.39/kg at the time of the study) and an increase in production costs, particularly for biosecurity (e.g., disinfectant), the outbreak had severe consequences on the profitability of medium- and large-scale farmers. Downstream, the effects of ASF on interviewed traders, slaughterhouses, processors, retailers revealed a major shift in trading patterns, with much greater trade now occurring with large farms. These actors further experienced a sharp drop in the volume of pigs traded since the ASF outbreak that was driven by consumer fears about disease transmission from sick pigs to humans.

The study revealed significant changes in the governance of transactions along the pig chain due to ASF. Prior to the ASF outbreak, focus group discussions revealed that pig buyers could enter pig pens freely to see the pigs before deciding whether to buy or not, and payment had been made in cash on the spot. After ASF, pigs were shown to buyers through camera or apps (Zalo, Viber, etc.) rather than direct observation, and payment was transferred through bank accounts to minimize the risk of ASF transmission. Surveyed slaughterhouses noted that they became more selective in selecting pigs for slaughtering as a strategy to win customer trust and keep their reputation in the context of rising food safety concerns during ASF. Amongst surveyed farmers, enhanced collective action in the form of farmer cooperatives was effective in helping farmers cope with ASF. During the outbreak, one cooperative in the study site allocated funds to buy disinfectants and lime for members to increase disinfection around farms. Meetings were organized more regularly for cooperative farm members to update on the ASF situation, introduce effective preventive and control measures, and facilitate the supply of breeding pigs. The cooperative also proactively contacted pig traders from other provinces to purchase pigs from its members when the contracted slaughterhouses reduced capacity.

Assessment of ASF Impacts at Sector Level

Simulation results of the VPM model showed that in the baseline scenario with a 5% shock to demand for traditional and commercial pork, national pig supply falls by nearly 28% in the traditional sector, and by over 11% in the commercial sector in 2019 compared to the no-outbreak scenario (**Figure 1**). This is driven by sharp declines in supply, particularly in the largest production region (Red River Delta) where pork supply in the two sectors decreases by 87 and 26%, respectively. These declines persist throughout the simulation period even after the year of the outbreak (2019).

On the other hand, an ASF outbreak leads to an increase of over 5% in pig supply from the modern sector, driven by consumer preferences for perceived safer products. Supplies from the modern pig sector increase at a more modest rate of 0.5% compared to the no-outbreak scenario since 2020–2027 and start to decrease after 2028. Supply shortages trigger significant increases in the pig prices by 45% in the traditional sector, 14%

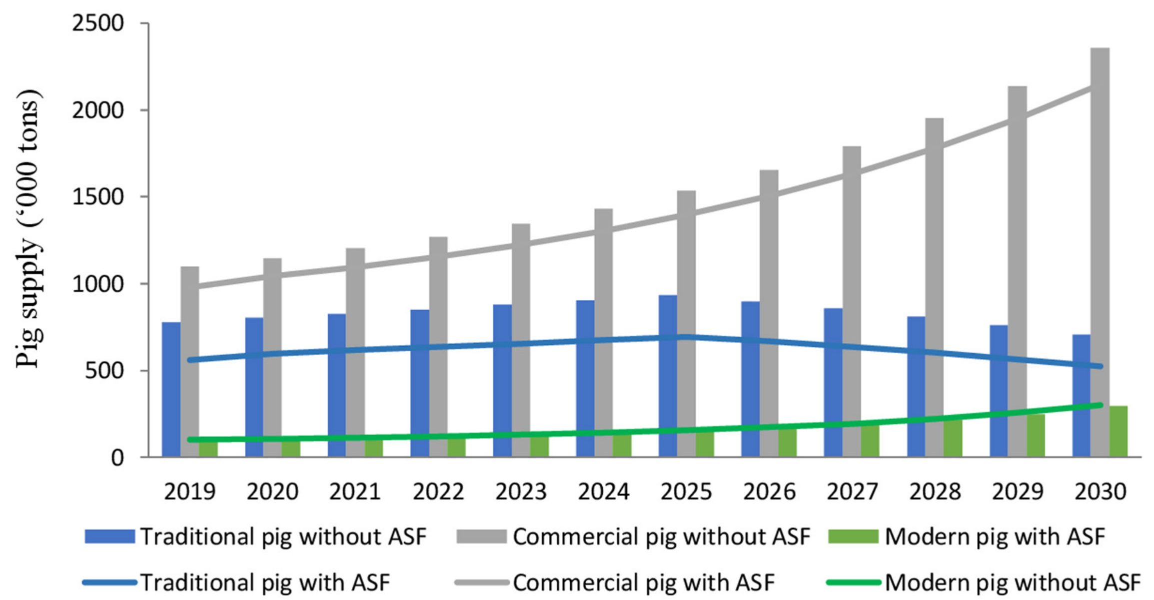


FIGURE 1 | Pig supply projection with and without ASF outbreak under baseline assumptions (5% reduction in demand from traditional and commercial sectors) (Source: Model simulations). The bars are the baseline, and the lines are the level post-ASF.

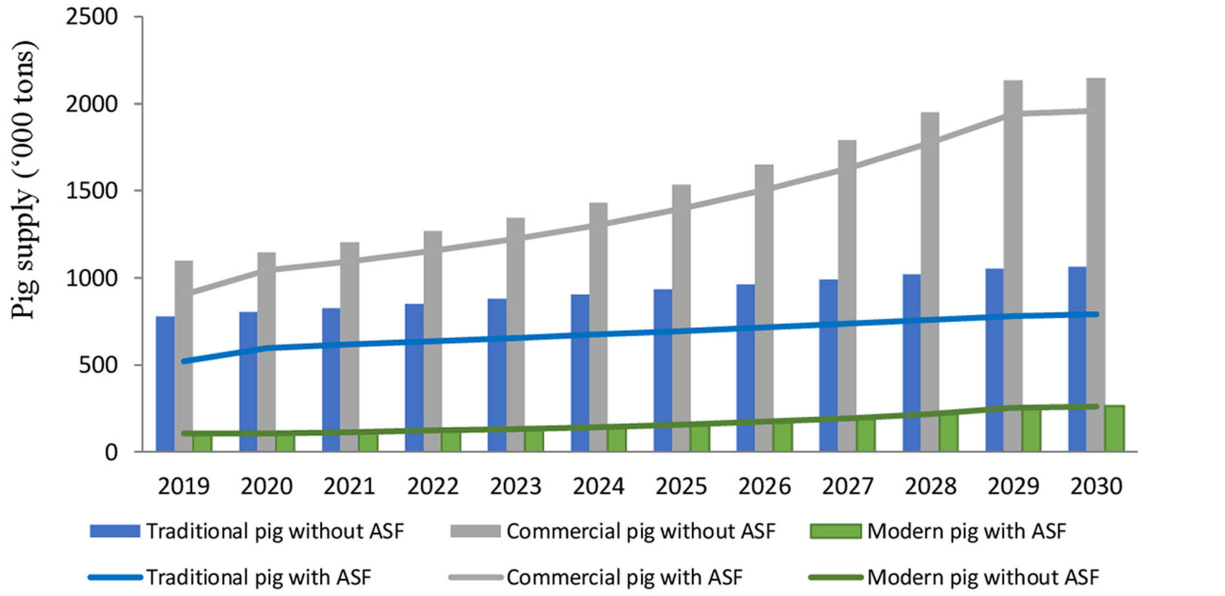


FIGURE 2 | Pig supply projection with and without ASF outbreak under baseline assumptions (20% reduction in demand from traditional and commercial sectors) (Source: Model simulations). The bars are the baseline, and the lines are the level post-ASF.

in the commercial sector and 11% in the modern sector in 2019. From 2020 to 2030, similar growth rates in prices hold for traditional and commercial sector but increase at a declining rate for the modern sector.

Under this scenario, despite the negative impacts of ASF on the supply side, the total revenue of the pig sector does not fall. Rather, the losses in affected farms are offset by higher income in remaining farms due to higher prices for pork. Nationally, pig sector income in 2019 increases by just over 3% (US$89 million), with changes of nearly 4% (equivalent to US$41 million) in the traditional sector, 1.6% (US$24 million) in the commercial sector, and 17% (equivalent to US$24 million) in the modern sector compared to a no-outbreak scenario.

If we consider a higher demand shock of 20%, we observe somewhat sharper declines in the pork supply of the traditional sector (33.2%) and the commercial sector (17.9%) compared to the previous simulation (**Figure 2**). Meanwhile, pig prices increase at significantly lower rates than the previous simulation (by nearly 26% in the traditional sector, but just by 0.3% in the commercial sector compared to the no-outbreak scenario). Total revenue losses under a 20% demand decline are estimated at US$420 million, led by declines in the traditional sector (nearly 16% decline, or a loss of US$172 million) and the commercial sector (18%, or a loss of US$269 million), with only the modern sector showing gains in revenue (a 14% rise, or US$20 million). These results highlight the sensitivity of our sector revenue projections to changes in demand, with more information needed to quantify how demand changed during the 2019 ASF outbreak.

Under the high-growth scenario, the impacts of an ASF outbreak on supply, demand and income are relatively similar to the previous baseline scenario but at a larger magnitude in absolute values. The Red River Delta and Southeast continue to be the most affected regions showing sharp declines in pork supply annually, especially in the traditional sector. Pig prices in all pig sectors increase at considerably larger rates (2–3 times higher than the 2019 -level) in comparison to the baseline scenario after 2026.

In both the baseline and high-growth scenarios, the share of production from the traditional sector is likely to decrease, while the commercial and modern sectors increase their shares. By 2030, ∼20% of total pigs in Vietnam are produced by the traditional sector while over 70% are from the commercial and modern sector in the no-outbreak scenarios. ASF outbreaks accelerate this process, as evidenced by the shift of a 5% share in pork sales from the traditional sector to the commercial and modern sector.

We remark that our scenarios only consider ASF events affecting the smallholder sector, with the modern sector not impacted by ASF. While this aligns generally with the Vietnamese experience, this is not necessarily the case in other settings (e.g., China). Our results should be construed as a best-case scenario, as sizable outbreaks from the modern sector would imply sharper losses to the pig sector as a whole.

Assessment of ASF Impacts at National Level

At national level, we computed the change in GDP induced by a reduction of the value of pig output from the different ASF outbreak scenarios. The SAM allows us to compute the percentage change in GDP which we applied to the 2018 value of GDP (US$245 billion) as reported by the World Bank. The best-case scenario results in a nearly 0.4% reduction in GDP, equivalent to a loss in national income of US$880 million. The worst-case scenario of a 50% loss in pig stocks is estimated to cause a decline of GDP of 1.8% and a loss in national income of US$4.4 billion (**Table 3**).

Among the different economic sectors, feed-related sectors (prepared feed, maize, edible roots and tubers, and vegetable seeds) show sharp declines ranging from 1.76% to just over 3%. Veterinary services also fall by over 2%, while services associated with wholesaling, transport, and input provision fall more modestly but not insignificantly. The value of total economic output from the scenario is estimated to fall by 0.45% as a result of ASF. More serious outbreaks result in a larger percentage declines, with a 50% decline in the value of pigs reducing output in maize by over 13%, animal feeds by over 15%, and veterinary services by over 11% (**Table 4**).

The employment effects associated with different ASF outbreak scenarios were also estimated.

TABLE 3 | Impacts on GDP induced by a reduction in the value of pig output caused by ASF under different scenarios.

Scenario	Percentage % in GDP	Change in 2018 GDP (billion USD)
10% reduction in pig output	−0.36%	−0.88
25% reduction in pig output	−0.90%	−2.20
50% reduction in pig output	−1.80%	−4.40

Source: Computed with the 2012 Vietnam SAM, using data from World Bank to calibrate the change in GDP value (see https://data.worldbank.org/indicator/NY.GDP.MKTP.CD?locations=VN&view=chart).

Under the best-case scenario, we estimate a loss of nearly 247,000 formal sector jobs in Vietnam, of which over 86,000 occur in the pig sector, over 35,000 in wholesale and retail trade, and nearly 25,000 in the rice sector. In percentage terms, the animal feeds sectors (−3.01%) and veterinary services (−2.17%) face disproportionate losses. The worst-case outbreak of 50% of Vietnam's pigs culled would lead to over 1.2 million, or 2.3%, in job losses, with a 44% reduction, or over 431,000 jobs lost in the pig sector, nearly 176,000 jobs lost in wholesale trade and retail, and nearly 125,000 jobs lost in the rice sector (**Table 5**).

The distributional impacts of ASF outbreak scenarios on household groups are summarized in **Table 6**. In the best-case scenario, household income falls by nearly US$600 million in aggregate, with the lowest three quintiles receiving the highest losses in percentage terms, though these changes in percentage terms are only slightly larger than those faced by upper quintile groups. The rural farm sector in aggregate faces income declines of over US$338 million. In the best-case scenario, the change in income induced by an ASF ranges from −0.3 to −0.45% in rural areas, and −0.23 to −0.36% in urban areas, suggesting that outside specialized producers, pigs are a part of a broader diversification strategy with income shocks buffered to some extent from other agricultural and non-farm activities. Larger outbreaks magnify these effects, with the worst-case scenario leading to a reduction in household income by US$3 billion, and a reduction of rural farm income by US$1.7 billion.

TABLE 4 | Sectors most negatively affected* by a reduction in the value of pig output caused by ASF under different scenarios.

Sector	% change in value		
	10% reduction in pig output	25% reduction in pig output	50% reduction in pig output
Rice	−0.52%	−1.30%	−2.61%
Maize and other cereals	−2.63%	−6.58%	−13.16%
Edible roots and high-starch tubers	−1.76%	−4.40%	−8.80%
Oleaginous vegetable seeds	−2.00%	−5.00%	−10.00%
Other perennial crops	−0.69%	−1.72%	−3.45%
Products of pigs	−9.71%	−24.26%	−48.53%
Agricultural services	−0.59%	−1.47%	−2.94%
Vegetable and animal oils and fats	−0.78%	−1.94%	−3.88%
Prepared animal feeds	−3.01%	−7.53%	−15.07%
Pesticides and other agrochemical products	−0.72%	−1.80%	−3.59%
Basic pharmaceutical products, pharmaceutical preparations	−0.77%	−1.92%	−3.84%
Wholesale and retail trade	−0.55%	−1.37%	−2.73%
Freight rail transport services	−0.55%	−1.37%	−2.73%
Freight transport services by road, transport services via pipeline	−0.54%	−1.35%	−2.71%
Sea and coastal, inland freight water transport services	−0.55%	−1.37%	−2.73%
Freight air transport service	−0.55%	−1.37%	−2.73%
Veterinary services	−2.17%	−5.42%	−10.85%
TOTAL EFFECTS (all sectors)	−0.45%	−1.12%	−2.24%

*Source: Computed with the 2012 Vietnam SAM. *Most negatively sectors are those that had a reduction in output of −0.5% or more based on the lowest output shock scenario.*

TABLE 5 | Employment impacts of ASF in selected sectors under alternative scenarios.

	10% reduction in pig output		25% reduction in pig output		50% reduction in pig output	
	% change	Change # jobs	% change	Change # jobs	% change	Change # jobs
Rice	−0.48%	(24,944)	−1.20%	(62,361)	−2.39%	(124,722)
Maize and other cereals	−1.21%	(8,233)	−3.02%	(20,582)	−6.03%	(41,163)
Edible roots and high-starch tubers	−1.35%	(6,327)	−3.38%	(15,816)	−6.76%	(31,633)
Oleaginous vegetable seeds	−1.48%	(2,451)	−3.69%	(6,127)	−7.38%	(12,255)
Products of pigs	−8.80%	(86,284)	−22.01%	(215,710)	−44.01%	(431,419)
Fish products	−0.23%	(10,080)	−0.58%	(25,201)	−1.17%	(50,402)
Prepared animal feeds	−3.01%	(6,813)	−7.53%	(17,032)	−15.07%	(34,065)
Wholesale and retail trade	−0.55%	(35,186)	−1.37%	(87,966)	−2.73%	(175,931)
Veterinary services	−2.17%	(235)	−5.42%	(586)	−10.85%	(1,173)
Other agriculture	−0.32%	(23,548)	−0.81%	(58,871)	−1.61%	(117,741)
Other sectors	−0.17%	(42,664)	−0.42%	(106,659)	−0.84%	(213,318)
TOTAL	−0.46%	(246,764)	−1.15%	(616,911)	−2.30%	(1,233,822)

Source: Computed with the 2012 Vietnam SAM.

TABLE 6 | Impacts on household income groups induced by a reduction in the value of pig output caused by ASF under different scenarios.

Household classification	Estimated total income in 2018 (million USD)	10% reduction in pig output		25% reduction in pig output		50% reduction in pig output	
		% change	Change in income (million USD)	% change	Change in income (million USD)	% change	Change in income (million USD)
Urban farm—first quintile	552	−0.36%	(1.99)	−0.90%	(4.98)	−1.81%	(9.97)
Urban farm—second quintile	1,032	−0.36%	(3.71)	−0.90%	(9.27)	−1.80%	(18.55)
Urban farm—third quintile	2,291	−0.36%	(8.35)	−0.91%	(20.88)	−1.82%	(41.77)
Urban farm—fourth quintile	3,211	−0.34%	(10.79)	−0.84%	(26.96)	−1.68%	(53.93)
Urban farm—fifth quintile	5,077	−0.31%	(15.97)	−0.79%	(39.93)	−1.57%	(79.85)
Urban non-farm—first quintile	224	−0.28%	(0.64)	−0.71%	(1.60)	−1.42%	(3.19)
Urban non-farm—second quintile	923	−0.29%	(2.65)	−0.72%	(6.63)	−1.44%	(13.25)
Urban non-farm—third quintile	3,190	−0.26%	(8.25)	−0.65%	(20.62)	−1.29%	(41.24)
Urban non-farm—fourth quintile	10,532	−0.24%	(25.30)	−0.60%	(63.25)	−1.20%	(126.50)
Urban non-farm—fifth quintile	49,595	−0.23%	(113.31)	−0.57%	(283.28)	−1.14%	(566.55)
Rural farm—first quintile	8,298	−0.45%	(37.03)	−1.12%	(92.57)	−2.23%	(185.15)
Rural farm—second quintile	13,174	−0.43%	(57.02)	−1.08%	(142.56)	−2.16%	(285.12)
Rural farm—third quintile	16,800	−0.44%	(73.40)	−1.09%	(183.51)	−2.18%	(367.01)
Rural farm—fourth quintile	19,602	−0.42%	(82.18)	−1.05%	(205.45)	−2.10%	(410.91)
Rural farm—fifth quintile	21,935	−0.41%	(89.35)	−1.02%	(223.38)	−2.04%	(446.77)
Rural non-farm—first quintile	633	−0.37%	(2.33)	−0.92%	(5.83)	−1.84%	(11.66)
Rural non-farm—second quintile	1,926	−0.39%	(7.61)	−0.99%	(19.02)	−1.97%	(38.04)
Rural non-farm—third quintile	3,191	−0.35%	(11.24)	−0.88%	(28.10)	−1.76%	(56.21)
Rural non-farm—fourth quintile	5,204	−0.33%	(17.37)	−0.83%	(43.43)	−1.67%	(86.87)
Rural non-farm—fifth quintile	10,481	−0.30%	(31.31)	−0.75%	(78.27)	−1.49%	(156.54)
TOTAL	177,871	−0.34%	(599.81)	−0.84%	(1499.54)	−1.69%	(2999.07)

Source: Computed from the 2012 Vietnam SAM. Note that the definition of household groups and quintiles stem from the SAM as constructed and are elaborated in the database itself, see https://www.wider.unu.edu/database/2012-social-accounting-matrix-viet-nam.

Evaluation of ASF Compensation Scheme

Since the first outbreak of ASF, the government issued three legal documents regulating different compensation rates for different periods in 2019. The compensation schemes were applied for two groups of beneficiaries including pig producers (i.e., households, farmers, cooperatives, etc.) and enterprises (**Table 7**).

Resolution 02/2017/NĐ-CP applied for pig owners having pig herds culled due to ASF before 20 March 2019. According to

TABLE 7 | Compensation schemes for ASF infected stakeholders.

	Resolution 02/2017/NĐ-CP (dated on 1 January 2017)	Resolution No. 16/NQ-CP (dated on 7 March 2019)	Decision No. 793/QĐ-TTg (dated on 27 June 2019)
Compensation rates for pig producers	VND 38,000/kg (US$1.64) regardless of pig type	• For piglets and fatteners of all kinds: 80% of market price • For breeding pigs: 1.5–2.0 times higher than	• For piglets and fatteners of all kinds: VND 25,000/kg (US$1.09) of live pigs • For breeding pigs: VND 30.000/kg (US$1.30) of live pigs
Compensation rates for small and medium enterprises	Ineligible	• 30% of producers' compensation rates • For great-grandparent and grandparent pigs: VND 500,000/head (US$21.7)	• For piglets and fatteners of all kinds: VND 8,000/kg (US$0.35) of live pigs • For breeding pigs: VND 10,000/kg (US$0.43) of live pigs • For great-grandparent and grandparent pigs: VND 500,000/head (US$21.7)
Fund allocation for compensation	• For mountainous and Central Highlands provinces, the central budget supports 80% of the support rate • For other centrally run cities and provinces that contribute *50% or more* of their revenues to the central budget, the provincial reserve funds shall be used for the support • For other centrally run cities and provinces that contribute *<50%* of total revenues to the central budget, the central budget supports 50% of the support rate • For provinces that have not yet been able to balance their budget revenues and expenditures, the central budget supports 70% of the support rate • For seriously affected provinces, if the local budgets cannot cover the costs (exceed 50% of the local reserve budget), the central budget will support the difference		

Source: Authors' compilation from various policy documents.

this Resolution, pig owners received an average compensation rate of US$1.64/kg regardless of pig type. However, only those who had registered with the Commune People's Committee as farmers who raised livestock were eligible for the compensation. This Resolution gave little reason for pig farmers to actively report disease outbreaks and cull infected pigs for three reasons. Firstly, the compensation rate was relatively lower than the market prices prior to the first ASF detection. For instance, on 20 February 2019, the prices of live pigs were between US$2.11–2.41/kg in southern provinces, between US$1.94–2.11/kg in central provinces, and $1.98–2.24/kg in the North. Secondly, the issuance of a homogenous compensation rate (e.g., per live weight kg of pig regardless of types) could possibly lead to different application by different provinces based on what had occurred during previous HPAI outbreaks. During the HPAI outbreaks in 2004, while the government set a compensation rate of US$0.23 per head of poultry regardless type and weight, Hanoi applied US$0.23 per breeding poultry and US$0.46 per broiler while Ho Chi Minh City supported rates of US$0.70 per broiler of more than 8-week age, US$0.46 per broiler of <8-week age, US$0.23 per head of all poultry from 1-to-4 week age, and US$0.14 for all poultry <1 week age. Different compensation rates applied by provinces were considered as a major factor in inducing the movement of infected animals from one province to neighboring provinces and therefore enhancing disease spread (27). Lastly, the requirement of mandating registration for compensation eligibility was likely to be infeasible in the context of Vietnam, where the majority of pig farms were small-scale, located in residential areas, and did not have initial registration.

In order to promptly address the shortcomings above, the Vietnamese government subsequently released Resolution No. 16/NQ-CP on 7 March 2019. According to the updated scheme, different compensation rates were applied for different types of pigs and the rates aligned with market prices. Piglets and fatteners of all kinds were to be supported at the rate of 80% of the local market prices at the time and place of the outbreak, while breeding pigs received higher support (1.5–2.0 times). The condition of mandatory pig production registration with the Commune People's Committee as required prior to the outbreak was lifted as well. In addition to pig producers, the Resolution added small and medium enterprises (excluding those being subsidiaries or having dominant shared capital from large scale enterprises) as another beneficiary group of the compensation scheme. This category would receive support equivalent to 30% of the producer rates. The new compensation rates were regarded as meeting the expectation of those affected by ASF but could still cause difficulty in their implementation. Given the strong fluctuation of daily market prices, especially under the context of continuous ASF outbreaks, it was very difficult and time consuming to identify a market price base for setting up the compensation rates.

Different provinces still defined different ways to translate this regulation into practice. For instance, Hanoi city used the prices announced daily by CP company as a reference base. Every day from 8 a.m. to 10 a.m., the Department of Finance updated the CP prices on its website (https://sotaichinh.hanoi.gov.vn) and all districts and wards in Hanoi would utilize that price to define the compensation rates for households that had pigs culled on that day. Therefore, the rates were adjusted constantly aligning with the daily market fluctuation. Hung Yen province also referred to CP prices for determining the support rates, but the rates were only adjusted if the CP prices went up or down more than 20%. Consequently, since the effective date of the Resolution, Hung Yen province only adjusted their rates twice. From 20 March to 5 May 2019, their rates were fixed at US$2.07/kg for breeding pigs and US$1.39/kg for other pig types. After 6 May 2019, these rates were reset at US$1.63/kg and US$1.09/kg, respectively. Eight key informant interviews with the central and provincial authorities revealed that the constant adjustment of the compensation rates based on the market prices may lead to more complications in compensation procedures because the provincial department of finance that was responsible for fund disbursement required a detailed explanation of the reference base for compensation rate setup (e.g., what price, what date, and what time). In addition, the interviewees emphasized that the application of different compensation rates for households being infected in different periods would be possibly perceived as unfair if the information provided did not work well when the compensation was delivered to households.

Due to the significant losses caused by ASF, a further constraint was that the central and provincial budgets were not able to cover the compensation rates stated in Resolution No. 16/NQ-CP above. On 27 June 2019, the government issued Decision No. 793/QĐ-TTg adjusting the compensation rates down to US$1.09/kg for piglets and fatteners of all kinds and US$1.30/kg for breeding pigs, which were applied for pig producers. For small and medium enterprises, the corresponding rates were US$0.35/kg and US$0.43/kg, respectively. The new rates were established based on production cost rather than market prices as previous regulations and covered ∼80% of total production cost.

In all of the legal documents above, the level of financial contribution from the central government and provincial authorities were clearly stated. While Hanoi and Ho Chi Minh city were able to mobilize their own budgets to cope with ASF, other provinces struggled with financial constraints. For instance, up until end-July 2019, Hanoi spent US$56.5 million for the control and prevention of ASF, including for compensation, with 100% of the budget from the city's reserve fund. The city completed compensation for almost 70% of infected households with the average time for disbursement ranging from 5 to 7 days in the early period of ASF outbreaks to around half month in the peak period. Meanwhile, Hung Yen province, with total estimated losses of US$20.4 million, could not meet the suggested risk sharing level of 50%, as its total reserve fund was only US$4.34 million. The province therefore had to rely on the central budget for doing compensation. Most recently, on 17 July 2019, the central government transferred US$55.2 million to support six provinces, of which Hung Yen received US$7.83 million. This partly explained the delay of compensation procedures and the uncertainty in the amount of time taken for farmers to receive compensation, which consequently influenced behaviors of those affected by ASF and the effectiveness of controlling disease spread. Our case study in Duc Thang commune in Hung Yen province showed that both local authorities and farmers had no clear idea regarding when the money would be approved and transferred to compensate farmers. The full compensation also might not be delivered all at once but in several stages over many months or years. For these reasons, many farmers decided to quickly sell pigs with ASF suspected symptoms instead of declaring outbreaks to the animal health authority. Two interviewed farmers in the case study confessed that they would attempt to sell their suspected pigs before ASF was confirmed, even at significantly lower prices, to recover a part of their investment rather than waiting for several years to get higher compensation.

The reliance on the central government for compensating farmers not only happened for ASF but also for other disease outbreaks, which was argued to influence the responsiveness of different provinces to outbreaks. For example, in a survey of six provinces heavily affected by HPAI outbreaks in 2004 including Ho Chi Minh city, Ha Tay (currently a part of Hanoi city), Thai Binh, Vinh Phuc, Tien Giang, and An Giang, only Ho Chi Minh city could quickly compensate infected farmers using its own budget, while other provinces were mainly dependent on central government resources. The actual percentage contributed by these provinces was far below the suggested levels of 50%, particularly Tien Giang (11%), and An Giang (8%) (27).

DISCUSSION

Changes in Production and Sales Patterns Along the Value Chain

Despite various disease control efforts by the government, farmers, and several donor-supported projects, ASF cases increased throughout 2019. The outbreak caused severe direct and indirect losses among pig producers and other value chain actors, and significantly changed patterns of production, governance, and sales along the value chain.

With only 20–30% of income derived from pig production, smallholders tended to be more diversified in their sources of income and therefore were more insulated from outbreaks of ASF due to their reliance on other agricultural and non-agricultural activities. Medium- and large-scale producers, on the other hand, derive 50–100% of their income from pigs, and an ASF outbreak can both devastate livelihoods and prevent their transition toward more modernized production practices. Given a reduction in prices by nearly 50% and an increase in production costs, particularly for biosecurity (e.g., disinfectant), the outbreak has had severe consequences on such farmers.

The effects of ASF on downstream value chain actors were severe, which was evidenced a halving in the volume of pigs traded as reported by a number of interviewed traders, processors, and slaughterhouses. The outbreak also caused a major shift in trading patterns toward large farms with more secure pig supplies, and the increased use of technology rather than traditional face-to-face transaction modes to reduce the virus transmission risk. Also, consumers tended to shift their consumption behavior toward safer pork products which show clear, traceable origins and are supplied by trusted distribution channels, increase of online shopping and decrease of physical shop visits. Since the emergence of ASF outbreaks, modern retail channels (e.g., supermarkets, convenient stores, etc.) recorded a 20–30% increase in sales while traditional markets posted a 20–30% decline in sales (28).

In the short and medium-term, ASF-infected pig farms were encouraged to shift production to other species such as cattle or poultry. Provincial authorities tried to create favorable conditions for farmers to access necessary resources for such a production switch. For instance, Hung Yen province had several ongoing projects focusing on VietGAHP chicken production and beef cattle production. During this period, these projects were being given priority for pig farmers to be engaged in. Such a switch at large scale might result in a rapid increase of poultry and cattle herds, which raises concerns about the possibility of related disease outbreaks such as HPAI and foot and mouth disease in the future. However, from the management point of views, these diseases are considered as being controlled more easily than ASF due to the existence of vaccines. In addition, the government has already established an action plan to cope with these diseases. Most recently, on 16 July 2019 MARD sent an official dispatch No. 4981/BNN-TY to all provinces with regard to enhancing the implementation of national action plan on preventing and controlling HPAI during the period 2019–2025.

Changes in Trajectories of Pig Production Systems

The ASF outbreak posed adverse impacts on the domestic pork supply and demand, especially in the traditional sector. Smallholder pig producers in the Red River Delta and Southeast suffered the highest losses driven from sharp declines in supply. Meanwhile, the modern sector with higher levels of biosecurity (and in the model not assumed to be impacted by ASF) and high technology growth was less likely to be affected and even benefits from the outbreak, which is evidenced by increased supply and income throughout the simulation period. While we would expect the gradual reduction in importance of the smallholder sector, particularly given Vietnam's livestock development strategy which promotes the development of commercial and modern farms, model results indicate that an ASF outbreak will accelerate this process.

Completely replacing small-scale farms with commercial-modern farms might not likely occur in the short term. In other words, smallholder farmers will continue to derive livelihoods from pig farming and meet a certain market. Thus, an important question is how best to effectively manage this transition in a manner that also buffers against disease shocks like ASF in the future.

The effectiveness of Duc Thang cooperative in facilitating sales and helping farmers cope with ASF provides insights on the role that collective action can play in this transition. In Vietnam, farmer groups can be organized through a very simple form of common interest groups which are self-managed by farmers that share a common interest or through more complicated form of cooperatives which are formally established under the Law on Cooperation (29). Improved coordination between various actors has been observed through the establishment of farmer groups through (i) encouraging farmers to adopt new technologies, such as VietGAHP, (ii) facilitating linkages between their members and input suppliers by signing contracts for buying animal feed, veterinary medicine and services, and credit with reliable suppliers to get better quality inputs at more favorable prices; and (iii) facilitating linkages with more stable market outlets, which creates win-win relationships, not only for farmers to stabilize their production but to also ensure a more stable source of products in both quantity and quality for buyers. The establishment of farmer groups has been strongly supported by the government and development projects of non-governmental organizations. Empirical evidence shows that the organization of farmer groups has many benefits, including better access to quality inputs and services, reduced exposure to production and market risks and reduced transaction costs (both in terms of input procurement and output marketing), and increased returns from pig production. For instance, Lapar et al. (30) indicated that members of cooperatives could obtain an increase of 16% in their profit margins per kg of live weight pig, based on a 25–30% decrease in production costs and 15–20% increase in selling prices. Pig traders could also reduce their costs of collecting and grading pigs by about 20%. Scholl et al. (29) also found that farmer group members had significantly larger pig herds than non-members (26.8 vs. 6.8); and the income of the farmer group members increased by US$827 per year compared to their counterparts.

Despite these encouraging results, the sustainability of these farmer groups after the intervention projects finish is still untested. Scholl et al. (29) showed that farmers identified external project interventions, not internal factors, as reasons for group success. For instance, subsidies from the projects in any form, either technical training or in-kind payments (pigs or monetary value of a pig, pig feed, financial incentives, etc.), were highlighted as key reasons for the successful operation of farmer groups. That explains why many farmer groups may have appeared to be successful at the time of project implementation but failed to maintain their operations once support from the project was withdrawn at the end of project implementation (29). Thus, in order to ensure the long-term development of these institutional models, factors such as member selection, management, trademark registration, strict quality control, and written contracts with regular customers should be given more attention.

Impacts on Job Losses

The adverse impacts of the ASF outbreak were not restricted to the pig sector but also extended to other related sectors of the economy. For instance, the ASF outbreak depressed Vietnam's animal feed consumption, especially that used for pig feed. Prior to the ASF outbreak, pork production accounted for the vast majority of the total feed market of ∼30 million tons. After the outbreak occurred, the feed industry experienced a 30–50% drop in sales (28). Consequently, and as revealed by the SAM, the outbreaks led to a significant loss of jobs in the pig sector and the relevant sectors, estimated as up to 247,000 jobs in the best-case scenario of 10% of Vietnam's pigs culled and 1.2 million jobs in the worst scenarios of 50% pigs culled. Social assistance schemes that target prospectively affected sectors, particularly those outside the immediate pig sector, should be considered and deployed to cushion the short-term impacts of ASF.

An additional consideration on the employment and livelihoods side is the degree to which smallholder livelihoods may be affected by ASF outbreaks. As noted earlier, smallholders are often not as negatively impacted as emerging commercial farmers, as smallholders diversify their income sources (31, 32).

However, those farmers in crop-livestock systems or engaged in services that support pigs may face multifaceted negative impacts from ASF that compound income losses. Indeed, from the standpoint of household income, results from the SAM show that the poorest farm households and the poorest two quintiles of non-farm households had the largest negative effects from ASF, suggesting that while smallholders may avoid the pig-related losses associated with commercial farmers, they may still be impacted in other ways outside of direct effects to pigs.

Effectiveness of the ASF Compensation Scheme

The implementation of the ASF compensation scheme was found to be inconsistent, with changing rules, heavy bureaucratic burdens on applicants, and significant delays in administration. A more transparent compensation system should be considered to improve confidence in public authorities and enable value chain actors to champion ASF control efforts rather than impeding it through rational self-interest. More generally, future compensation programs need to be rethought to more specifically encourage and reward good stewardship in the form of biosecurity investments. In a theoretical paper, Gramig et al. (33) note that compensation programs typically try to get producers to invest in both biosecurity and report disease, when in fact decisions to invest and report involve different types of information problems and need different incentive-compatible mechanisms to ensure compliance. They suggest a "carrot-and-stick" approach to de-link these different problems, with compensation indemnities used to induce investments in proper biosecurity, and a schedule of fines to ensure adequate disease reporting. Blanket compensation shifts the risk of disease wholly to government, and in the absence of risk classification undermines the ability of government to get farmers to self-insure through biosecurity investments (33).

Removing the requirement of having the farm registered (with the Commune People's Committee) in order to claim compensation could be a temporary solution in the current context of a vast number of unregistered smallholder farms affected by ASF. However, in the long term, reintroduction of farm registration as a compulsory criterion for compensation is recommended to enhance biosecurity on farms. This process will require a preparation period, for instance a 1-to-2-year period for transitioning, in parallel with a massive information and awareness campaign to communicate this new requirement.

The ASF outbreak in Vietnam rekindled debates on the modalities of compensation. The Vietnam experience to date show significant variation in compensation rates that could fuel movements that militate against disease control. The disconnect between central and local disbursement of compensation funds further complicates matters, with delays at regional level impeding local level efforts of control. At the same time, traditional compensation programs focus primarily on producers, yet the results from this paper show severe losses faced by various value chain actors (e.g., a reduction of 50% or more in traded volumes reported by traders and slaughterhouses), not to mention downstream effects in ancillary industries (animal health services, animal feed). As some of these actors can also serve as vectors for disease risk, providing adequate incentives for their compliance is also necessary. In the context of Rift Valley fever in Kenya, Rich and Wanyioke (9) proposed the idea of privately managed disease control funds based on a levy on sales that could be managed by producer organizations or cooperatives, as well as the possibility for government to back stand-by loans or letters of credit to deal with short-term cash flow disruptions. Indeed, one of the interviewees from a focus group discussion highlighted the role that could be played by livestock funds, for example a US$1/pig head checkoff fee that could be managed by a farmer association and used to co-insure against disease risk, support biosecurity investment, and/or improve production. This is particularly important to manage disease compensation at local level, where contingency budgets have proven inadequate at prompt disbursement. Given the various disease incursions that have faced the pig sector in the past decade, developing modalities for such funding mechanisms and their disbursement between national and local levels based on partnerships between the public and private sector should be encouraged.

CONCLUSION

This study provides an important and comprehensive analysis of the impacts of the 2019 ASF outbreak in Vietnam using a mixed methods approach. The results highlighted the adverse direct and indirect impacts of ASF at different levels (i.e., at farm, sector, national level) as well as the effectiveness of the government's compensation scheme to respond and control ASF spread. Policy implications to better control and minimize ASF's adverse impacts in future include the improvement of market linkages along the pig value chain through the effective establishment and organization of farmer groups, social assistance to support those displaced by ASF, and improvements to the system of compensation with greater emphasis on developing improved risk-sharing and funding mechanisms across national and local levels.

DATA AVAILABILITY STATEMENT

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

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Institute Review Board at the Hanoi University of Public Health (No. 66/2019/YTCC-HD3). The participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

ThinhN-T and KR conceived, designed the study, and took the lead in writing the manuscript. ThinhN-T, SD-X, HL, HN-V, and PP reviewed the pig value chain case study and analyzed the compensation scheme. LP-T-N, QN-N, ThinhN-T, TT-C, and KR ran the VPM model to quantify the impacts of ASF at sector level. KR used the SAM to analyze the ASF impacts at national level. All authors contributed to the article and approved the submitted version.

FUNDING

This research was funded by the Food and Agriculture Organization of the United Nations (FAO—Contract number: LOA-FAVIE.2019.12– TCP/VIE/3604) and the Australian Center for International Agricultural Research (ACIAR—Contract number: C001752).

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fvets.2021.686038/full#supplementary-material

REFERENCES

1. Ouma E, Dione M, Birungi R, Lule P, Mayega L, Dizyee K. African swine fever control and market integration in Ugandan peri-urban smallholder pig value chains: An ex-ante impact assessment of interventions and their interaction. *Prev Vet Med.* (2018) 151:29–39. doi: 10.1016/j.prevetmed.2017.12.010
2. Chen W, Zhao D, He X, Liu R, Wang Z, Zhang X, et al. A seven-gene-deleted African swine fever virus is safe and effective as a live attenuated vaccine in pigs. *Sci China Life Sci.* (2020) 63:623–34. doi: 10.1007/s11427-020-1657-9
3. Gregorio Torres. *GF-TADs Global Control of African Swine Fever. Presentation at the Webinar on African Swine Fever: An Unprecedented Global Threat - A Challenge to Livelihoods, Food Security and Biodiversity.* Call for action (2020). Available online at: http://www.gf-tads.org/events/events-detail/en/c/1152886/
4. DAH. *Daily Report on Animal Diseases to Minister of MARD* (2020).
5. FAO. ASF- Lessons learned in Viet Nam and future perspectives. In: *Presentation at the International Conference on ASF: Current Situation and Future Plan at Vietnam National University of Agriculture*. Hanoi (2019).
6. MARD. Current situation of Vietnam pig production. In: *Presentation at the Workshop Development of Economic Model for Forecasting the Pig Sector Organized by the Institute of Policy and Strategy for Agriculture and Rural Development (IPSARD).* Hanoi (2017).
7. DAH. ASF in Vietnam. *Presentation at the International conference on ASF: Current Situation and Future Plan at Vietnam National University of Agriculture*. Hanoi (2019).
8. DAH. *ASF Situation in Vietnam*. Report update by Epidemiology Division, DAH to MARD (2019).
9. Rich KM, Wanyioke F. An assessment of the regional and national socio-economic impacts of the 2007 Rift Valley Fever outbreak in Kenya. *Am J of Trop Med Hyg.* (2010) 83:52–7. doi: 10.4269/ajtmh.2010.09-0291
10. Rich KM, Berends J, Cooper GS. Enriching value chains through maps: reflections and lessons from spatial group model building in Myanmar and India. *Dev Pract*. 31. doi: 10.1080/09614524.2021.1907545
11. Rich KM, Winter-Nelson A, Miller GY. Enhancing economic models for analysis of animal disease. *Rev Sci Tech OIE.* (2005) 24:847–56. doi: 10.20506/rst.24.3.1617
12. Schoenbaum MA, Disney WT. Modeling alternative mitigation strategies for a hypothetical outbreak of foot-and-mouth disease in the United States. *Prev Vet Med.* (2003) 58:25–52. doi: 10.1016/S0167-5877(03)00004-7
13. Rich KM, Winter-Nelson A. An integrated epidemiological-economic analysis of foot and mouth disease: applications to the southern cone of South America. *Am J Ag Econ.* (2007) 89:682–97. doi: 10.1111/j.1467-8276.2007.01006.x
14. Schroeder T, Pendell D, Sanderson M, McReynolds S. Economic impact of alternative FMD emergency vaccination strategies in the Midwestern United States. *J Ag Appl Econ.* (2015) 47:47–76. doi: 10.1017/aae.2014.5
15. Minot N, Rich K, Que NN, Phong NA. *Vietnamese Pig Sector Model 2014: Users Manual, Version 1*. Nairobi: International Livestock Research Institute (2015). Available online at: https://core.ac.uk/download/pdf/132683349.pdf (accessed June 17, 2021).
16. Lapar ML, Ouma E, Lule P, Que NN, Khoi DK, Rich KM. Application of a multi-market partial equilibrium model to evaluate the impact of technology and policy on smallholders in the pig sectors of Vietnam and Uganda. *Paper Presented at the PIM Pre-Conference on Rural Transformation in the 21st Century: Challenges for Low-Income, Late-Transforming Countries at the International Conference of Agricultural Economists*. Vancouver, BC (2018).
17. Minot N, Goletti F. Export liberalization and household welfare: the case of rice in Vietnam. *Am J Ag Econ.* (1998) 80:738–49. doi: 10.2307/1244060
18. Rich KM, Winter-Nelson A, Nelson GC. Political feasibility of structural adjustment in Africa: an application of SAM mixed multipliers. *World Dev 25.* (1997) 2105–14. doi: 10.1016/S0305-750X(97)00099-5
19. Garner MG, Lack MB. An evaluation of alternate control strategies for foot-and-mouth disease in australia: a regional approach. *Prev Vet Med.* (1995) 23:9–32. doi: 10.1016/0167-5877(94)00433-J
20. Mahul O, Durand B. Simulated economic consequences of foot-and-mouth disease epidemics and their public control in France. *Prev Vet Med.* (2000) 47:23–38. doi: 10.1016/S0167-5877(00)00166-5
21. Pendell DL, Leatherman J, Schroeder TC, Alward GS. The economic impacts of a foot-and-mouth disease outbreak: a regional analysis. *J Ag App Econ.* (2007) 39:19–33. doi: 10.1017/S1074070800028911
22. Roeder P, Rich KM. Chapter 15: The global effort to eradicate rinderpest. In: Spielman DJ, Pandya-Lorch R, editors. *Proven Successes in Agricultural Development: A Technical Compendium to Millions Fed*. Washington, DC: International Food Policy Research Institute (2010). p. 407–36.
23. CIEM-WIDER. *2012 Social Accounting Matrix - Viet Nam*. (2016). Available online at: https://www.wider.unu.edu/database/2012-social-accounting-matrix-viet-nam
24. Breisinger C, Thomas M, Thurlow J. *Social Accounting Matrices and Multiplier Analysis: An Introduction with Exercises.* Vol. 5. Washington, DC: International Food Policy Research Institute (2009).
25. Miller RE, Blair PD. *Input-Output Analysis: Foundations and Extensions*. 2nd ed. Cambridge: Cambridge University Press. (2009). doi: 10.1017/CBO9780511626982
26. International Labour Organization. *Assessing the Effects of Trade on Employment: An Assessment Toolkit*. Geneva: International Labour Organization (2019).
27. Riviere-Cinnamond A. *Compensation and Related Financial Support Policy Strategy for Avian Influenza: Emergency Recovery and Rehabilitation of the Poultry Sector in Vietnam*. Esard working paper. Washington, DC: The World Bank (2005).
28. USDA. *GAIN Report Number:VM9027 - African Swine Fever in Vietnam.* (2019). Available online at: https://apps.fas.usda.gov/newgainapi/api/report/downloadreportbyfilename?filename=African%20Swine%20Fever%20in%20Vietnam_Hanoi_Vietnam_6-20-2019.pdf (accessed March 5, 2021).
29. Scholl K, Markemann A, Megersa B, Birner R, Zarate AV. Impacts of projects initiating group marketing of smallholder farmers – a case study of pig producer marketing groups in Vietnam. *J Cooperat Organiz Manag.* (2016) 4:31–41. doi: 10.1016/j.jcom.2016.03.002
30. Lapar ML, Vu TB, Nguyen TS, Tiongco M, Jabbar M, Staal S. The role of collective action in overcoming barriers to market access by smallholder producers: some empirical evidence from northern Vietnam. In: *Research Workshop on Collective Action and Market Access for Smallholders, 2–5 October 2006.* Cali (2006).
31. Barrett CB, Reardon T, Webb P. Nonfarm income diversification and household livelihood strategies in rural Africa: concepts,

dynamics, and policy implications. *Food Policy.* (2001) 26:315–31. doi: 10.1016/S0306-9192(01)00014-8
32. Chenais E, Boqvist S, Emanuelsn U, von Brömssen C, Ouma E, Aliro T, et al. Quantitative assessment of social and economic impact of African swine fever outbreaks in northern Uganda. *Prev Vet Med.* (2017) 144:134–48. doi: 10.1016/j.prevetmed.2017.06.002
33. Gramig BM, Horan RD, Wolf CA. Livestock disease indemnity design when moral hazard is followed by adverse selection. *Am J Agric Econ.* (2009) 91:627–41. doi: 10.1111/j.1467-8276.2009.01256.x

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

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

Copyright © 2021 Nguyen-Thi, Pham-Thi-Ngoc, Nguyen-Ngoc, Dang-Xuan, Lee, Nguyen-Viet, Padungtod, Nguyen-Thu, Nguyen-Thi, Tran-Cong and Rich. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.

frontiers in Veterinary Science

ORIGINAL RESEARCH
published: 18 November 2021
doi: 10.3389/fvets.2021.687708

Investigating the Socio-Economic and Livelihoods Impacts of African Swine Fever in Timor-Leste: An Application of Spatial Group Model Building

Jared Berends[1,2]*, *Joanita Bendita da Costa Jong*[3], *Tarni Louisa Cooper*[4,5], *Kanar Dizyee*[2], *Olavio Morais*[3], *Abrão Pereira*[6], *Dominic Smith*[5,7] and *Karl M. Rich*[2,8]

[1] The New Zealand Institute for Plant & Food Research Limited, Auckland, New Zealand, [2] International Livestock Research Institute, West Africa Regional Office, Dakar, Senegal, [3] Ministry of Agriculture and Fisheries, Government of Timor-Leste, Dili, Timor-Leste, [4] School of Veterinary Science, The University of Queensland, Gatton, QLD, Australia, [5] School of Agricultural and Food Sciences, The University of Queensland, St. Lucia, QLD, Australia, [6] Menzies School of Health Research, Dili, Timor-Leste, [7] Griffith Asia Institute, Griffith University, Brisbane, QLD, Australia, [8] Ferguson College of Agriculture and Department of Agricultural Economics, Oklahoma State University, Stillwater, OK, United States

OPEN ACCESS

Edited by:
*Erika Chenais,
National Veterinary Institute, Sweden*

Reviewed by:
*Tamsin Sarah Barnes,
The University of Queensland, Australia
Anne Conan,
City University of Hong Kong, Hong Kong SAR, China
Alexis Delabouglise,
Institut National de la Recherche Agronomique (INRA), France*

***Correspondence:**
*Jared Berends
Jared.Berends@gmail.com*

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

Received: 29 March 2021
Accepted: 18 October 2021
Published: 18 November 2021

Citation:
Berends J, Bendita da Costa Jong J, Cooper TL, Dizyee K, Morais O, Pereira A, Smith D and Rich KM (2021) Investigating the Socio-Economic and Livelihoods Impacts of African Swine Fever in Timor-Leste: An Application of Spatial Group Model Building. Front. Vet. Sci. 8:687708. doi: 10.3389/fvets.2021.687708

Small-scale pig farming is highly important to the economic and social status of households in Timor-Leste. The presence of an African Swine Fever (ASF) outbreak in Timor-Leste was confirmed in 2019, a major concern given that around 70% of agricultural households practice pig farming. This research used a virtual spatial group model building process to construct a concept model to better understand the main feedback loops that determine the socio-economic and livelihood impacts of the ASF outbreak. After discussing the interaction of reinforcing and balancing feedback loops in the concept model, potential leverage points for intervention are suggested that could reduce the impacts of ASF within socio-economic spheres. These include building trust between small-scale farmers and veterinary technicians, strengthening government veterinary services, and the provision of credit conditional on biosecurity investments to help restock the industry. This conceptual model serves as a starting point for further research and the future development of a quantitative system dynamics (SD) model which would allow *ex-ante* scenario-testing of various policy and technical mitigation strategies of ASF outbreaks in Timor-Leste and beyond. Lessons learned from the blended offline/online approach to training and workshop facilitation are also explored in the paper.

Keywords: African Swine Fever, spatial group model building, Timor-Leste, value chain, livelihoods

INTRODUCTION

Small-scale pig farming plays a vital role within Timorese economic and social spheres. Across both urban and rural settings, over 70% of agricultural households raise pigs, with the average household keeping fewer than three pigs (1). Pigs are kept by around 114,598 households with a national herd total of 453,444 (1). The most common pig production system is an extensive scavenging system, with only a small portion of pigs raised in confined smallholder semi-intensive and intensive systems (2). Pigs are highly valued for cultural ceremonies, with pork consumption outside of these times being relatively low (3). Such is the value placed on pigs that households will continue to purchase them for cultural purposes even when they are unable to supply them from their own household farms. The significant cultural value is reflected in the high monetary price of pigs in Timor-Leste. The average herd of a small-scale farmer is valued at US$ 1200, making pigs the largest contributor to household incomes from the livestock sector (2, 3). This is a significant savings stock in a country where 70% of the population lives on less than US$ 3.20 per day (3).

Since independence in 2002, Timor-Leste has made strides toward socio-economic progress as evidenced by steady rises in nominal income per capita (US$ 508 in 2002–US$ 1237 in 2018) and the Human Development Index (0.505 in 2000–0.626 in 2018). The economy remains largely dependent on oil and gas, which accounts for around 33% of total GDP, and finances 90% of the state budget (4). Most of Timor-Leste's population of 1.2 million people are not involved in formal regular employment; instead, households depend upon multiple small livelihood activities and subsistence agriculture (4). Around 41.8% of the population live below the national poverty line with undernourishment of under-five children a persistent issue (5). As found in other Southeast Asian countries, household pig farming in Timor-Leste functions as an important livestock bank for the poor; pigs are sold during times of financial stress or to fund lumpy expenses, such as education costs.

The presence of an ASF outbreak in Timor-Leste was confirmed in September 2019. Before testing was scaled back due to COVID-19 restrictions, it had spread to eight out of 13 municipalities. Within 6 months of detection, nationwide mortalities had exceeded 50,000 pigs, around 11% of the national herd (2). Underpinning the potential for widespread socio-economic impacts of an ASF outbreak is the chronic under-investment in the veterinary sector and the important role pig farming plays in livelihoods and cultural ceremonies, particularly for the most vulnerable households sitting below or around the poverty line (3, 6).

The need for an analytical tool to evaluate the potential impact of ASF on small-scale pig producers and their livelihoods and the future opportunities to restock pig herds after an ASF outbreak motivates the use of a systems approach. We deployed a system dynamics (SD) approach to capture and model the multiple feedback effects within the pig value chain (VC) system, particularly the interactions between small-scale producers, household savings, disease outbreak, and the veterinary system. A unique advantage of SD approaches is that models of the system can be co-created with community members and other stakeholders through a well-documented process known as group model building (GMB) (7). In a recent evolution of GMB, spatial aspects and drivers of livestock systems have been incorporated within a process termed spatial group model building (SGMB), enriching the scope of information gathered through stakeholder facilitation and improving model design and outputs (8, 9).

This paper covers the process and tools used to pilot SGMB in Timor-Leste to understand the feedback loops and relationships that contribute to the socio-economic and livelihoods impacts of the recent ASF outbreak. A simple conceptual model of the socio-economic impacts of ASF within small-scale pig farming systems is presented. This concept model indicates several prospective feedback loops which drive behavior in the pig VC in Timor-Leste. Following a discussion on the interaction of reinforcing and balancing feedback loops, potential leverage points for intervention are suggested that could reduce the impacts of ASF within socio-economic spheres. Two critical innovations, one methodological and one practical, which enhance our knowledge of the livelihoods impacts of animal disease are also highlighted in the paper. First, to the research team's knowledge, participatory SD methods have not previously been used in Timor-Leste. The paper demonstrates that SGMB tools provide a simple and effective platform for VC actors to exchange perspectives and come to a common understanding on the key dynamic relationships which determine impacts in livestock systems. Second, the work in Timor-Leste piloted a hybrid online/offline form for participatory engagement given COVID-19 travel restrictions, which is elaborated upon in this paper as an example for future applications.

MATERIALS AND METHODS

Overview of SD and SGMB Methodology

SD approaches are increasingly used to construct qualitative and quantitative models of agricultural systems and VCs (10–13). SD is a modeling and analytical paradigm developed during the mid-1950s by Professor Jay W. Forrester. At its core, SD is an approach to solving problems based on dynamic behavior in complex systems and it has since been applied in diverse fields, such as economics, public policy, environmental studies, defense, commodity cycles, and management (14). SD practitioners develop models as a means of understanding the consequences of behavior resulting from interactions and feedback between different actors and/or decisions. Within SD modeling, systems are represented by stocks, flows, converters, and feedback loops. Stocks reflect the state of the system at a given point in time, and represent, for example, an accumulation of services, goods, funds, or knowledge. Flows denote changes over time and regulate the inflow and output of goods or services from a stock, with converters determining the rate of flows over time or affecting other converters. Feedback loops are circular causalities that regulate flows through delayed circular causal (and often nonlinear) relationships among model components (15). Recently, SD models have been deployed to conduct *ex-ante* impact assessments of livestock sectors in countries such as Botswana (16, 17), Namibia (18), Indonesia (19), and Myanmar (20). This has also included previous application in Uganda in the context of measures to mitigate an ASF outbreak across VC actors (21).

The process of GMB co-creates SD models through facilitation with stakeholders in focus group discussions (7). These models provide a platform for stakeholders to jointly analyze the impacts and trade-offs of potential policy or technical interventions prior to investments being made, thus leading to a more robust decision-making process that is co-owned by the group. The SGMB process builds upon the widely used tools and techniques developed within GMB methods. GMB and SGMB sessions typically comprise of 10–15 people; larger groups slightly complicate the use of participatory GIS (Geographical Information Systems) techniques (9). These sessions act as focus group discussions and should comprise a diverse set of VC stakeholders, with balance in terms of roles and gender carefully maintained. They are facilitated by a team which typically includes a lead facilitator, assistant facilitator, note takers, a process coach who manages and supervises the team, and a lead modeler who converts focus group discussions into working SD models (7, 9). While some of these roles can be combined, a minimum of three people is needed to facilitate these sessions, with the role of the lead facilitator, note taker, and modeler always distinct. Agendas for each session are carefully planned and aim to provide a roadmap for each GMB session, guiding the facilitation team in the process, team roles and behaviors, time available, and desired outputs (22, 23). Training of the facilitation team, including mock sessions, is an integral precursor to the process with a particular focus on the team's attitudes, skills, and teamwork (7). Within SGMB, a reference group of technical experts complements the focus group discussions with VC stakeholders. The reference group provides feedback and an external reality check on the process and information collected through regular discussions, which can be through a combination of formal meetings and/or *ad hoc* interactions (emails, phone calls, etc.) (24).

Both SGMB and conventional GMB techniques lead focus group discussions through "scripts," which are a set of guided activities aimed at achieving a specific objective in the facilitation and modeling process (23). The initial scripts in a set of GMB sessions seek to organize the process (logistics, participant invitations, etc.), introduce the approach to stakeholders, gauge participant expectations through a "Hopes-and-Fears" exercise, and introduce basic concepts of systems thinking (stocks, flows, converters, feedback loops) by using simple, practical examples. Conventional GMB sessions then move toward the facilitation of key system variables and reference modes with stakeholders (i.e., dynamic trends of behavior) (25). By contrast, SGMB sessions follow the introductory scripts with an extended participatory exercise using principles of GIS. A participatory facilitation tool, known as Layerstack, was previously developed to help facilitators and participants come to a common, visualized understanding of the system (8). Layerstack is a type of offline GIS in which plastic acetates serve as data "layers" overlaid on a base map of the region in question. Layer definitions are pre-defined by the facilitation team and can include patterns of trade, land use, socio-economic characteristics, and animal disease outbreaks. Various consumables (stickers, markers, post-it notes) are used to label spatial characteristics by participants, and reference modes and running legends are directly drawn on the edges of the map to illustrate trends in spatial variables.

From the Layerstack exercise, which typically takes place over a 90- to 120-min period, a subsequent set of scripts are implemented that identify and prioritize problems; elucidate the causes and consequences of prioritized problems; and reveal core system modules for further stakeholder-led modeling and identification of parameters and model structure (9). In previous applications, four to five SGMB sessions were held over a 6- to 8-week period culminating in the initial concept model with quantified parameters. Subsequent work by the facilitation team further refines and parameterizes the model developed with stakeholders (and informed by the reference group) over the following few months, after which a finalized quantitative SD model is presented to participants for wider feedback and refinement. Available primary and secondary data complement the process; in some cases, a rapid VC analysis using conventional techniques precedes the SGMB sessions (20, 26). The quantitative SD model is validated by stakeholders to ensure it is an accurate representation of the system, and through a series of standard tests, including ensuring parameters hold real-world meaning and the model is able to replicate historical trends [see Forrester and Senge (27)]. Following validation the model is used to conduct an *ex-ante* impact evaluation of potential intervention scenarios. The results of scenario-testing are then shared with stakeholders to support decision-making and encourage the ownership of recommendations (7).

Research Team

Researchers from the University of Queensland (UQ) and the International Livestock Research Institute (ILRI) partnered with six staff from Veterinary Services within Timor-Leste's Ministry of Agricultural and Fisheries (MAF) and Menzies School of Health Research (MSHR) to conduct the field research. Due to COVID-19 travel restrictions, UQ and ILRI conducted online training and provided support for MAF and MSHR staff who facilitated the three face-to-face SGMB workshops in Dili, Timor-Leste with 13 participants from the pig VC. Ethical clearance (approval number 2020001543) was obtained from UQ prior to conducting the research.

Training of the SGMB Team

Training on SD and SGMB was conducted in June 2020 and led by ILRI team members. MAF and MSHR staff participated in six initial online training sessions of 90–120 min, covering: (i) an introduction to systems thinking and SGMB; (ii) how to plan an SGMB process; and (iii) how to use key SGMB tools (Layerstack, cause and consequence mapping, and the development of concept modules). Training sessions were conducted online via Zoom (https://zoom.us/) and utilized a range of online engagement tools, such as Padlet (https://padlet.com/), Jamboard (https://jamboard.google.com/), and Vecta (https://vecta.io/). Padlet is a document storage system which allows easy access to training materials and contained links to the Jamboard and Vecta web pages. Jamboard is a web-based platform operated by Google for real-time collaboration and brainstorming, providing a simple way of replicating a whiteboard online. It allows participants to write sticky notes and link/cluster them together by color or with freehand text in a shareable fashion with others in the workshop. Vecta is a free online editor for collaborative graphics editing. It mimics the participatory GIS features of Layerstack by including a feature whereby layers of information can be overlayed on top of one another. While training activities covered critical points of SD and SGMB theory, sessions were weighted toward the use of the tactile participatory modeling tools to build the skills and confidence of MAF and MSHR staff to facilitate critical elements of upcoming SGMB sessions.

Following the formal training workshops, another two sessions were held to develop the agendas (included in this article's **Supplementary Materials**) for the three SGMB workshops and to conduct a practice run of participatory tools. These practice runs helped MAF, MSHR, and ILRI researchers to trial different workshop techniques, ultimately settling on a blended online and offline approach. This approach consisted of MAF and MSHR staff facilitating in-person SGMB workshops using tactile participatory tools and a virtual coaching presence from ILRI and UQ using Zoom and WhatsApp (https://www.whatsapp.com/) voice and video technologies. Additional MAF staff joined these practice sessions to act as mock workshop participants. Further one-to-one coaching sessions were held with facilitators in the days leading up to the SGMB workshops to respond to questions around facilitation techniques of participatory tools.

SGMB Process

Given that the focus of the study was to pilot SGMB tools to develop a simple concept model, it was decided to shorten the process to three workshops. These were held at the MAF office in Dili, Timor-Leste over a 10-day period in August 2020. Workshops were scheduled to last for half a day, starting in the morning and concluding with a lunch for attendees. The MAF and MSHR team selected Tasi Tolu, a peri-urban area in Dili as the model's boundary because of the mixture of urban and rural villages and the accessibility of workshop participants. MAF and the MSHR were confident that pig farming in Tasi Tolu was broadly representative of practices throughout Timor-Leste with workshop participants recruited by MAF staff through their networks of local veterinary offices in Tasi Tolu, i.e., purposive sampling. A total of 13 participants from across the pig VC attended workshop one, which dropped to 12 for workshop two and nine for workshop three. Of the 13 participants, two were female, and while most participants identified themselves as pig farmers (9), pig traders (2) and veterinary technicians (3) also attended. The attending pig farmers were backyard producers, typically keeping between two to five hogs at any given time. Workshop dropouts came from pig trader and producer segments of the VC. SGMB workshop one and two were held on consecutive days and SGMB workshop three 9 days later which may explain the drop in attendance. Participant travel costs were reimbursed and they were provided with participation certificates from MAF.

MAF and MSHR staff facilitated the workshops, playing the key SGMB roles of lead facilitator, assistant facilitator, and note taker. Additional roles were added to the in-country team given the blended workshop approach. A liaison/translator role was established to maintain a virtual connection with the team from ILRI who fulfilled the process coach roles. The liaison/translator would translate critical elements and act as the process coaches' "voice" into the workshop. This allowed researchers from ILRI to ask further questions and provide nuanced course correction during participatory exercises. During breaks in the workshop, the process coaches were able to speak directly to the lead facilitator, providing additional feedback and encouragement. Two video links between the process coaches and the workshop were maintained by way of a broad camera link that captured the entire workshop space (via Zoom) and a second handheld camera link (via WhatsApp) through which the liaison/translator could show details of workshop outputs, such as Layerstack maps. The modeler function was undertaken by a member of the ILRI team who also acted as one of the process coaches.

The objective of the first workshop was to introduce SD and SGMB principles to workshop participants and to use Layerstack to understand the spatial dynamics of the pig VC and the socio-economic impacts of ASF. The hopes-and-fears exercise (9) at the start of the workshop helped address any concerns or misunderstandings held by participants. This proved useful in unearthing an assumption held by some attendees that the workshop was a training on ASF. These participants readily accepted the facilitator's explanation that the purpose of the workshop was to co-create a model to learn more about the socio-economic impacts of ASF. The physical Layerstack toolkit previously used to conduct participatory GIS exercises (9) was not available due to COVID-19 related postal delays. As such, the underlying A3 map of Tasi Tolu was taped to the workshop wall and plastic sheets overlaid onto it to collect the layered spatial and temporal information. Following an introduction to Layerstack, 15 min was allocated for each of the five layers that covered (i) pig production zones; (ii) key inputs and services for pig production; (iii) the movement of pigs from pig production zones to other VC nodes (i.e., villages, traders, butchers, wholesalers, retailers); (iv) other livelihood practices and their contributions to household incomes and socio-economic status; and (v) impact of ASF on livelihoods. A prioritization exercise on problems related to ASF elucidated during Layerstack was then conducted. Participants individually wrote down one key problem and after a brief summary of the problems by the facilitator, participants voted for their top problem, ultimately prioritizing (i) the lack of technical veterinary services available and (ii) the loss of household income from pig farming.

The second SGMB workshop began with a recap of these two problems and an introduction to the basic terminology of SD (stocks, flows, and converters) using the water-in-a-glass script (9). Following this, cause-and-consequence maps of the priority problems were constructed. To initiate this interaction, a plenary discussion on the nature of the problems was held, culminating in the development of reference modes on the whiteboard which included temporal and spatial characteristics of the problems. The reference mode is a visualization of the current trend and trajectory of a problem over time. It is used to help characterize and describe the problem and ensure there is consensus among participants as to its nature and evolution. Reference modes utilize "behavior over time" graphs; in this research, this consisted of drawing out the pig population over the last 10 years and the last year. Next, participants identified and discussed the problem's root causes and expanded consequences which were placed on the whiteboard. The causal relationships and key feedback loops which drive system behavior were then identified by participants by asking them to identify consequences of problems that circled back to alter original problem causes. Based on the issues and relationships identified in the cause-and-consequence maps, participants and the facilitation team selected four thematic areas that govern behavior in the pig VC system during an ASF outbreak. These thematic areas became the modules for further development using SD terminology: pig production, veterinary services, socio-cultural practices, and farm finances; ultimately acting as the concept model's boundary. The 8-day space between workshop two and three enabled the modeler from ILRI to develop simple preliminary stock and flow diagrams of these modules for expansion in the third workshop.

The aim of the third SGMB workshop was to develop simple qualitative concept modules using basic SD terminology to capture participant understanding of the relationships in the pig farming system and the impacts of ASF. Concept modules are a qualitative tool that visually represents the most critical parts of any system (i.e., a closed boundary) and capture dynamic complexity by documenting the polarity of relationships between stocks, flows, and converters, and the identification of feedback loops and time delays (14). Following a refresher on these key SD concepts, the facilitator presented the preliminary stock and flow diagrams to participants and added structure based on their feedback and responses to question prompts. These diagrams were sketched on whiteboards to allow for their iterative development and included the polarity of relationships (i.e., the direction of cause and effect relationships) and feedback loops identified. Once the structures of the individual modules were developed, they were then combined to pinpoint inter-module connections. Following the third workshop the concept model was revised by the modeler and shared with the research team for finalization.

RESULTS

Overview of the Pork Value Chain

Along with the development of the concept model, the SGMB workshops helped frame the underlying problems and behaviors in the pig system in Tasi Tolu. Participants noted that there had been a steady decline in pig stocks in the target area over the last 5 years related to the application of a law that banned the free roaming of pigs in urban areas. Without the ability to let their pigs roam, pig farmers faced increased housing and feed costs. Pig feed mainly came from leftover household food and restaurant scraps. Piglets were usually purchased from within or nearby villages but there was no formal credit mechanism to help farmers restock after frequent disease outbreaks. Very few of the farmers had a relationship with the local veterinary technician (VT) and relied on traditional methods or medicine purchased from the local agricultural input supplier to maintain healthy pigs. None of the farmers present vaccinated their pigs. Farmers retained their pigs for traditional cultural purposes but also sold to neighbors and the local pork wholesale market when the household required cash. These pig sales typically comprise 20–30% of the household's yearly cash income. This supplements the other main livelihoods in the area of fishing, small livestock raising (goats, chickens, and ducks), operating small consumer supply shops, and selling of smoked fish and palm syrup. While income from other livelihoods would generally enable pig farmers to restock following a disease outbreak, the scarcity and high price of piglets and sows following the recent ASF outbreak had prevented many farmers from reinvesting. The ASF outbreak had also caused a high-level of mistrust in the system, as farmers were worried that they could not prevent or contain a future ASF outbreak nor could they verify the health of pigs and piglets flowing into their village.

The SGMB participants prioritized two main problems in the pig system that exacerbated the current situation. First, there was a lack of technical veterinary services available to pig farmers. While there is a general standard of one VT per administrative post, it was acknowledged that this is insufficient to meet the requirements of farmers, with SGMB members suggesting village-level workers were necessary. Along with a lack of human resources, existing VT lacked transportation and communication equipment to conduct regular visits to villages. Some participants noted that government revenue from pigs was low and therefore this decreased the incentive to invest in support services. The second problem identified centered on the loss of household income from pig farming. With limited access to formal financial services and high prices, farmers were unable to invest in pig farming, robbing them of a vital safety net. Hogs were often kept and sold to cover lumpy household cash requirements, such as school fees and uniforms or investments in other livelihoods, such as purchasing new fishing equipment or stock for shops. Furthermore, hogs were required for cultural ceremonies like weddings and funerals. The lack of hogs and high purchase prices further exacerbated the loss of household savings and potentially alienated households from relatives who often form a reciprocal social safety net.

Concept Model of the Timor-Leste Pig System

The key output of the research process is a basic concept model of the pig system in Timor-Leste, as shown in **Figure 1**. The concept model was developed by participants over the course of the SGMB workshops and later refined by the research team. All participants actively engaged in the model building process, though the three male veterinary technicians were the most active. Originally the concept model was to be shared with participants and other stakeholders for comments, though time limitations prevented this verification step. This concept model includes interactions between production practices, livelihood and socio-economic and cultural dimensions, farmer knowledge, and animal health infrastructure that determine system responses to an ASF outbreak.

The SGMB process identified prospective feedback loops that drive system behavior. These loops are denoted as "R," Reinforcing or "B," Balancing feedback loops in **Figure 1**. Reinforcing feedback loops amplify behavior and when activated result in either exponential growth or decay (28). In contrast, the balancing feedback loop is a self-adjusting loop that seeks to counteract and oppose change, thus balancing the

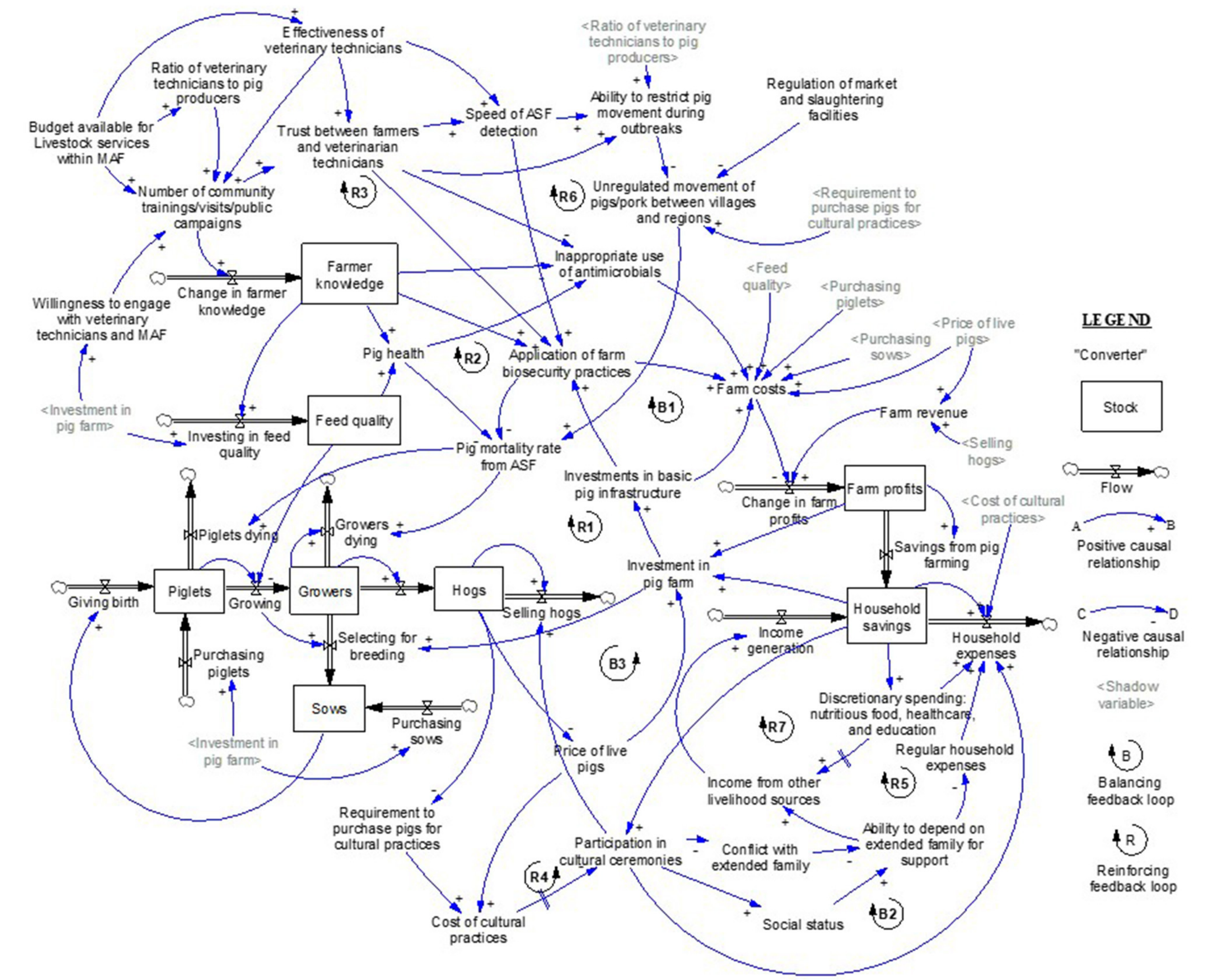


FIGURE 1 | Concept model of the Timor-Leste pig system, including interactions between marketing dynamics, production practices, livelihoods and socio-cultural dimensions, farmer knowledge, and animal health infrastructure. Gray parameters are repeated "shadow" variables from the concept model. "R" indicates reinforcing feedback loops and "B" indicates balancing feedback loops in the system. Unboxed text represents key converters (also known as parameters) in the model while boxed text represents key stocks in the system and black arrows show flows into and out of these stocks. Blue arrows show critical casual relationships between stocks, flows, and converters with the + sign indicates movement in the same direction as the origin of the change and the—sign indicates movement in the opposite direction to the origin of change.

system to some level of stasis or equilibrium (14). A brief explanation of the core feedback loops follows. To aid understanding of the concept model, relationships within certain loops are described in unidirectional terms, i.e., increasing or decreasing; however, all feedback loops can operate in either direction (28). A figure of each individual loop is found in the **Supplementary Materials B**.

R1: Farm Production Investments

Changes in profits alter farmer willingness to invest in pig farming, which causes farmers to expand/contract the size of their pig farms through changing the number of breeding sows and the volume of piglets purchased. This affects the number of hogs sold and leads to further increases/decreases in farm profits.

R2: Farm Biosecurity/Health Investments

Changes in farm profits affect investments in pig feed, infrastructure (pig pens, watering systems, etc.), and the willingness of farmers to engage with (and pay for the services of) VT and MAF staff. This in turn impacts a farmer's application of biosecurity practices and the level of pig health, altering the pig mortality rate from diseases, such as ASF. Changes in mortality rates alter the proportion of pigs dying, affecting the number of hogs sold, leading to further changes in farm profits.

B1: Farm Costs

Increasing investments in pig production and biosecurity/health investments lead to higher farm costs which lower profits and reductions in these investments.

R3: Trust

Trust between VT and farmers increases when they engage more frequently through trainings, field visits, and public awareness campaigns, and advice provided by VT increases farmer knowledge and improves pig health. As trust grows, farmers are more likely to report unexplained pig deaths to VTs, allowing earlier detection of ASF and the prompter application of farm biosecurity practices and adherence to movement restrictions between villages and regions. These lessen the pig mortality rate from ASF which results in higher farm profits and household savings, leading to higher post-ASF outbreak investments in pig production and an increased willingness of farmers to engage with VT and MAF staff. The increased trust also prevents the inappropriate use of antimicrobials, lessening farm expenditure and further increasing farm investments and trust with VTs and MAF.

R4: Providing Hogs for Cultural Practices

When hog numbers in a village decrease, farmers must increasingly purchase pigs for cultural purposes rather than using pigs from their own stocks. As pig stocks reduce this further inflates the price of purchasing pigs and the financial cost of cultural practices. Given the high cultural value placed on pigs, there is a delay between the rising costs of cultural practices and reduced participation in cultural ceremonies. Until this point is reached, purchasing pigs for cultural practices increases household expenditure and draws down household savings, reducing the ability of farmers to reinvest in pig farming and furthering lowering the overall number of hogs in the system.

B2: Reducing Participation in Cultural Practices

When household savings fall and the price of live pigs increase, at some point, households lessen their participation in cultural ceremonies involving the use of pigs or other livestock. The reduction in demand to purchase pigs for cultural ceremonies causes stocks of hogs to rise. This lowers the price of live pigs, reducing the financial costs associated with cultural practices and increasing household savings which leads households to start participating in cultural ceremonies again.

R5: Social Capital

When farmer participation in cultural ceremonies falls, there is a loss of face and less contact time between family members. As a result, the likelihood of misunderstanding and conflict with extended family members rises, and household social status falls, both of which decrease the ability to depend on extended family members for support. This lessens the ability of households to generate income from other livelihoods or meet regular household needs through gifts-in-kind or cash provided by extended family members. This reduces the stock of household savings and further limits the household's ability to participate in cultural ceremonies.

R6: Movement of Pigs

When the number of hogs in one geographic location decreases, people purchase hogs from another village/region for cultural practices, increasing the movement of pigs across the country. This growth in movement raises the rate of spread of ASF across Timor-Leste, leading to further pig deaths and a shortage of hogs.

R7: Poverty Spiral

As household savings decrease, the household's ability to purchase nutritious food, healthcare, and education fall which, after some time, will negatively impact their ability to generate earning, thereby further reducing household savings.

B3: Restocking

As the number of hogs in the system decreases the price of live pigs rise, incentivizing investment in pig farming. This increases the number of hogs in the system and diminishes the price of live pigs.

DISCUSSION

Leverage Points

The concept model of the pig VC allowed the identification of potential leverage points to help mitigate the socio-economic impacts of an ASF outbreak in Timor-Leste. Leverage points are parts of the system that, when changed, can multiply positive impacts through the rest of the system by their ability to influence critical feedback loops.

Firstly, trust building between small-scale pig farmers and VT is a possible catalytic intervention. The concept model shows that increased trust and connection points assist prevention, reaction, and recovery from an ASF outbreak. In the R3: Trust loop, repeated farmer engagements with VTs and MAF increases farmer technical knowledge, fuelling investments in quality feed, improving biosecurity practices, and strengthening the use of appropriate antimicrobials. Along with repeated exchanges, the quality of the services provided by VT and MAF also strengthens trust. When increased knowledge and investments in good animal husbandry practices result in noticeably lower pig mortality rates, farmers strengthen their links with VTs and MAF, reinforcing knowledge gains and farm investments (R1 and R2).

As trust and connection points grow with MAF, small-scale pig farmers are more likely to report pig deaths and adhere to movement restrictions during outbreaks, working to decrease the mortality rate. The promotion of pig producer groups (PGs) as a possible intervention strategy can facilitate this process as they can foster adherence to group biosecurity rules, peer-to-peer learning, and lower monitoring costs for MAF (29). A high degree of group trust based on the social capital and social relationships of farmers has been shown as critical for PG success in Timor-Leste (30). Another critical aspect of whether farmers gain or lose trust in the system is the effectiveness of investments. In other words, do investments in biosecurity, infrastructure, and good animal husbandry practices prevent the acceleration of the R4 (providing hogs for cultural events), R5 (social capital), and R7 (poverty spiral) loops and enable pig farmers to "hang on" during a disease outbreak and later reinvest in pig farming? The ability to come through a shock like ASF with stock or capital for reinvestment has a positive impact on the whole system as it allows the number of hogs in the system to rebound quickly again and stabilizes the price of live pigs, allowing for a gradual reinvestment and restocking by farmers hardest hit by the disease. This suggests a public-private-partnership approach could be beneficial in not only creating win-win solutions to ensure continuing pig supplies but also to improve trust among the system actors, such as input suppliers, traders, and retailors.

Secondly, strengthening the capacity of MAF to provide effective services will further increase trust in the system. This entails having enough VTs to ensure pig producers can access applicable training, quality veterinary services, and timely information on disease outbreaks and preventative measures. The perceived and actual quality of services plays a critical role as pig farmers' trust and engagement depends on the perceived benefit of VT services (i.e., improved pig health, early detection of disease outbreaks, lower mortality rate) outweighing time and financial costs. Strengthening MAF services operates directly on feedback loops R2 (knowledge gains leading to improved pig health and biosecurity practices), which is countered by B1 (increasing costs) to determine if the R1: Farm investment loop operates in a virtuous manner which stimulates the R3: Trust loop. Increasing MAF capacity comes at a cost to the government of Timor-Leste as funds would need to be diverted from other government priorities. To ensure sustainability of MAF services and continuing activation of the R3 loop, institutional arrangements and fee gathering mechanisms that can lessen the financial burden on MAF should be investigated. Examples that could be considered (and later modeled) include PGs, Village Livestock Workers, and co-payments for VT services.

Lastly, following an ASF outbreak, support should be given to help pig producers restock their farms. Start-up loans or cash grants could be provided to small-scale pig farmers conditional upon application of farm biosecurity practices. In this system, the strong demand for live pigs for cultural practices may keep the price of restocking pig farms beyond the financial ability of the poorest small-scale farmers, particularly those who exhausted household savings due to the presence of the R4: Providing hogs for cultural purposes loop. Even when the B2 loop is activated, and farmers reduce their participation in cultural practices this may further exacerbate the R7: Poverty Spiral loop as the R5: Social capital loop may have caused a reduction in household savings. Providing microloans or cash grants to restock pig farms could help to stabilize live pig prices, lower the costs of cultural practices, and steady social capital stocks. Importantly, loans or grants would also ensure the B3: Restocking loop is activated, increasing the scale and diversity of small-scale farmers who re-engage in pig farming. If these loans or grants are made conditional upon investments in biosecurity practices and attendance at VT training, they would lower the susceptibility of the pig industry to future disease shocks and help activate the R3: Trust loop. Microfinance loans have been criticized for delivering modest pro-poor outcomes, potentially causing over-indebtedness, and delivering mixed performance in the SME sector (31). Moreover, the unsuitability of many MFI loan products to the agriculture sector is often highlighted, citing short loan terms that do not synchronize well with farm production cycles and regular repayment schedules that preclude borrowers from undertaking investments in lumpy assets (32). Different financial products should therefore be investigated and modeled for their impact on the system, including letters of credit, standby loans, and graduated/deferred interest loans that allow farmers to maintain positive cashflows, the latter of which are particularly critical given the high set-up and production costs and lengthy production cycles inherent to pig farming (20). The lengthy production cycle of pigs may result in continued price rises that could potentially harm farmers who did not access these credit facilities. The impact of microcredit across different farmer archetypes could be further tested by developing a quantitative SD model and comparing microcredit against other restocking options, such as importing breeding stock from neighboring regions.

Blended SGMB Process

The blended offline and online nature of the SGMB workshops necessitated by travel restrictions was unique to this study and several lessons emerged that can be applied to similar processes in the future. The offline, tactile SGMB tools encouraged strong levels of participation from a diverse set of stakeholders and information surfaced in discussions which was new and pertinent to the MAF team. SGMB exercises follow in the rich vein of easy-to-understand participatory rural appraisal (PRA) methods (33) with the aim of drawing multi-layered contextual knowledge and facilitating robust discussions that change the mental models of participants (7). The research showed that following online training sessions that focused on theory with multiple offline opportunities to practice helped build the confidence of MAF staff to use these new tools. Early in the process the research team discussed moving participatory exercises to a full online approach; for example, using Vecta for the Layerstack exercise. This was trialed during the training of the SGMB team and slow internet speeds, intermittent loss of power and connectivity, and the unfamiliar nature of the tools combined with feedback from MAF and MSHR staff led to the development of a blended approach: offline for workshop participants but online for coaching and support of the facilitation team.

The use of two video links helped the remote process coaches guide the facilitation of the SGMB exercises. The broad video link capturing the dialogue and interactions amongst workshop members helped gauge the level of participation and acceptability of the tools (i.e., who was participating, was there active dialogue around key points, were any group members excluded?). Meanwhile, the focused video link was controlled by the translator/liaison, meaning it could be directed to an area of interest in the workshop (i.e., a conceptual model) at the discretion of the process coaches.

While there was little hindrance in remote workshop observation (beyond occasional internet black outs), it proved more challenging for remote process coaches to interject and help steer the workshop in real-time. This was partly due to the time delay in relaying messages through the translator/liaison to the workshop facilitator as well as the language barrier of communicating between Tetum and English. The translator/liaison role was essentially overloaded as the individual had to perform multiple tasks: videorecording the session, translating the workshop dialogue from Tetum to English, communicating with the two process coaches, and then digesting messages to then help coach the facilitator or ask a question to the plenary. As workshops extended into the 5-h mark, this became an exhausting process. For future virtual workshops, it would help to have one member of the facilitation team act as a pure translator who also managed the second video link and then an additional individual as the liaison between the process coaches and the facilitator.

The SGMB workshop exercises consistently went over time and the last exercise from workshops one and two had to be moved to the following session. This shortened the time available to develop concept modules (the final output of the workshops) and did not allow review and consolidation of the concept modules by the modeler between workshops two and three. Delays during the workshop could be overcome through better workshop preparation (having all resource material ready) and less repetition of exercise explanations. However, the nature of virtual process coaches and a first-time facilitation team meant delays were, to an extent, unavoidable. For example, compared to face-to-face facilitation, cues such as body language and participation levels could not be as quickly interpreted, and translations and explanations had to pass through an additional channel (the translator/liaison). Future processes should allow for the additional time required for a blended workshop approach and contain additional workshop sessions. Extra spacing between workshops would also help ensure that the large volume of workshop information collected could be translated and analyzed between workshops and further team members (beyond the lead facilitator) could have an opportunity to prepare with the process coaches. Another option would be to reduce the amount of material covered in each session, having more frequent but shorter duration workshops of 2–3 h. This latter option would have also helped prevent participant fatigue and the higher dropout rates when workshops are spread over several weeks.

The advantages of SGMB over conventional GMB highlighted in this research mirror those observed in Rich et al. (9) in Tanintharyi, Myanmar and Bihar, India. While space is an important distinguishing component and area of added value in SGMB, there are important features of the SGMB facilitation process that streamline the gathering of information and highlight patterns and associations that standard GMB would likely not. For example, the ability of stakeholders to attribute and discuss trade patterns, the evolution of disease outbreaks, and the socio-economic impacts of ASF was enhanced by SGMB. Conventional GMB exercises could eventually draw out this information, but the use of a spatially-mediated tools (like Layerstack) allows that information to be collected at the onset of the workshop so that all participants have a common understanding of the setting which is used as a shared reference in the later model building exercises. From a model building standpoint, the SGMB process, by modularizing system attributes based on space, allowed a richer and more efficient means of model conceptualization, which given the online means of facilitation saved both resources and time. The research team would have liked to probe deeper on the spatial drivers of disease, marketing, and social phenomena, over and beyond what was reported in this paper. The balancing of working with a new in-country team with no previous SD or modeling experience and the newness of all participants to conducting the training and workshop online pre-empted the full potential of the technique. Even with these limitations, the research demonstrated that spatial tools, like Layerstack, can successfully be adapted and used in a blended offline/online setting to generate the information required for fit-for-purpose models.

A number of limitations within this research should be noted as they impact the model's results and applicability to the wider pig industry in Timor-Leste. Literature suggests that participatory processes can be biased toward community members who already wield power (34), prove exclusionary to the marginalized (35), and mask invisible problems and power imbalances (36). The negative impact of power differentials between participants on GMB outcomes is also well documented (7, 37). In this research there were power imbalances amongst participants and between participants and facilitators and this could have inhibited open discussion and dialogue in SGMB sessions. Male participants outnumbered female participants and tended to dominate discussions and in some exercises active participation was limited to a smaller subset of attendees. While SGMB facilitators took steps to encourage all participants to contribute to discussions, the research could have broken into smaller group sessions (three to five participants) and increased female representation in both participants and facilitators to help mitigate gender and power imbalances like in previous GMB studies (24) and prevent "group-speak" (25). Additionally, an experienced gatekeeper embedded in the workshop could have paid attention to this and encouraged broader involvement or transmitted any concerns or questions quickly to the rest of the SGMB team (7). Lastly, participants were selected for the research through the networks of VT associated with MAF. This limited the representation of VC actors in the study and potentially swayed the prioritization of problems.

CONCLUSION

This first-time application of a blended, hybrid online/offline SGMB process in Timor-Leste resulted in a rich conceptual model of the socio-economic and livelihood impacts of ASF in Timor-Leste. While there were additional challenges from the virtual nature of training, coaching, and session facilitation, the resultant model highlighted critical feedback loops which explain system behavior during an ASF outbreak that other animal health impact assessments have not explored. This led to the identification of potential leverage points for intervention by the government of Timor-Leste and development partners.

The next step in the process is to share the concept model for feedback with stakeholders in Timor-Leste, including SGMB participants and MAF staff to ensure the current structure (stocks, flows, feedback loops) accurately represents the system. The concept model was developed using Tasi Tolu as the model boundary, meaning the model and leverage points are influenced by the peri-urban context, i.e., improved access to services, and a restricted group of VC stakeholders. The verification and feedback process would require a wider group of stakeholders to agree that the model and scenarios are representative of the wider country. Once consensus is reached on the basic structure, the concept model could be expanded into a full quantitative SD model. This would require parametrization of the model variables and additional structure to support scenario-testing. As showcased in the paper, the qualitative concept model provides insights into possible leverage points in the system; however, a quantitative SD model would allow a fuller range of scenario-testing of potential interventions and trade-off analysis in terms of impacts across VC actors, time horizons, and resource constraints (i.e., financial and human capital). For example, the impact of start-up loans/cash grants on small-scale farmers could be compared against investments in training and expansion of VT or the introduction of charges for VT services. This would enable a cost-benefit analysis of standalone interventions along with intervention combinations to investigate multiplier effects. A quantitative model would also provide insight into potential negative consequences of interventions, or trade-offs that might exist across the VC nodes or impact dimensions (e.g., economic vs. equity) (10, 17, 21, 26).

The concept model presented in this paper and a future quantitative model could be readily adapted to other areas of investigation in Timor-Leste as further modules are developed and linked. For instance, the household cashflow model can be expanded so that links between investments in the pig VC and household expenditure on healthcare, education, and nutrition can be considered as part of the decision-making on intervention options. Once a robust SD model of the socio-economic and livelihood impacts of ASF in Timor-Leste is constructed and validated, it can be adapted to other contexts and requirements. The high economic and cultural value placed on pigs (38) and the recent outbreak of ASF means the model could be used to similar effect in Papua New Guinea. In countries where ASF is not yet present, such as the Solomon Islands, the model could be adapted to help understand the cost-benefit of various prevention mechanisms.

DATA AVAILABILITY STATEMENT

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

ETHICS STATEMENT

The research received ethical clearance from the University of Queensland Institutional Research Ethics Committee (approval number 2020001543). Informed consent was obtained from all human subjects. The patients/participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

AUTHOR CONTRIBUTIONS

TC, DS, KD, and KR conceived the study. JB, KD, and KR trained the research team and developed the methodology and analyzed the data. AP, JB, JoB, KD, KR, and OM collected the data. JB wrote the first draft of the manuscript. AP, DS, JoB, KD, KR, OM, and TC reviewed and edited the final manuscript.

FUNDING

The research was undertaken within the ACIAR-LS/2019/187 Small Research Activity, Developing a Regional African Swine Fever Socioeconomic and Livelihood Impact Assessment Framework, funded by the Australian Government's Australian Centre for International Agricultural Research.

ACKNOWLEDGMENTS

The authors would like to acknowledge the excellent work of the six MAF and MSHR staff who facilitated the SGMB process. This included organizing participants, preparing the workshop space, and facilitating the sessions as well as attending all the training and coaching sessions.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fvets.2021.687708/full#supplementary-material

REFERENCES

1. Ministry of Agriculture and Fisheries. *National Report on Final Census Results*. (2020). Available online at: http://www.fao.org/fileadmin/templates/ess/ess_test_folder/World_Census_Agriculture/WCA_2020/WCA_2020_new_doc/TLS_REP_ENG_2019_01.pdf
2. Barnes TS, Morais O, Cargill C, Parke CR, Urlings A. First steps in managing the challenge of African Swine Fever in Timor-Leste. One *Health*. (2020) 10:100151. doi: 10.1016/j.onehlt.2020.100151
3. Smith D, Cooper T, Pereira A, da Costa Jong J. Counting the cost: the potential impact of African Swine Fever on smallholders in Timor-Leste. *One Health*. 8:100109. (2019) doi: 10.1016/j.onehlt.2019.100109
4. World Bank. *Timor-Leste Systematic Country Diagnostic: Pathways for a New Economy and Sustainable Livelihoods*. (2018). Available online at: http://documents1.worldbank.org/curated/en/524131528837983427/pdf/TL-SCD-0228B-lowres-03212018.pdf
5. International Food Policy Research Institute. *Global Nutrition Report 2016 From Promise to Impact Ending Malnutrition By 2030*. Washington, DC: International Food Policy Research Institute (2016).
6. Weaver J, Siengsanan J, Tagliaro E. *OIE PVS Gap Analysis Mission Report: Timor-Leste*. (2014). Available online at: https://www.oie.int/fileadmin/Home/

eng/Support_to_OIE_Members/docs/pdf/PVS_Gap_Analysis_FinalReport_Timor_Leste.pdf
7. Vennix JA. *Group Model Building: Facilitating Team Learning Using System Dynamics*. Chichester: Wiley (1996).
8. Rich KM, Rich M, Dizyee K. Participatory systems approaches for urban and peri-urban agriculture planning: the role of system dynamics and spatial group model building. *Agric Syst.* (2018) 160:110–23. doi: 10.1016/j.agsy.2016.09.022
9. Rich KM, Berends J, Cooper GS. Enriching value chains through maps: Reflections and lessons from spatial group model building in Myanmar and India. *Dev Pract*. (2021) doi: 10.1080/09614524.2021.1907545. [Epub ahead of print].
10. Dizyee K, Baker D, Omore A. Upgrading the smallholder dairy value chain: a system dynamics ex-ante impact assessment in Tanzania's Kilosa district. *J Dairy Res.* (2019) 86:440–9. doi: 10.1017/S0022029919000840
11. Dizyee K, Rich KM. A system dynamics approach to chain/network analysis in the primary industry sector: case studies of beef, dairy, and amaranth in the developing world. In: *Paper presented at the 3rd Asia-Pacific System Dynamics Society Conference.* Brisbane, QLD (2020).
12. Lie H, Rich KM, van der Hoek R, Dizyee K. An empirical evaluation of policy options for inclusive dairy value chain development in Nicaragua: a system dynamics approach. *Agric Syst.* (2018) 164:193–222. doi: 10.1016/j.agsy.2018.03.008
13. Rich KM, Ross RB, Baker DA, Negassa A. Quantifying value chain analysis in the context of livestock systems in developing countries. *Food Policy.* (2011) 36:214–22. doi: 10.1016/j.foodpol.2010.11.018
14. Sterman J. *Business Dynamics. Systems Thinking and Modeling for a Complex World*. New York, NY: Irwin/McGraw–Hill (2010).
15. Hamza K, Rich KM, Wheat ID. A system dynamics approach to sea lice control in Norway. *Aquacult Econ Manag.* (2014) 18:344–68. doi: 10.1080/13657305.2014.959210
16. Dizyee K. *A System Dynamics Approach to Chain/Network Analysis in the Primary Industry Sector: Case Studies of Beef, Dairy, and Amaranth in the Developing World* (dissertation). Armidale, NSW: University of New England (2017).
17. Dizyee K, Baker D, Rich KM. A quantitative value chain analysis of policy options for the beef sector in Botswana. *Agric Syst.* (2017) 156:13–24. doi: 10.1016/j.agsy.2017.05.007
18. Naziri D, Rich K, Bennett B. Would a commodity-based trade approach improve market access for Africa? A case study of the potential of beef exports from communal areas of namibia. *Dev Policy Rev.* (2015) 33:195–219. doi: 10.1111/dpr.12098
19. Dahlanuddin, Henderson B, Dizyee K, Hermansyah, Ash A. Assessing the sustainable development and intensification potential of beef cattle production in Sumbawa, Indonesia, using a system dynamics approach. *PLoS ONE.* (2017) 12:e0183365. doi: 10.1371/journal.pone.0183365
20. Berends J, Rich KM, Lyne MC. A pro-poor approach to upgrade value chains in Tanintharyi region of Myanmar. In: *Paper presented at the 3rd Asia-Pacific System Dynamics Society Conference.* Brisbane, QLD (2020). Available online at: https://hdl.handle.net/10568/107462
21. Ouma E, Dione M, Birungi R, Lule P, Mayega L, Dizyee K. African swine fever control and market integration in Ugandan peri-urban smallholder pig value chains: an ex-ante impact assessment of interventions and their interaction. *Prev Vet Med.* (2018) 151:29–39. doi: 10.1016/j.prevetmed.2017.12.010
22. Hovmand PS, Andersen DF, Rouwette E, Richardson GP, Rux K, Calhoun A. Group model-building 'scripts' as a collaborative planning tool. *Syst Res Behav Sci.* (2012) 29:179–93. doi: 10.1002/sres.2105
23. Luna-Reyes LF, Martinez-Moyano IJ, Pardo TA, Cresswell AM, Andersen DF, Richardson GP. Anatomy of a group model-building intervention: building dynamic theory from case study research. *Syst Dyn Rev.* (2006) 22:291–320. doi: 10.1002/sdr.349
24. Lie H, Rich K, Burkart S. Participatory system dynamics modelling for dairy value chain development in Nicaragua. *Dev Pract.* (2017) 27:785–800. doi: 10.1080/09614524.2017.1343800
25. Hovmand PS. *Community Based Systems Dynamics*. New York, NY: Springer (2014).
26. Cooper GS, Rich KM, Shankar B, Rana V, Ratna N, Kadiyala S, et al. Identifying 'win-win-win' futures from inequitable value chain trade-offs: a system dynamics approach. *Agric Syst.* (2021) 190:103096. doi: 10.1016/j.agsy.2021.103096
27. Forrester JW, Senge PM. Tests for building confidence in system dynamics models. In: Legasto AA, Forrester JW, Lyneis JM, editors. *System Dynamics: TIMS Studies in the Management Science*, *Vol. 14*. New York, NY: North-Holland (1980). p. 209–28.
28. Sherwood D. *Seeing the Forest for the Trees: A Managers Guide to Applying Systems Thinking*. London: Nicholas Brealey Publishing (2002).
29. Markelova H, Meinzen-Dick R, Hellin J, Dohrn S. Collective action for smallholder market access. *Food Policy.* (2009) 34:1–7. doi: 10.1016/j.foodpol.2008.10.001
30. Lopes M, Nesbitt H, Spyckerelle L, Pauli N, Clifton J, Erskine W. Harnessing social capital for maize seed diffusion in Timor-Leste. *Agron Sustain Dev.* (2015) 35:847–55. doi: 10.1007/s13593-015-0293-2
31. Banerjee AV, Duflo E. *Poor Economics*. New York, NY: PublicAffairs (2011).
32. Pellegrina LD. Microfinance and investment: a comparison with bank and informal lending. *World Dev.* (2011) 39:882–97. doi: 10.1016/j.worlddev.2011.03.002
33. Narayanasamy N. *Participatory Rural Appraisal. Principles, Methods, and Application*. New Delhi: SAGE Publications (2009).
34. Guijt I, Shah MK. Waking up to power, conflict and process. In: Guijt I, Shah MK, editors. *The Myth of Community*. London: IT Publications (1998). p. 1–23.
35. Kapoor I. The devil's in the theory: a critical assessment of Robert Chambers' work on participatory development. Third *World Q.* (2002) 23:101–17. doi: 10.1080/01436590220108199
36. Mosse D. Authority, gender and knowledge: theoretical reflections on the practice of participatory rural appraisal. *Dev Change.* (1994) 25:497–526. doi: 10.1111/j.1467-7660.1994.tb00524.x
37. Van Nistelrooij LPJ, Rouwette EAJA, Verstijnen IM, Vennix JAM. Power-leveling as an effect of group model building. In: *Proceedings of the 2012 International Conference of the System Dynamics Society*. Albany, NY (2012).
38. Ayalew W, Danbaro G, Dom M, Amben S, Besari F, Moran C, et al. Genetic and cultural significance of indigenous pigs in Papua New Guinea and their phenotypic characteristics. *Anim Genet Resour.* (2011) 48:37–46. doi: 10.1017/S2078633611000026

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

The reviewer TSB declared a shared affiliation, though no other collaboration, with several of the authors TC and DS to the handling editor.
The reviewer TSB declared a past co-authorship with one of the authors OM to the handling editor.

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

Copyright © 2021 Berends, Bendita da Costa Jong, Cooper, Dizyee, Morais, Pereira, Smith and Rich. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.

frontiers in Veterinary Science

ORIGINAL RESEARCH
published: 30 November 2021
doi: 10.3389/fvets.2021.733157

Descriptive and Multivariate Analysis of the Pig Sector in North Macedonia and Its Implications for African Swine Fever Transmission

*Kathleen C. O'Hara[1], Daniel Beltrán-Alcrudo[2], Mark Hovari[2], Blagojco Tabakovski[3] and Beatriz Martínez-López[1]**

[1] Center for Animal Disease Modeling and Surveillance (CADMS), School of Veterinary Medicine, University of California, Davis, Davis, CA, United States, [2] Food and Agriculture Organization of the United Nations (FAO) Regional Office for Europe and Central Asia, Budapest, Hungary, [3] Food Veterinary Administration, Skopje, Macedonia

OPEN ACCESS

Edited by:
Erika Chenais,
National Veterinary Institute, Sweden

Reviewed by:
Fedor Korennoy,
Federal Center for Animal Health (FGBI ARRIAH), Russia
Esther Kukielka,
Centers for Disease Control and Prevention (CDC), United States

***Correspondence:**
Beatriz Martínez-López
beamartinezlopez@ucdavis.edu

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

Received: 29 June 2021
Accepted: 09 November 2021
Published: 30 November 2021

Citation:
O'Hara KC, Beltrán-Alcrudo D, Hovari M, Tabakovski B and Martínez-López B (2021) Descriptive and Multivariate Analysis of the Pig Sector in North Macedonia and Its Implications for African Swine Fever Transmission.
Front. Vet. Sci. 8:733157.
doi: 10.3389/fvets.2021.733157

North Macedonia, a country in the Balkan region of Europe, is currently bordered to the north and east by countries with active African swine fever (ASF) outbreaks. The predominantly traditional backyard pig farming sector in this country is under imminent threat of disease incursion. The characteristics and practices of such sectors have rarely been described, and thus the implications for these factors on disease introduction and spread are poorly understood. Using a semi-structured questionnaire, 457 pig producers were interviewed, providing information on 77.7% of the pig population in North Macedonia. In addition, a pilot study of 25 pig producers in Kosovo was performed. This study aimed to provide a detailed description of the North Macedonian pig sector, to make comparisons with nearby Kosovo, and to identify areas with high-risk practices for targeted mitigation. Descriptive data were summarized. Results of the questionnaire were used to identify farm-level risk factors for disease introduction. These factors were used in the calculation of a biosecurity risk score. Kernel density estimation methods were used to generate density maps highlighting areas where the risk of disease introduction was particularly concentrated. Multiple correspondence analysis with hierarchical clustering on principal components was used to explore patterns in farm practices. Results show that farms were predominantly small-scale with high rates of turnover. Pig movement was predominantly local. The highest biosecurity risk scores were localized in the eastern regions of North Macedonia, concerningly the same regions with the highest frequency of wild boar sightings. Veterinarians were highly regarded, regularly utilized, and trusted sources of information. Practices that should be targeted for improvement include isolation of new pigs, and consistent application of basic sanitary practices including washing hands, use of disinfection mats, and separation of clean and dirty areas. This study provides the most complete description of the North Macedonian pig sector currently available. It also identifies regions and practices that could be targeted to mitigate the risk of disease incursion and spread. These results represent the first steps to quantify biosecurity gaps and high-risk behaviors in North Macedonia, providing baseline information to design risk-based, more cost-effective, prevention, surveillance, and control strategies.

Keywords: African swine fever, biosecurity risk score, kernel density estimation, multiple correspondence analysis, North Macedonia, Kosovo

INTRODUCTION

The Republic of North Macedonia is located on the Balkan Peninsula in Southeast Europe. It is bordered by Kosovo[1] and Serbia to the north, Bulgaria to the east, Greece to the south, and Albania to the west. Bulgaria and Serbia are currently experiencing outbreaks of African swine fever (ASF) in both domestic pigs and wild boar, while Greece reported a single introduction in domestic pigs in 2020. African swine fever is a World Organization for Animal Health (OIE) reportable, viral haemorrhagic disease of domestic and wild suids (1). Depending on the viral strain and host factors, ASF infection can present as peracute, acute, subacute, or chronic disease. The virus circulating in the Balkans (and the rest of Europe except for the Italian island of Sardinia, plus in Asia) is of genotype II and acute or peracute in its clinical presentation (among others, genotype II is also present in Africa) (1, 2). Peracute cases are rapidly progressive, presenting with high fever, lethargy, anorexia and/or sudden death. Acute cases may be characterized by high fever, depression, anorexia, vomiting, diarrhea, abortion, haemorrhagic lesions and/or sudden death; while subacute or chronic cases may range from inapparent to having intermittent fevers, lethargy, weight loss, skin ulcers, arthritis and/or respiratory signs (3, 4). When introduced to naïve populations, ASF can result in up to 100% lethality if no mitigation is enacted (4, 5). Wild boar and domestic pigs are equally affected by the disease. Wild boar are of concern due to their contribution to the maintenance and spread of this disease in Europe; while warthogs and likely bushpigs are asymptomatic and contribute to the sylvactic cycle in Africa together with soft ticks of the genus *Ornithodoros* (6–12). Disease transmission in both domestic and wild pigs can occur via direct contact with an infected animal, consumption of contaminated materials (e.g., swill feeding, discarded offal, scavenged carcasses or garbage), exposure to fomites, iatrogenically, or through the bite of infected *Ornithodoros* ticks if present in the area (7, 8, 13–17). No treatment and no vaccines currently exist for ASF. Control is dependent on strict biosecurity, surveillance, rapid detection and stamping out with compensation (5, 12, 14, 18, 19). The absence of a vaccine and the survival of the virus in ticks and the wild pig population, make full eradication after introduction is challenging, with few examples in recent years, namely Belgium, Czech Republic, and Greece (20). The introduction of ASF into a disease-free country can result in massive economic impacts via direct losses to the disease (i.e., mortality, stamping out, control measures etc.) or secondary losses associated with trade restrictions (21). In Europe, trade losses have greatly surpassed direct losses for countries exporting pigs and pork products. Control measures have been associated with high costs due to stamping out of infected farms. Within the Balkan region, ASF was first reported in Bulgaria in August 2018, in Serbia in August 2019, and in Greece in February 2020 (1). While Greece's only outbreak affected domestic pigs, Bulgaria and Serbia's outbreaks have impacted both domestic pig and wild boar populations (1). With this rapid timeline, the surrounding active outbreaks, and the mobility of infected wild boar, the pig industries in North Macedonia and Kosovo, while currently free of African swine fever, are under imminent threat of disease incursion.

Within North Macedonia, the Food and Veterinary Agency (FVA) developed programs and policies, and distributed educational materials, to aid in the prevention of ASF introduction into the country and to improve early detection efforts. The FVA had a full ASF awareness campaign starting in 2018, which included billboards and leaflets, and media releases via radio and television. With the support of the Food and Agriculture Organization of the United Nations (FAO), the following awareness and training efforts were implemented: (1) the distribution to field veterinarians of several hundreds of the FAO manual on ASF detection and diagnosis in Macedonian; (2) ongoing distribution of editable ASF leaflets; (3) four veterinarians attended a training-of-trainers event in September 2019; (4) 10 official veterinarians and 15 private veterinarians attended a biosecurity workshop in October 2019, (5) an ASF outbreak simulation exercise for official veterinarians was run in November 2019, and (6) a 4-week online certified training on ASF preparedness in Serbian. Additionally, FAO, in collaboration with the Veterinary Chamber of the Republic of North Macedonia (a non-profit organization of veterinarians and the veterinary statutory body for the country), undertook a survey of the pig industry to better characterize and define current husbandry practices, socioeconomic aspects, biosecurity capabilities, and disease awareness. FAO also administered this questionnaire to a small sample of pig farmers in Kosovo. This report will present the findings of this collaborative effort and provide some initial targets for ongoing mitigation efforts.

MATERIALS AND METHODS

A questionnaire was designed and implemented by FAO to gather information about husbandry, veterinary care, socioeconomics, the pork value chain, biosecurity, and disease awareness throughout the pig sector in North Macedonia and Kosovo. The

[1] All references to Kosovo should be understood to be in the context of United Nations Security Council resolution 1244 (1999).

questionnaires were adapted from earlier work conducted by FAO in Georgia (22, 23). FAO followed the principles of the declaration of Helsinki and the Belmont report when designing and implementing the survey. The Institutional Review Board (IRB) of UC Davis Administration issued an exemption from the requirement for IRB review, the reasons being that the surveys would not elicit responses that would place the respondents at risk if obtained by individuals not associated with the research. The exemption criteria are available at 45 CFR 46.101(b)(2)–U.S. Code of Federal Regulation, Protection of human subjects. All the interviewed producers were informed of the study purpose, and of the facts that participation in the interviews was voluntary and they could drop from the study at any time.

Questionnaire

Semi-structured questionnaires were originally written in English and subsequently translated into Macedonian. In Kosovo, questionnaires were presented in English and translated into Serbian and Albanian by the surveyor as needed. Questionnaires included sections on: husbandry, veterinary care, socioeconomics, pork value chain, biosecurity including cleaning protocols, visitor access, exposure to other domestic and wild pigs, swill feeding practices and waste management and ASF awareness (**Appendix 1**). All questions referred to the 12 months prior to the date of interview. Questions related to slaughter focused on homeslaughter practices. North Macedonia has 14 commercial slaughterplants that process multiple species; however, these were not captured in the survey.

Sample Selection

North Macedonia

Pig holdings, as identified by an annual census, were divided into three groups based on the number of pigs present: >100 commercial, 11–100 family farm, and 0–10 backyard farm. Based on the 2019 pig census, the pig population of North Macedonia consists of around 125,230 pigs, distributed across 2,315 farms with an average of 58 animals per farm. Under EU legislation, holdings with one pig for domestic purposes are not required to register, therefore these farms may be underrepresented in this count; illegal holdings are not thought to be an issue in North Macedonia. Five hundred farms were targeted, including all commercial farms ($n = 77$), and a 2:1 split of family ($n = 282$) and backyard ($n = 141$) farms focusing on those farms with the most pigs. North Macedonia is divided into progressively smaller administrative levels: regions, municipalities, and town/villages, respectively. Family and backyard farms were proportionally divided between regions (but not municipalities). Within regions, and taking into account the availability of private veterinarians, farms were randomly selected for interviews. These farms were then visited to administer the questionnaires in person.

Kosovo

In Kosovo the major distinction was made between commercial (> 100 animals) and non-commercial farms (≤100 animals). The pig population of Kosovo consists of around 42,000 pigs distributed between one commercial farm and 3,948 non-commercial farms with an average of 11 animals per farm. Twenty-five farms were surveyed during a pilot study in August-September 2020. One survey was carried out in the one commercial farm in Kosovo located in Viti, while the remaining 24 samples were divided evenly into 12 surveys from the Serbian speaking community in the North and 12 samples from the Catholic Albanian community in the West. Farms were selected based on convenience and recommendations of the local veterinary offices.

Data Collection

North Macedonia

In North Macedonia, questionnaires were conducted through the Veterinary Chamber of North Macedonia by private veterinarians selected based on the villages and municipalities they served. Prior to questionnaire implementation, training sessions were organized in each region for the interviewers, covering the survey goals, content, schedule, and basic interview techniques. Survey data was collected via the Epicollect5 mobile platform (24). Interviews were conducted between September 2019 and March 2020. A total of 457 questionnaires were implemented and are analyzed here. The semi-structured format of the survey allowed respondents to select multiple responses for some questions, therefore percentages discussed below represent the percent of respondents selecting a given answer—a given respondent may be counted across multiple answers if they selected more than one response.

Kosovo

In Kosovo one surveyor was hired and trained to fill in the twenty-five surveys in all of the locations. Data collection was also done via Epicollect5.

Data Definitions

When collecting information on the types of pigs, sows were defined as females with litters in the last 12 months. The total number of pigs per farm was calculated as the sum of the reported boars, fattening pigs, piglets, and sows.

Data Analysis

Descriptive statistics were computed from the questionnaire results from North Macedonia and Kosovo. Summary information on husbandry, veterinary care and practices, the pork value chain, biosecurity, and disease awareness, is presented as the proportion of respondents selecting or providing given answers (**Appendix 2**). Multiple choice questions allowed respondents to select multiple answers, meaning that one producer's response may contribute to the proportion of respondents for multiple answers. Data processing and analyses were performed in R Studio (v3.6.1) (25). Spatial visualization and analyses were performed in ArcGIS Desktop v10.7. Mapping was conducting using the World Azimuthal Equidistant Projection.

Biosecurity Risk Scores

Biosecurity risk scores were calculated for farms in North Macedonia using a subset of responses from the questionnaire. Based on established literature and subject matter expertise, risk factors for disease introduction were identified and 28 questions that reflect those factors were selected: 21 questions that were answered by all farms, and an additional seven questions that were answered by family and commercial farms only. The answers to each of these questions were dichotomized, such that high risk answers/behaviors were assigned a score of one, and no/low risk answers/behaviors were assigned a score of zero (**Supplementary Table 1**). Missing values were scored as zero. A biosecurity risk score was calculated as a non-weighted linear combination of these values for each farm. The higher the biosecurity risk score, the worse the biosecurity practices were on that farm (maximum score for all farms: 21, maximum score for family and commercial farms: 28). Biosecurity risk scores were calculated for North Macedonia; due to limited data biosecurity risk scores were not calculated for Kosovo.

Generation of Highest Biosecurity Risk Maps Using Kernel Density Estimation

Kernel density estimation (KDE) is a non-parametric method to estimate the probability density function of a variable (26). Using our biosecurity risk score, each farm serves as a point over which KDE fits a smooth curve with the true value at the exact location of the farm and diminishing values estimated with increasing distance from the farm/known biosecurity risk score. Using this method, we generated maps estimating the areas with highest biosecurity risk based on biosecurity risk scores from all farms. Additionally, we also generated risk maps using the biosecurity risk scores from family and commercial farms who answered both the initial 21 questions and the additional subset of seven biosecurity questions. KDE was used to generate risk maps for North Macedonia; risk maps were not generated for Kosovo due to the limited amount of data available. The kernel density function within ArcGIS was used, specifying a search radius of 10 Km and an output cell size of 1 Km.

Generation of Farm Profiles Using Multiple Correspondence Analysis With Hierarchical Clustering on Principal Components

Multiple correspondence analysis (MCA) is an extension of simple correspondence analysis used for analyzing the association between two or more qualitative variables (27–29). MCA is able to take the many variables generated by our survey responses and evaluate how they may be associated, e.g., if a respondent selected a specific answer to one question, is that associated with answering another question in a certain way? MCA further allows us to visualize the associations between variables by plotting them in space; variables near each other share a similar profile.

MCA was performed via forward stepwise selection selecting for the highest level of variance explained, resulting in the inclusion of nine categorical variables: household income from pigs, fate of meat and pork products produced, do you wash hands before going to pigs, do you use disinfection mat before going to pigs, which people are allowed access to your pigs, do you bring in external boar for mating purposes, biosecurity risk score, farm type and region. Farm type and region were used as supplemental variables, meaning they did not contribute to the calculation of the principle dimensions, but their coordinates were predicted to estimate how they might relate to those variables included in the analysis. Household income derived from pig production was divided into a categorical variable of ≤50%, or >50%. Fate of products was divided into slaughtered for home consumption vs. slaughtered for any other purpose. People pig access was divided into no access, veterinarians, and any other combination. External boar was divided into those farms that allowed their animals to interact with other pigs (their boar goes offsite, sows are crossed offsite, or external boar come to their farm), and those that allowed no interaction with other pigs. Biosecurity risk score was divided into low (0–2; lowest 50%), medium (3–5; middle 51–89%) or high (≥6; top 10%) risk.

After the MCA, we used hierarchical clustering on principle components (HCPC), which is a methodology that clusters individuals according to similar patterns of variable responses, e.g., two respondents who had similar answer profiles would be grouped together (30). HCPC grouped farms based on similar patterns in their survey responses. This allowed us to generate biosecurity farm profiles or groups of farms that share specific farm characteristics as defined by their questionnaire responses. MCA and HCPC were performed in R Studio using the FactoMineR (31) and factoextra (32) packages. HCPC was performed using Ward's criteria. The number of clusters was determined using the "elbow method," which entails plotting the explained variation as a function of the number of clusters and selecting the elbow of the curve as the best balance between number of clusters and variance explained (32).

RESULTS

A total of 457 surveys were completed in North Macedonia by March 29, 2020 (251 in 2019, 206 in 2020); 281 backyard (61.5% of respondents), 146 family (31.9% of respondents) and 30 commercial (6.6% of respondents) farms. The surveyed farms accounted for 77.7% of the pig population in North Macedonia. Additionally, a total of 25 questionnaires were administered during a pilot study in Kosovo, representing 24 non-commercial farms (≤100 pigs) and one commercial farm (>100 pigs). The breakdown of surveys by farm type and region/district are presented in **Figure 1**.

Husbandry

The number of sows, boars, fattening pigs, and piglets reported on North Macedonian farms was assessed by farm type (**Table 1**). Producers were asked about the current number of pigs, as well as the minimum and maximum numbers of each type of pig present on-site in the last 12 months (**Table 1**). Backyard and family farms tended to have more piglets than fattening pigs, in contrast to commercial farms in which fattening pigs predominate (**Table 1**). Overall, across pig and farm types, the number of pigs on any individual farm changed by about 30% over the course of a year. Commercial farms had more stable pig numbers, changing by 20–30%, compared to backyard or family farms whose pig numbers may change by up to 50–60%; fattening pigs and piglets had the highest turnover.

In North Macedonia, commercial breeds of pigs were the most common, with 96.7% of commercial farms, 65.8% of family

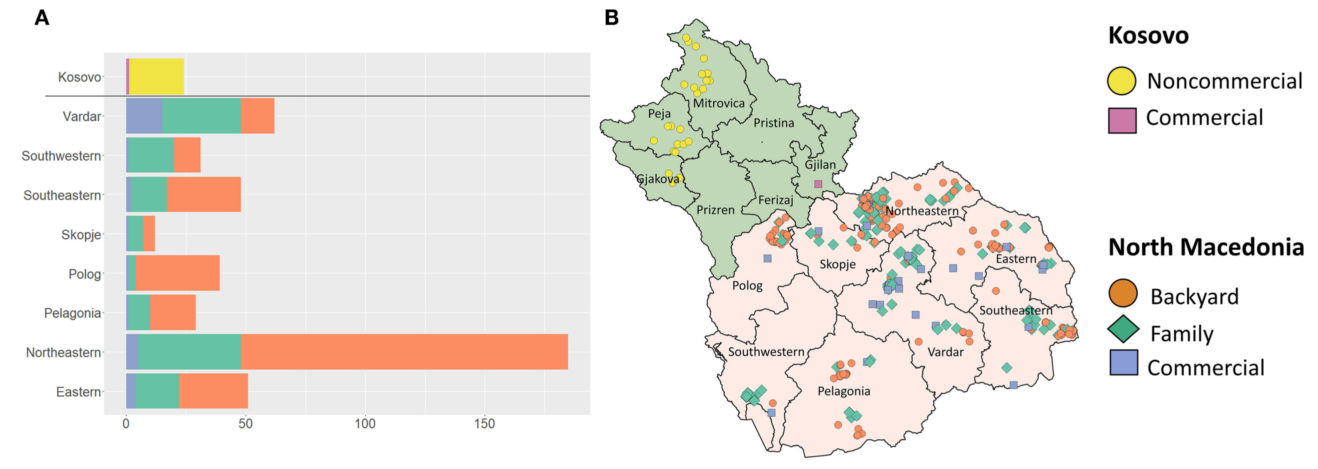


FIGURE 1 | (A) Number of questionnaires administered to North Macedonian pig producers by region and type of farm, and Kosovar producers characterized as commercial or non-commercial, during September 2019-March 2020. **(B)** Map of questionnaire sites by farm type. Kosovo: green, North Macedonia: orange. Kosovo districts and North Macedonia Regions: black lines.

farms, and 76.1% of backyard farms reporting only commercial breeds; the remainder reported local breeds only (commercial 0.0%, family 31.5%, backyard 22.4%), or a combination of local and commercial breeds (commercial 3.3%, family 2.7%, backyard 3.2%). In Kosovo, half of respondents reported only local breeds (48.0%), while the other half reported a combination of local and commercial breeds (48.0%); 4.0% reported commercial breeds only.

In North Macedonia, commercial operations used the highest proportion of hired workers to take care of their pigs (80.0%). Among backyard and family farms, husbands (83.8%) and wives (50.8%) were the most common pig caretakers, with children (21.5%), other family (15.9%), and rarely hired workers (2.8%) also contributing. More Kosovar respondents reported wives (80%) and kids (44%) caring for pigs, in addition to husbands (100%).

In North Macedonia, among backyard and family farms, the births of pig litters were seasonal; both farm types reported fewer litters over summer, with peaks in spring and winter (**Figure 2A**). Commercial farms reported litters being delivered throughout the year. The spring peak observed for backyard and family farms was variable by region, being most pronounced in Pelagonia, Northeastern, and Skopje (**Figure 2B**). Within Kosovo, births were concentrated in the spring, with the commercial farm reporting year-round litters.

North Macedonian pigs were predominately fed with grain (97.2%) and commercial feed (38.7%); commercial farms reported they only feed grain and commercial feed. About 15.1% of North Macedonian farms fed grass. Hay (7.2%) and agricultural by-products (6.6%) were each used to a lesser extent than other feed items. Butcher waste and food processing by-products were used by <1.0% of producers in North Macedonia. Food scraps were fed by 6.8% of farms in North Macedonia. Ninety-four percent of North Macedonian farms feeding food scraps reported the scraps they fed were from their own household. In North Macedonia, one backyard farm reported feeding scraps from a restaurant and one from a market. Of those North Macedonian farms feeding food scraps, 56.8% reported that they boil the scraps before feeding them to pigs. Only 3.5% of North Macedonian respondents report that their pigs were allowed to scavenge (during the day, returning at night), with the remainder keeping their pigs enclosed year-round. Three of these farms explicitly report allowing scavenging outside of the household during September-November; these three farms were all located in the Eastern region.

All of the Kosovar respondents reported feeding grain, while 44% reported feeding commercial feed. The commercial farm in Kosovo reported they fed grain and commercial feed, as well as hay and agricultural by-products. Hay was fed by 84% of respondents in Kosovo. Feeding butcher waste and food processing by-products was reported by 56.0% of respondents in Kosovo. Food scraps were fed by 80.0% of respondents from Kosovo; 100% of respondents reported the scraps were from their own household. One farm in Kosovo fed scraps from their own as well as another household. Additionally, one family farm reported feeding food scraps from a market. No farms reported boiling food scraps before feeding them to their pigs in Kosovo. All Kosovar producers kept pigs enclosed year-round, with no scavenging reported.

Veterinary Care

North Macedonian respondents reported an average of 14.6 contacts (including phone calls) with their veterinarian per year. Commercial farms consulted with veterinarians (mean number consults: 26.9, SD: 26.6) approximately twice as often as backyard (mean number consults: 12.1, SD: 17.0) and family farms (mean number consults: 16.9, SD: 18.6). Eighty-five percent of farms

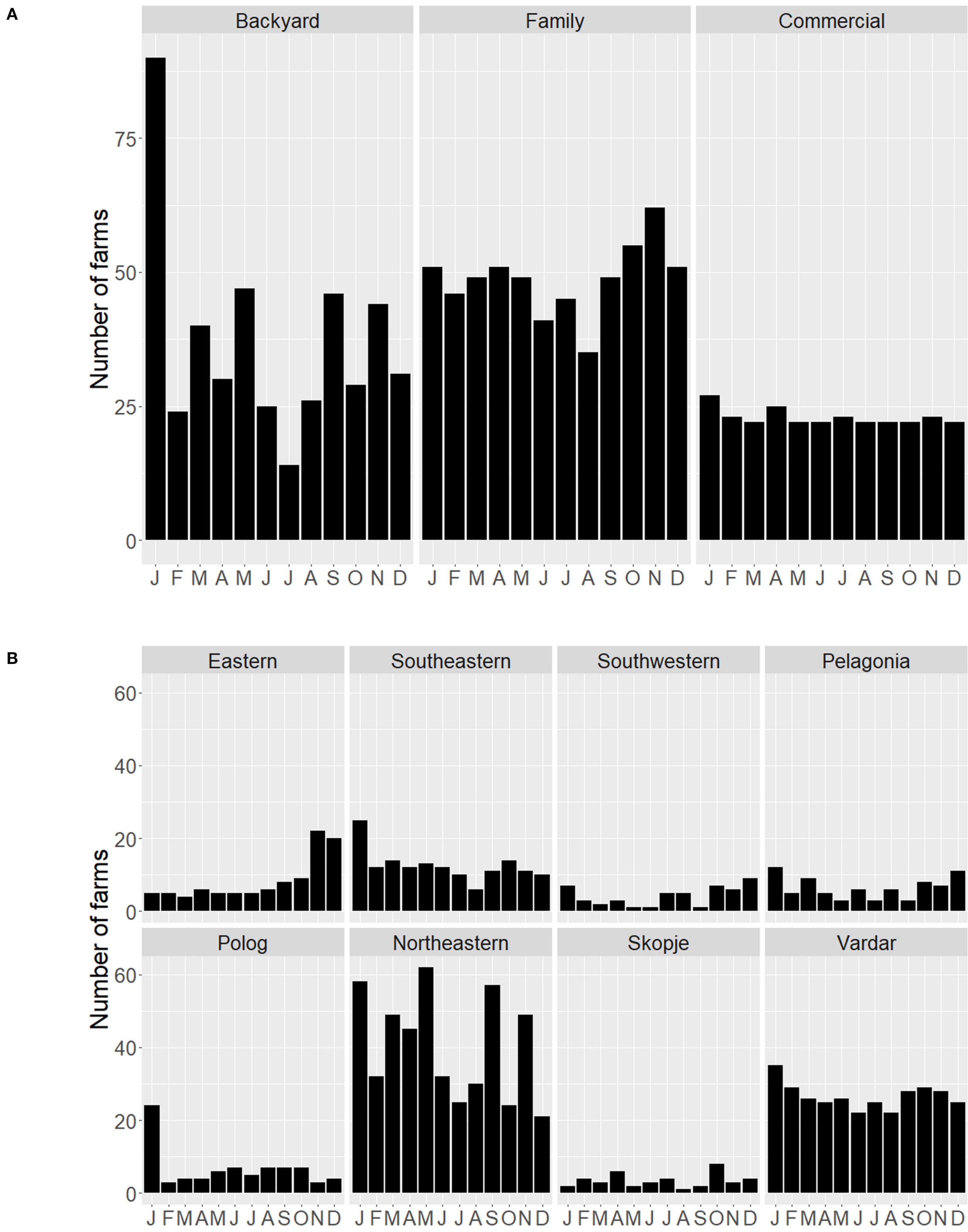


FIGURE 2 | Number of North Macedonian pig farms reporting litters per month by **(A)** farm type, and **(B)** region, based on questionnaires administered between September 2019 and March 2020.

TABLE 1 | Number of pigs by farm type as reported by questionnaires administered to North Macedonian pig producers between September 2019 and March 2020.

Farm types		Sows	Boars	Fattening pigs	Piglets	Total
All	Mean (SD)	7 (53)	1 (2)	121 (771)	84 (501)	213 (1,304)
	Median	1	0	2	6	11
	Avg minimum (SD)	8 (52)	1 (2)	97 (644)	66 (452)	
	Avg maximum (SD)	11 (59)	1 (3)	145 (866)	91(555)	
	%Change AvgMax-AvgMin	0.3	0.3	0.3	0.3	
Backyard	Mean (SD)	1 (4)	0 (1)	3 (7)	7 (12)	11 (18)
	Median	1	0	1	2	6
	Avg minimum (SD)	2 (2)	0 (1)	2 (3)	7 (12)	
	Avg maximum (SD)	3 (4)	0 (1)	5 (13)	11 (18)	
	%Change AvgMax-AvgMin	0.4	0.2	0.6	0.4	
Family	Mean (SD)	3 (5)	1 (2)	30 (64)	35 (54)	69 (112)
	Median	2	1	3	20	29
	Avg minimum (SD)	5 (7)	1 (1)	16 (37)	23 (46)	
	Avg maximum (SD)	9 (8)	1 (4)	43 (77)	48 (86)	
	%Change AvgMax-AvgMin	0.5	0.4	0.6	0.5	
Commercial	Mean (SD)	82 (195)	5 (6)	1,669 (2,584)	1,043 (1,707)	2,799 (4,386)
	Median	15	2	460	335	737
	Avg minimum (SD)	82 (189)	4 (5)	1,371 (2,171)	830 (1,597)	
	Avg maximum (SD)	103 (210)	6 (8)	1,945 (2,858)	1,047 (1,947)	
	%Change AvgMax-AvgMin	0.2	0.3	0.3	0.2	

The number of pigs currently on the farm were reported by type of pig. Producers also separately reported the maximum and minimum number of each type of pig that were on the farm in the last 12 months. Total pigs were calculated as the sum of the reported sows, boars, fattening pigs and piglets currently on-site. Percent change in average number of pigs was calculated as the difference between the average maximum and average minimum divided by the average maximum.
SD, standard deviation; Avg, average; Avg Minimum, average of the minimum number of each type of pig reported; Avg Maximum, average of the maximum number of each type of pig reported; %Change, percent change.

reported they consulted a veterinarian when they had a sick pig, with 43.9% also separating sick pigs and 8.6% disinfecting pens. Only 4.2% of North Macedonian respondents reported treating animals themselves. No farms reported selling off sick pigs or their meat, though two North Macedonian family farms reported sending remaining healthy pigs to slaughter if others became ill. Four percent of farms in North Macedonia reported killing and disposing of sick pigs. Kosovar responses to sick pigs were similar, with 84% reporting they consulted their veterinarian and 56% separated sick from healthy pigs. Cleaning and disinfecting of sick pig pens was reported by 24% of respondents. In Kosovo, 68% of respondents reported treating sick pigs themselves. No sick pigs were reported to be slaughtered or sold in Kosovo.

When asked what they do when an adult pig dies, across North Macedonian farm types, the most common responses were disposal via burial (47.3%) or pit disposal (26.6%), followed by contacting their veterinarians (19.7%) or the veterinary authorities (12.7%). No respondents reported selling the meat of pigs found dead or feeding carcasses to other pigs. In North Macedonia, 2.7% farms reported feeding meat of pigs found dead to dogs In Kosovo, adult pigs that died were thrown away (88.0%), disposed of in a pit (28.0%), or buried (8.0%). The commercial facility in Kosovo reported they contact their veterinarians. No respondents reported selling the meat of pigs found dead or feeding carcasses to other pigs. In Kosovo, 20.0% of farms reported feeding meat of pigs found dead to dogs.

The most common vaccine used in North Macedonia is that for classical swine fever (CSF), 87.7% of farms reported administration. In North Macedonia, erysipelas is the next most common at 32.8%, with Aujezsky's disease and Pasteurellosis rarely reported at 2.6 and 1.1%, respectively. Approximately 10.5% of North Macedonian farms (all backyard and family farms) use no vaccines at all. In Kosovo, 96.0% of Kosovar producers reported using CSF vaccines; however, only the commercial facility reported use of any additional vaccines beyond CSF. One non-commercial Kosovar farm reported using no vaccines.

Socioeconomics

In North Macedonia, the majority of farms reported pig rearing comprised only a proportion of the household income, with 29.1% of farms reporting all raised pigs were for home consumption only and only 11.6% of farms reporting pig rearing contributed more than 80.0% of the household income. Among backyard farms, 44.8% of pigs were reported to be raised for home consumption only, this number dropped to 2.7% for family farms. All of the producers interviewed in Kosovo reported household income from the pigs they raise (range: 2.0–80.0%). Removing the commercial farm, pig rearing contributed an average of 22.3% of household income on Kosovar farms.

About 19.5% of North Macedonian farms reported pig and/or piglet losses due to death on the farm or disappearance while free-ranging, with commercial farms having the highest proportion of respondents reporting such losses at 43.3%. In North Macedonia, results were similar for numbers of pigs reported lost to disease, with about 24.7% of farms reporting deaths due to disease. Approximately 66.7% of North Macedonian commercial farms report losses due to disease, vs. 18.5 and 28.1% of backyard and family respondents, respectively. Only 1.5% of respondents reported having pigs disappear or not return while they were free-ranging. These losses were reported by three backyard and four family farms, including two backyard farms that had advised their pigs were enclosed year-round. In Kosovo, 16% of respondents reported pig or piglet deaths on the farm (Kosovo has no free-ranging pigs and thus reported no deaths or losses while free-ranging); 88.0% of respondents reported pigs died due to disease.

Pork Value Chain

The majority of North Macedonian respondents reported buying or sourcing their pigs from backyard farms (37.4%) or their own farms (42.2%) (**Figure 3A**). The majority of commercial farms reported sourcing only from other commercial farms or their own facilities; however, in North Macedonia one commercial farm reported sourcing from backyard farms and one reported sourcing from a combination of family and commercial farms. In Kosovo, farms were more likely to source from non-commercial farms (64.0%), commercial farms (44.0%), and middlemen (28.0%), with only 12.0% sourcing from their own farms.

When buying in North Macedonia, the overall median number of pigs purchased was one. By farm type: backyard buyers bought a median of zero; family farms one; and commercial farms 21; with maximum purchases of 50, 200, and 25,000 for backyard, family, and commercial, respectively. Piglets for fattening (48.1%) and replacement sows (40.5%) were the most common types of pigs bought in North Macedonia (**Figure 3B**). Commercial farms buy throughout the year, while backyard and family farms tend to purchase early in the year (**Figure 3C**). In Kosovo, pigs for fattening (64.0%) and pigs fattened halfway (56.0%) were the predominate purchases, with replacement sows (28.0%) the next most common. Kosovar producers predominantly purchase their pigs at the beginning of the year: January (36%), February (52%), March (32%), April (12%).

The majority of backyard and family farms slaughtered their pigs at home, with 76.1% of North Macedonian farms reporting slaughter on-site by a family member (54.0%) or someone else (22.1%). North Macedonian farms slaughtering pigs at home overwhelming reported that they owned all the equipment used for slaughter or that the slaughterman brought everything needed. Only 2.1% of farms slaughtering pigs at home reported they borrowed all or only owned some equipment. Inedible materials from slaughter were primarily disposed of via offsite burial (33.6%) and pit disposal (26.1%) in North Macedonia. Sixteen percent of respondents in North Macedonia reported feeding inedible parts to dogs and cats. No respondents reported feeding parts to pigs. Fattened pigs were predominately slaughtered at the end of the year, with November the most common month across farm types, while the slaughtering of piglets had two peaks—April-May and November-January. Regarding the fate of pork products slaughtered at home, 90.2% of North Macedonian respondents reported the meat and products they produced were for home consumption, while most of the product from commercial farms ended up at butcher shops or with middlemen (**Figure 4A**). Backyard farms in North Macedonia reported they preserve (salt/smoke/dry) an average of 90.3% of meat slaughtered at home, with family farms reporting an average of 66.8%. This meat is then consumed over an average of 6.6 months for backyard farms and 4.5 months for family farms. Among those North Macedonian farms selling pigs, the majority reported selling to backyard farms (49.3%), markets (40.5%) and middlemen (33.4%) (**Figure 4B**). Almost all sales of meat and pork products were local. In North Macedonia this included sales within the same village (40.5%), same municipality (46.7%) or adjacent municipality (24.1%) (**Figure 4C**). One North Macedonian backyard farm located near the border reported sale of pork products in Bulgaria. In 19.5% of cases, North Macedonian sellers reported they were not aware of where their products ended up. In North Macedonia, fresh meat (87.9%) was the most common product sold or given away, followed by sausage (43.5%) and dried/smoked/salted meat (31.4%) (**Figure 4D**). Commercial farms sold consistently throughout the year, while backyard and family farms primarily sold at the end of the year (October-December).

About 64.8% of North Macedonian respondents answered questions regarding selling live pigs, suggesting there is a large segment of farms that do not sell pigs (this also corresponds with the numbers reporting production for home consumption only). The pigs sold in North Macedonia were primarily ready-to-slaughter pigs (50.9%) and piglets for fattening (69.4%). In a given year, North Macedonian commercial sites reported selling a median of 1,128 pigs (mean: 4,570, SD: 7,561, range: 0–24,000), compared to backyard and family farms with medians of 1.0 (mean: 7.0, SD: 14.1, range: 0–80) and 27.5 (mean: 150.0, SD: 587, range: 0–6,404) pigs sold, respectively.

All responses from Kosovo reported slaughter on-site, with approximately half of slaughter performed by family (47.8%) and half by someone else (52.2%). Having all the equipment needed for slaughter was reported by 39.1% of respondents, while 47.8% borrowed or shared with neighbors. In Kosovo 95.7% of respondents reported inedible materials from slaughter were fed to dogs and cats, 43.5% disposed of via pit disposal and/or 39.1% thrown offsite. The commercial farm in Kosovo reported off-site burial or collection. No respondents reported feeding parts to pigs. Fattened pigs were reportedly slaughtered in October (25%), November (100%) and December (50%). Piglets were slaughtered in May (18.2%), June (77.3%) and July (45.5%). Pork products from homeslaughter were predominantly for home consumption (100.0%), or sold or given to relatives, friends and family (80.0%); however, pork products were also reportedly sold to middlemen (32.0%) and restaurants or bars (16.0%). Sale of pork products was primarily local, sold in the same village (100.0%), same municipality (95.4%), or adjacent municipality (52.4.0%). Pork products were also sold Skopje (28.6%). Fresh meat (100.0%), dried/smoked/salted meat (81.1%), fresh fat (38.1%),

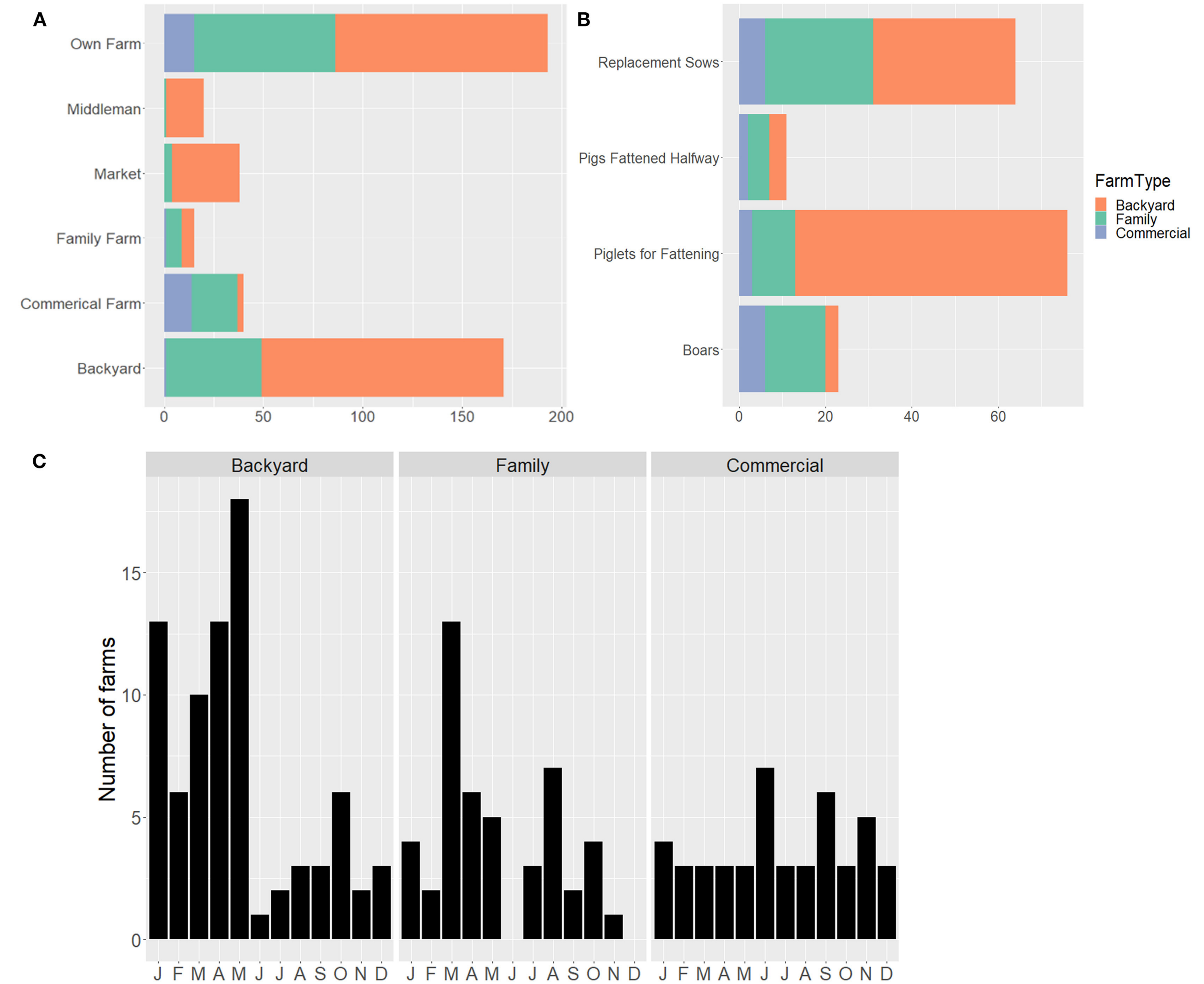


FIGURE 3 | North Macedonian producer's pig buying practices by farm type by **(A)** source of pigs, **(B)** type of pig purchased, and **(C)** when pigs were purchased by month, based on questionnaires administered between September 2019-March 2020 (281 backyard, 146 family, and 30 commercial farms). Types of pigs: replacement sows = intact female pig for breeding; pigs fattened halfway = pigs over 25 kg but under market weight; piglets for fattening: pigs from weaning to about 25 kg; boar: intact male pig for breeding.

and sausage (14.3%) were the most commonly sold or gifted pork products.

About 44.0% of Kosovar respondents answered questions regarding selling live pigs. Among those selling pigs, 81.3% reported selling to backyard farms, followed by middlemen (54.5%) and family farms (27.3%). No respondents reported selling pigs to commercial farms or markets. The majority of pigs sold in Kosovo were ready-to-slaughter pigs (63.6%), piglets for fattening (54.5%) and pigs fattened halfway (45.5%). Pigs were primarily sold during October-November and April-June.

Biosecurity

Basic Biosecurity

Producers were asked about a variety of biosecurity and sanitation practices on their farms. Over 90.6% of North Macedonian producers reported that their home or farm was fenced, with 98.2% reporting that their pig pens were fenced. Only 23.4% of North Macedonian producers reported isolating newly purchased pigs; of those who do isolate, the mean time was 24.9 days (SD: 12.2, range: 1–60). Even among commercial farms, the isolation of new pigs was not reported to be consistently practiced (46.7%). Equipment lending or borrowing between neighbors was reported by only 3.7% of respondents in North Macedonia, with commercial farms never lending or borrowing equipment. Changing shoes (94.1%) or clothes (92.8%) before going to the pigs was common in North Macedonia, with hand washing before going to the pigs being slightly less consistent (87.1%). Disinfection mats were used less reliably (68.5%). In general, commercial farms were the most consistent with their biosecurity practices, with all farms reporting fenced properties,

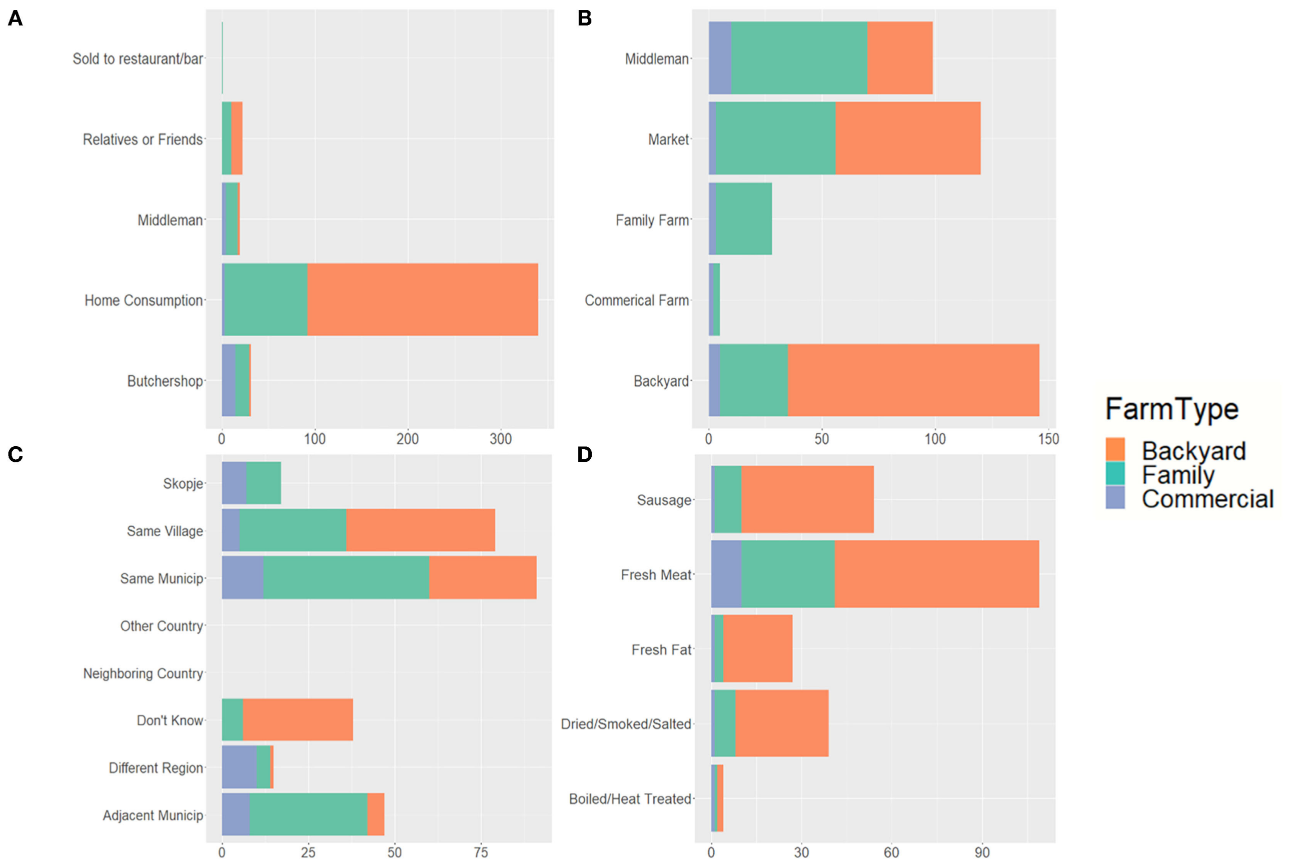


FIGURE 4 | North Macedonian producer's pig selling practices by farm type by **(A)** fate of products sold, **(B)** who producers were selling to, **(C)** location of buyers, and **(D)** product type produced by farm, based on questionnaires administered between September 2019 and March 2020 (281 backyard, 146 family, and 30 commercial farms). One producer did report selling to pork products to Bulgaria. Due to survey wording, sausages cannot be differentiated as fresh vs. cooked or other.

fenced pig pens, and consistent practices of changing shoes and cloths, washing hands and using disinfection mats before going to pigs.

In Kosovo, 100% of respondents reported their farm/home was fenced; 92% reported their pigs were kept in a pen or fenced in. Among Kosovo respondents 40.0% reported isolating new pigs. Sharing of equipment was reported by 72.0% of respondents. In Kosovo, changing clothes (40.0%) and washing hands (28.0%) were performed less frequently than in North Macedonia; only the commercial farm used disinfection mats.

Visitors to Farm

Next, producers were asked about the exposure of their pigs to people visiting the farm and pigs from other premises. Veterinarians were the most common persons allowed access to pigs at 86.7% in North Macedonia. Twenty-three percent of North Macedonian farms had restricted access, with no one allowed near the pigs. Friends (9.0%), neighbors (8.5%), and buyers (8.1%) were each allowed in at a low rate. Slaughtermen had access at 4.2% of farms in North Macedonia. Only 1.8% of North Macedonian farms allowed fellow pig farmers access to their pigs. Commercial farms were generally the most restrictive, with 36.7% allowing no access and 56.7% only allowing access to veterinarians; one North Macedonian commercial farm reported allowing fellow pig farmers and one allowed buyers onsite. In Kosovo, veterinarians were allowed on 100.0% of farms. Among Kosovar respondents 28.0% allowed neighbors, 36.0% allowed buyers, and 28.0% allowed slaughtermen, to access their pigs. Fellow pig farmers were allowed access by 76.0% of Kosovar respondents.

Pigs From Outside the Premises

Bringing in external boar to cross with sows was reported by 8.6% of respondents in North Macedonia, including three commercial facilities. Most North Macedonian farms reported either using artificial insemination (35.9%) or owning their own boars (35.9%). Only 2.9% of farms, and only backyard and family farms, reported taking their sows offsite for breeding. Of the Kosovar farms assessed, 40.0% did not have breeding animals on-site; among those who did, 32.0% brought in an external boar, 12.0% sent their sows offsite, and 12.0% had their own boar. Artificial insemination was only reported by the commercial farm in Kosovo.

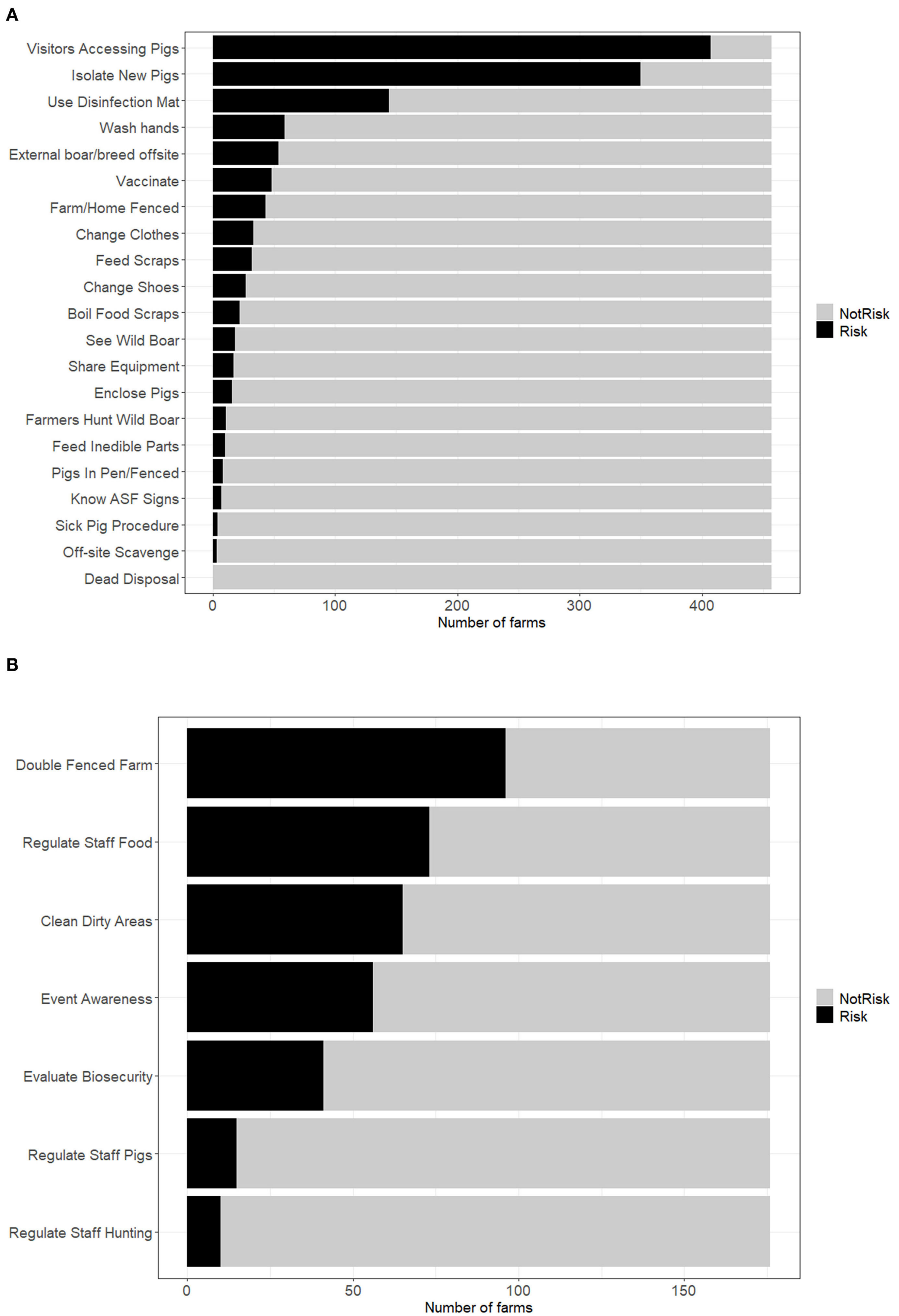


FIGURE 5 | Dichotomous scoring responses for questions administered to North Macedonian pig producers between September 2019 and March 2020, characterizing reported practices as no/low risk vs. contributing risk for ASF introduction based on biosecurity characteristics for **(A)** all farms, and **(B)** family and commercial farms. Scores were used to calculate biosecurity risk scores. "Not risk" answers were assigned a score of zero, "risk" answers were assigned a score of one. Two separate sets of biosecurity risk scores were developed to account for additional information provided in a subset of biosecurity questions that was only answered by family and commercial farms.

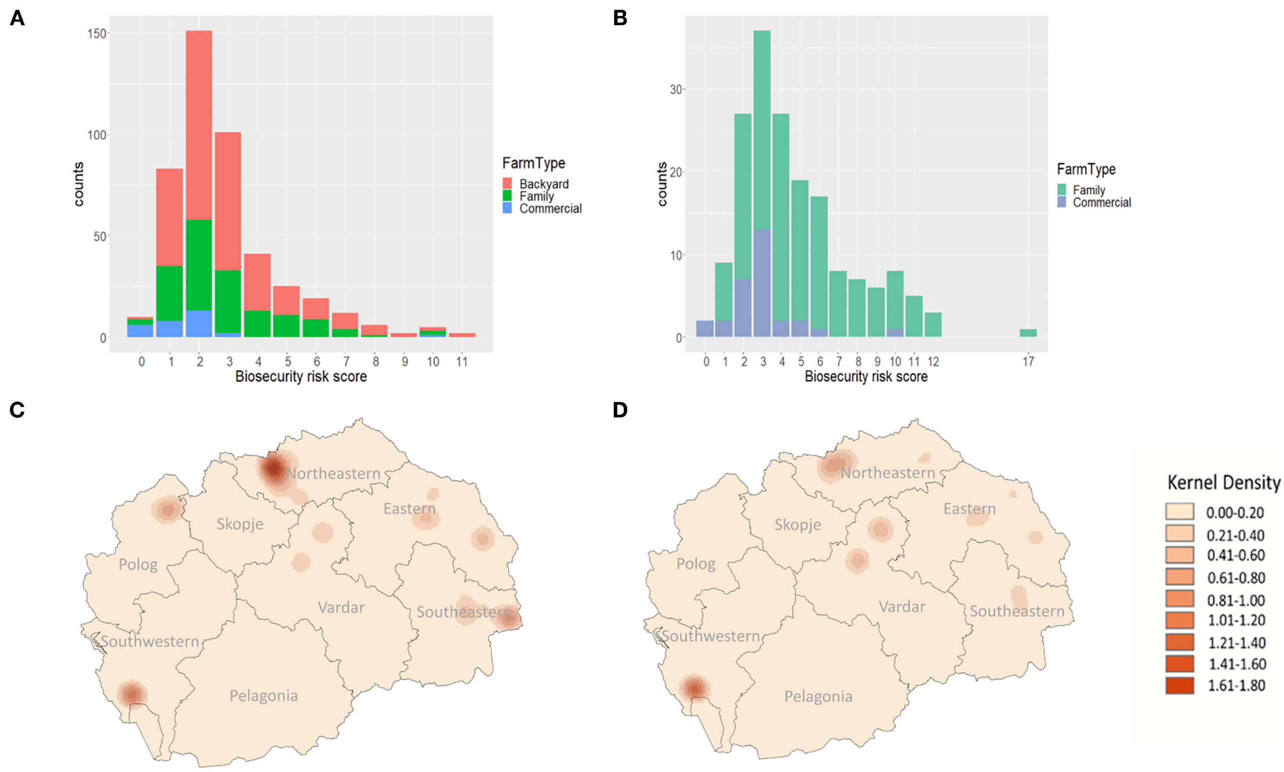


FIGURE 6 | Biosecurity risk scores for **(A)** all pig farms, and **(B)** family and commercial pig farms, administered questionnaires in North Macedonia between September 2019 and March 2020. Biosecurity risk scores represent a non-weighted linear combination of values assigned to dichotomized survey questions in which higher scores representing higher risk. Kernel density estimation (KDE) mapping of biosecurity risk scores for **(C)** all pig farms, and **(D)** family and commercial pig farms administered questionnaires in North Macedonia between September 2019 and March 2020.

In North Macedonia, only 3.9% of farms reported having seen wild boar in the proximity of the farm in the last 12 months, with most sightings occurring late in the year. Wild boars were reported throughout the year in the Northeastern region, in November in the Eastern region, and in October and December in Vardar. Those farms who had seen wild boar were all in the eastern regions of the country. Among pig producers, 2.4% in North Macedonia reported hunting wild boar. Only one farm in Kosovo reported seeing wild boar. Hunting wild boar was reported by 8.0% of Kosovar respondents.

Waste Disposal

Most farms in North Macedonia reported their household waste was collected by the municipality (77.2%). In North Macedonia, burning (9.2%) and throwing/dumping household waste off-site (8.1%) were the next most common disposal routes, with on-site burial of waste rarely reported (3.1%). All but one commercial farm report waste removal by the municipality. No farms reported burying off-site or discarding household waste on their premises. One third of North Macedonian farms reported that there was no disposal site available for household waste in their village. In North Macedonia, most village disposal sites were fenced sites (46.8%), with unfenced sites less common (11.1%). Burial (2.5%) or burning (5.8%) of household waste at village disposal sites was rare. In Kosovo, 68.0% of respondents reported household waste was collected by the municipality, with discarding household waste offsite the next most common form of disposal (36.0%). One farm reported burning some of their household waste. No disposal site available for household waste in the village was reported by 80.0% of Kosovar respondents; 12.0% reported a fenced disposal site, 4.0% a non-fenced disposal site, and 4.0% burial at the disposal site. No burning of waste at village disposal sites was reported.

Manure was most commonly disposed of in unfenced (49.2%) or fenced (27.8%) gardens or fields, or stored on-site (36.5%) in North Macedonia. Rarely manure was disposed of at a dumpsite (8.3%). It was very uncommon to sell or give away pig manure (1.3%) in North Macedonia. In Kosovo, manure disposal was highly variable: 84.0% dump off-site, 36.0% spread in unfenced fields, 32.0% sell or give away, 20.0% store in a pit, and 8.0% spread in fenced fields.

Advanced Biosecurity (Only North Macedonian Family and Commercial Farms)

A second series of biosecurity questions was targeted at family and commercial farm operations: 39.2% of farms reported having a double fence; 55.5% reported having separate clean and dirty

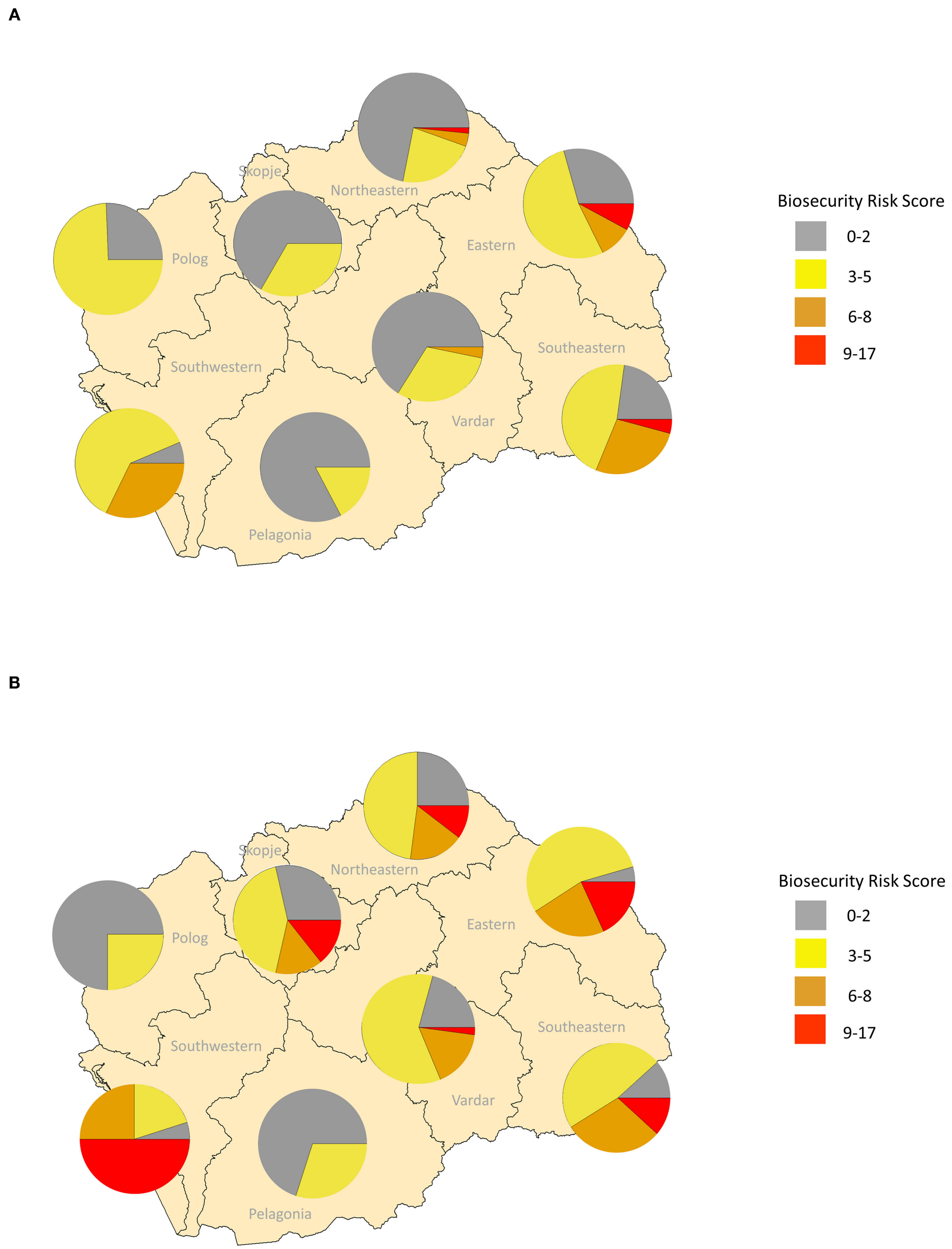


FIGURE 7 | Mapping of biosecurity risk score by North Macedonian region. Pie charts represent the proportion of pig farms with the corresponding biosecurity risk scores in each region for **(A)** all farms, and **(B)** family and commercial farms. Biosecurity risk scores represent a non-weighted linear combination of values assigned to dichotomized survey questions collected between September 2019 and March 2020 in which higher scores represent higher risk.

FIGURE 8 | Multiple correspondence analysis (MCA) and hierarchical clusters of principal components (HCPC) results for North Macedonian pig farms using farm characteristics and practices reported in questionnaires administered between September 2019 and March 2020, with region and biosecurity risk score categories *(Continued)*

FIGURE 8 | used as supplemental variables. **(A)** Graph of the correlation of categorical variables by dimension. The distance between points gives a measure of their similarity; variables that group together have similar profiles. The distance from the axis represents the level of correlation that variable has with the given dimension; variables near the origin have low correlation with either dimension. Red: analyzed variables, Green: supplemental variables. Variables: WashHands_Yes/No: wash hands before going to pigs, External Boar_Yes/No: allow interaction with external pigs, DisinfectionMat_Yes/No: use disinfection mat, SltHome/SltOther: slaughtered for home consumption vs. other, NoAccess/VetAccess/OtherAccess: allow no access to pigs, allow only veterinarians to access pigs, allow other people (neighbors, buyers, fellow pig farmers) to access pig, Income ≤ 50/Income > 50: household income from pig rearing ≤50 vs. >50%, Commercial/Family/Backyard: farm type. **(B)** Plot of HCPC results. HCPC groups respondents into clusters based on their similar response profiles. Our analysis generated three clusters. The red cluster corresponds to high biosecurity risk farms, and groups respondents who reported not washing hands before going to pigs, allowing external pigs on the farm, allowing visitors other than veterinarians to access pigs and not using disinfection mats. The blue cluster groups respondents with profiles including commercial farms, household income from pigs >50%, not allowing visitors to access pigs, and slaughter done by someone outside the household. The green cluster groups the remaining respondents whose responses were not highly correlated with either dimension.

areas for employees; and 42.1% reported restricting the kind of food products employees could bring on-site for their own consumption. No commercial farms allowed workers to keep their own pigs at home, with 86.8% of all respondents reporting workers could not keep pigs. Similarly, all but one commercial farm reported their workers were not allowed to hunt in their free time, with 91.1% of all respondents not allowing workers to hunt.

When asked about having detailed disinfection protocols, 55.3% reported protocols for vehicles, 68.8% for equipment, and 65.2% for people. Eighty-nine percent of commercial farms reported protocols in place for vehicles, equipment and people, compared to 41.2% of family farms.

About one third of farms report never re-assessing their biosecurity procedures. However, 27.1% were reassessing each month, with 18.6% doing so every 3 months, and 10.9% twice a year. Commercial farms were more likely to reassess more often.

Forty-three percent of farms reported never organizing events to educate workers about ASF; however, 14.6% did so each month, 12.3% every 3 months, 15.4% every 6 months, and 14.6% once a year. Commercial farms organized training more often.

ASF Awareness

Producers were asked a series of questions regarding where they get information on animal diseases, their level of concern, and to test their knowledge of ASF. The most common sources of animal health information in North Macedonia were veterinarians (96.3%), television (75.6%), the internet (39.4%), and leaflets (29.8%). No one reported getting animal health information at church. These responses were consistent with responses about where producers heard about ASF. One percent of North Macedonian producers report not having heard of ASF—this represents three backyard farms, three family farms and one commercial farm. Reported sources of animal information were similar in Kosovo: veterinarians (96.0%), television (72.0%), local authorities (48.0%), newspapers (32.0%), leaflets/posters (20.0%). Among the Kosovo respondents, 32.0% reported not having heard of ASF.

Given a list of pig diseases—ASF, Aujezsky's disease, classical swine fever (CSF), foot-and-mouth disease (FMD), porcine reproductive and respiratory syndrome virus (PRRS), swine influenza, Seneca Valley virus (as a control; has not been reported in the region)—producers were asked to rank the top three diseases of most concern. African swine fever (85.6%), CSF (85.3%) and swine influenza (41.4%) were the predominant diseases of concern in North Macedonia. While ASF and CSF were consistently of concern, the remaining diseases showed some regional variation. In Kosovo, 68.0% of farms did not list ASF in their top three disease of concern, rather CSF (92.0%), swine influenza (92.0%), and FMD (68.0%) predominated.

In recognizing the signs of ASF, the most commonly reported signs from North Macedonian producers were: hemorrhages on the skin (60.6%), reduced appetite (60.0%), fever (60.0%) and sudden death (52.1%). Only 2.4% reported not knowing the signs of ASF, consistent with the previous numbers who had reported not hearing of ASF. Only 1.5% of producers thought ASF was zoonotic. The most common North Macedonian responses regarding the ways their pigs might contract ASF were: introduction or exposure to diseased animals (87.1%), fomites, e.g., infected boots or cloths (49.9%), and feeding infected pork products (39.2%). Twenty-four percent were concerned about transmission routes not relevant to ASF, such as 20.4% mosquitoes, 3.5% wind and 1.8% bad vaccines. In Kosovo, the most commonly reported clinical signs related to ASF were fever (68.0%), diarrhea (64.0%), reduced eating (44.0%), and sudden death (40.0%). Kosovar respondents reported diseased animals (76.0%), feeding infected pork products (28.0%), and fomites (20.0%) as paths of ASF transmission. Twenty percent of respondents did not know how ASF could infect their pigs.

When it comes to reporting suspect ASF cases, 76.4% of producers in North Macedonia reported they would quickly report ASF to veterinary authorities if they suspected it on their farms. Twenty-three percent in North Macedonia advised they would wait a few days to report due to concerns about it being a false report. In North Macedonia, only two farms would wait a few days to report to the veterinary authorities due to concern for financial losses. In Kosovo, 48.0% of respondents said they would quickly report suspect ASF, 12.0% would wait a few days due to concerns about a false report, and 40.0% would wait due to concern for financial losses.

Finally, when asked why an owner may not report ASF, producers in North Macedonia reported not knowing how to report (39.6%), being unclear about what might happen after reporting (31.1%), the culling of their pigs (27.8%), the subsequent restriction of sale of their pigs (24.3%), damaged reputation (15.1%), and no compensation (9.8%), as the top reasons. Only 2.4% said the owner would prefer to deal with the disease themselves. Reporting being too time consuming was only cited by 0.8% of respondents. In Kosovo, 60.0% reported not knowing how to report, 64.0% were concerned about post-reporting unknowns, 36.0% were concerned about banned sales, 28.0% felt reporting was too time consuming, 20.0% were concerned about their reputations and 16.0% were concerned about their pigs being culled.

Biosecurity Risk Scores and High-Risk Areas for ASF Introduction

A subset of survey questions was selected to reflect the biosecurity practices and associated risk level of each farm in North Macedonia. The responses to these questions were dichotomized into low/no risk or contributing risk based on whether a farm performs or does not perform certain activities, e.g., vaccinating vs. not vaccinating pigs (**Supplementary Table 1**). The distribution of these answers is presented in **Figure 5**. The most common high-risk practices reported were allowing visitors (e.g., veterinarians, fellow pig farms, buyers, neighbors, friends) to access the farm, failure to isolate new pigs, and not using a disinfection mat. Among those questions targeted to family and commercial farms, more variability in answers was noted, with the most common high-risk practices including: not having a double fence, not regulating the food workers bring on the farm, not having separate clean and dirty areas, and not having events in which to educate and increase the awareness of employees about ASF.

Most farms have low biosecurity risk scores—indicating low risk of disease introduction and good biosecurity (**Figure 6**). When evaluating scores across all farm types, the highest biosecurity risk scores (those with the worst biosecurity) were generally observed among backyard and family farms. In both the all-farm and family and commercial focused assessments, commercial farms tended to score better (lower) than other types of farms (**Figure 6**).

Risk maps generated using the all-farm biosecurity risk scores, identified areas of high risk for ASF introduction in the Northeastern, Southwestern, and Southeastern regions of North Macedonia (**Figure 6C**). When focusing on family and commercial farms, the Southeast region's focus is no longer highlighted and the Eastern region becomes lower in risk (**Figure 6D**); however, the high-risk areas in Northeastern and Southwestern regions remain. While the KDE maps identified high risk areas in the Northeastern and Southwestern regions, those individual farms with the highest biosecurity risk scores were located in the East, with the Southeastern region having the largest proportion of high-risk scoring farms (**Figure 7A**). Among the family and commercial farms subset, the highest individual scores were observed in the Northeastern and Eastern regions, with a high level of variability observed in the Southwestern region (**Figure 7B**). Among this subset, the Eastern and Southwestern regions have the highest proportions of high-risk biosecurity risk score farms.

Generation of Farm Profiles Based on MCA and HCPC

MCA grouped not washing hands, allowing access to external boar, allowing access to people other than veterinarians, and not using a disinfection mat as variables highly correlated with dimension 2 and high biosecurity risk scores (**Figure 8A**). Low and medium biosecurity risk scores were more difficult to delineate, as factors grouped around the X-Y axis did not strongly contribute to differentiating farms for these dimensions. Commercial farms grouped with pig rearing being more than 50% of household income, allowing no people to access pigs, and slaughtering for a purpose other than home consumption as variables highly correlated with dimension 1. Hierarchical clustering identified three separate groups of respondents with similar profiles, or pattens of responses to questions about their farm practices (**Figure 8B**).

DISCUSSION

This study provides the most complete profile of the pig industry in North Macedonia available, covering 77.7% of the pig population in the country, thanks to the large sample size and the comprehensive survey responses from pig producers on their husbandry practices, the pork value chain, biosecurity practices, and disease awareness. The recent ASF introductions into Bulgaria, Greece, and Serbia, highlight the need to better understand the pig sector in this region and to inform future targeted interventions. Like other countries in the Balkans, North Macedonia and Kosovo have numerous risk factors for ASF introduction including many low biosecurity small holder farms, free ranging pigs, farms practicing swill feeding, high wild boar suitability, and high connectivity to ASF positive countries through international travel (33, 34). This study has provided an in-depth description of the North Macedonian pig sector, contrasted these practices with those in Kosovo, and highlighted target areas for disease risk mitigation efforts.

North Macedonian farms had a high rate of turnover among their pigs; this is consistent with census data that shows a relatively large proportion of small farms do not maintain pigs year-to-year, making registration of, and outreach to, these small holder farms a challenge. The predominant use of commercial feed (97.2%) and grain (38.7%) suggests sites selling pig feed may provide good venues to access producers. The reports of feeding scraps and inedible parts to dogs and cats poses a zoonotic concern, not for ASF, but for other diseases such as pseudorabies or echinococcosis. Education on the risks of feeding food scraps to pets, and their role in the transmission of zoonoses, could be added to materials targeting swill feeding.

The North Macedonian pig sector seems to make good use of their veterinarians and to trust them as an information source (96.3%). However, only a third of producers called their veterinarians or the veterinary authority when they had pigs die. This should be highlighted as a major gap in current passive surveillance, a critical element for early detection and eradication. Burial and pit disposal predominated as methods of dead pig disposal; depending on the depth of burial, these methods should limit the access of wildlife to carcasses. The last outbreak of CSF in North Macedonia occurred in 2008 (1), yet vaccine compliance remains high. The vaccination campaign, financially sponsored by the state for farms with fewer than ten pigs, was suspended in October 2019 and North Macedonia is currently in the process of applying for CSF-free status. No other vaccines are compulsory. This history of vaccine compliance suggests that if an ASF vaccine were to become available, North Macedonia could expect high compliance from its producers, especially if financially backed. However, it should be mentioned, the initial phases after discontinuing a vaccine campaign are challenging, in that cases of ASF may be mis-diagnosed as re-emerging CSF. Diagnostic confirmation will be especially critical in differentiating the cause of illnesses among cases with similar clinical presentations.

A large number of households report raising pigs for home consumption and as a source of supplemental income. This reliance on pigs to feed families, as well as contribute to household income, highlights the extent to which an ASF introduction would impact the food and financial security of these producers. Adequate indemnity programs and education about these programs will be needed to support producers and get buy-in on timely disease reporting. Commercial farms reported higher rates of death and disease than backyard and family producers. These systems should be evaluated for potential husbandry, health (e.g., vaccination) and biosecurity interventions that may reduce these losses.

The pork value chain is predominantly localized, which may limit disease spread if ASF is introduced (35). The sale and slaughter of pigs is also highly seasonal. Religion and cultural habits may influence these patterns as well as the probability of ASF introduction into domestic pigs. Serbians in the North, and Catholic Albanians in the West, keep pigs and may have different practices and seasonality in their pig rearing and trade. The large concentration of Muslims in Western North Macedonia likely contribute to the low density of pig farms in this area.

Biosecurity is highest among commercial farms, but sanitary practices were in general fair to good. The primary areas that could consistently be improved upon would be the use of disinfection mats, the creation of separate clean and dirty areas, and the implementation of consistent disinfection protocols. The efficacy of disinfection mats and boot baths is dependent on removal of visible debris before use, and the use of appropriate disinfectants at adequate concentrations and for enough time (36, 37). While effective when used properly (36, 38), successful implementation of disinfection mats in small-holder settings may be a challenge due to lack of funds for disinfectants, rapid soiling, and improper protocols. Isolation of new pigs was reportedly uncommon—this may be associated with a lack of space, all-in all-out practices, or low perceived value. However, the overall percentage of producers reporting separating sick pigs was higher than that reporting isolating new pigs—suggesting that while areas for complete isolation may not exist, some level of separation may be possible. In general, most farms did not allow visitors near their pigs. Backyard and family farms were most likely to allow visitors to their premises to access their pigs. Training and future outreach should continue to highlight the risk of new pigs and visitors introducing disease. Visitors accessing pigs/farms was identified as a significant risk factor for disease introduction to backyard farms in Romania, and a case study of a backyard farm in Bulgaria cited visitors as the most likely route of ASF introduction (39, 40). Enclosure of pigs, and the removal and treatment of trash by the municipality, should help restrict wild-domestic pig interfaces contributing to disease exposure. While very few wild boar sightings were reported, ASF introduction via wild boar was listed as the highest risk pathway for Eastern Europe by recent studies (41). Outbreaks in wild boar in Bulgaria and Serbia confirm this risk in the region. Additional data on wild boar populations in these countries is needed.

Addressing hurdles to timely reporting is critical to a country's disease detection. Kosovar producers reported a high level of concern about the financial implications of reporting, suggesting the need for clear messaging and planning around indemnity for animals culled to control disease. In both North Macedonia (39.6%) and Kosovo (60%), producers reported not knowing how to report suspect ASF, while about a third of respondents in each country were concerned about post-reporting unknowns, culling, and restricted sale of pigs. Concern about reputation or attempting to control disease oneself, was less commonly reported than previous studies in the region have shown (42). These results indicate the need for transparency and communication about reporting. North Macedonia is in the process of improving their national surveillance programs. While they have ASF and CSF programs designed, they have not been widely implemented. The country currently relies heavily on passive surveillance, and the use of government authority to place quarantines during disease investigations. This heavy reliance on passive surveillance further emphasizes the need for education about diseases of concern, how to prevent disease introductions (e.g., biosecurity), what to look for, how to report, and what to expect during a disease investigation.

Our biosecurity risk scores and KDE maps highlight specific areas for targeted intervention. On the KDE maps we observe diminishment of the foci in the Southeast and Eastern regions, while retaining the foci in the North and West, when focusing on family and commercial farms vs. focusing on all farms, indicating that high biosecurity risk scores from family and commercial farms were contributing to high risk of ASF introduction in the North and Southwest, while backyard farms likely have a more important role for risk in the South and East. While the highest biosecurity risk scores were focused in the East, Southeast and West, our KDE maps register the highest risk areas in the West and North. This may be due to the small number of farms with high biosecurity risk scores and KDE being influenced by the number of farms in an area, particularly in the North; future work could consider standardizing biosecurity risk in a region by the number of farms in that region. Outreach for backyard farms at high risk of ASF introduction should be targeted in the East, particularly in Southeastern region. More general campaigns to reach all farm types are warranted in Southwestern, Northeastern and Eastern regions. Primary areas in which improvements could be made include: isolating/separating new pigs, using disinfection mats, and limiting access of visitors to pigs. Among family and commercial farms, investment in double fencing, separate clean and dirty areas, and educational training would improve current biosecurity risk scores.

MCA and HCPC divided farms into three groups—dimension 1 which captured commercial farms, dimension 2 which captured farms with high-risk practices, and a third group made up of the remaining farms. Our analysis suggests that farms with certain high-risk behaviors were likely to have profiles that demonstrated multiple risky behaviors resulting in an overall high biosecurity risk score profile. The specific behaviors that were highly correlated with dimension 2—not washing hands, allowing visitors including friends, neighbors, buyers, and slaughtermen, and external pigs onto the farm, and not using a disinfection mat—were correlated with high-risk biosecurity risk scores. This grouping generated a profile of responses to this subset of questions. Farms with similar responses are expected to have poor biosecurity practices, and thus high biosecurity risk scores, and should be targeted for education and improved biosecurity, i.e., a farm that does not practice regular handwashing before working with their pigs likely has other poor biosecurity habits, will likely have a high biosecurity risk score, and should be targeted for intervention.

The Kosovo pilot study was intended to gain awareness of practices in their pig sector to support the expansion of FAO activities, including biosecurity training that is actively under development. The low sample size from the pilot study in Kosovo implies we should interpret these results with caution. However, a few marked contrasts between North Macedonia and Kosovo, that may impact the risk of ASF spread, should be noted. Kosovo has good, consistent practices around keeping pigs confined and not allowing scavenging. However, Kosovar pig producers reported a much higher rate of swill feeding, and not treating food scraps that were fed to pigs. These responses indicate that while swill feeding is banned in surrounding European Union countries, it is still widely practiced in this region and should be highlighted as a topic for education campaigns (33). In general, losing pigs to illness was more widely reported in Kosovo than North Macedonia. The disposal of inedibles from slaughter and dead pig carcasses as thrown offsite and fed to dogs, could provide access from wildlife. More visitors and pigs from other farms were allowed on-site, and manure was moved offsite through sale and disposal methods, providing the means for disease introduction and spread. One third of respondents said they had not heard of ASF (compared to 1.5% in North Macedonia), and it was not reported as a top disease of concern from Kosovar producers. All of this suggests that education campaigns targeted at informing producers about ASF, its introduction pathways, clinical presentation, and how to report and seek aid, could improve early detection and reduce disease dissemination risk among these producers. The best means of reaching pig producers is through their veterinarians and television; North Macedonians also used the internet, while Kosovars preferred newspapers.

With data collected via a questionnaire, this study is subject to reporting bias by the respondents. In North Macedonia in particular, with questionnaires being administered by veterinarians, producers may have been more likely to report higher usage of veterinarians, higher levels of care, and stricter biosecurity practices. Additionally, outreach and educational campaigns targeting ASF awareness have been ongoing since 2018, which may have led producers to change or at least report higher quality practices. FAO training did occur in September, October, and November of 2019, while the initial phases of the survey were underway; however, these trainings were primarily targeted at veterinarians vs. producers and are not thought to have had much impact on the respondents. Survey responses are being used to inform updates and development of training materials for producers in the region. In the calculation of the biosecurity risk scores, non-answers were assigned a value of zero. This practice may have resulted in an underestimation of the biosecurity risk scores for some farms.

Overall, this study has provided a thorough review of the practices of the pig sector in North Macedonia, highlighting some similarities and contrasts with neighboring Kosovo, and discussing the potential strengths and vulnerabilities regarding the risk of ASF introduction and spread. We have highlighted some specific aspects (and regions) for improvement via additional and targeted educational campaigns and risk reduction interventions. This information will be of great value to inform risk assessments of ASF introduction/exposure, and modeling of ASF spread, if it is eventually introduced into the country. Ultimately, all of these tools will contribute to better prevention, early detection, and control efforts for ASF in North Macedonia and Kosovo.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available upon request.

AUTHOR CONTRIBUTIONS

KO'H performed the initial draft preparation, data curation and validation, development of the R-code, and formal analysis under supervision of BM-L. DB-A, MH, and BT developed the questionnaire and initiated recruitment of farms included in the study, collected and organized the raw data, and contributed to data cleaning and validation. BM-L supervised the development, implementation and interpretation of the analytic approach. All authors contributed to the project conceptualization and critical and extensive review and editing of the submitted manuscript.

FUNDING

Data collection was conducted by FAO through the Technical Cooperation Programme (TCP) (TCP/RER/3704 and TCP/KOS/3703). Data analysis was supported by The Ecology and Evolution of Infectious Diseases Program, Grant No. 2019-67015-28981 from the USDA National Institute of Food and Agriculture and the UC Davis Graduate Group in Epidemiology.

ACKNOWLEDGMENTS

Authors would like to acknowledge and thank the North Macedonian and Kosovar pig producers for their participation and provision of data.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fvets.2021.733157/full#supplementary-material

REFERENCES

1. World Organisation for Animal Health (OIE). *World Animal Health Information Database (WAHIS)* (2021). Available online at: https://wahis.oie.int/#/home (accessed April 25, 2021).
2. Njau EP, Entfellner JBD, Machuka EM, Bochere EN, Cleaveland S, Shirima GM, et al. The first genotype II African swine fever virus isolated in Africa provides insight into the current Eurasian pandemic. *Sci Rep.* (2021) 11:13081. doi: 10.1038/s41598-021-92593-2
3. Penrith ML, Vosloo W. Review of African swine fever: transmission, spread and control. *J South Afr Vet Assoc.* (2009) 80:58–62. doi: 10.4102/jsava.v80i2.172
4. Blome S, Gabriel C, Beer M. Pathogenesis of African swine fever in domestic pigs and European wild boar. *Virus Res.* (2013) 173:122–30. doi: 10.1016/j.virusres.2012.10.026
5. Sánchez-Vizcaíno JM, Mur L, Gomez-Villamandos JC, Carrasco L. An update on the epidemiology and pathology of african swine fever. *J Comp Path.* (2015) 152:9–12. doi: 10.1016/j.jcpa.2014.09.003
6. Pérez J, Fernández AI, Sierra MA, Herráez P, Fernández A, Martín de las Mulas J. Serological and immunohistochemical study of African swine fever in wild boar in Spain. *Vet Rec.* (1998) 143:136–9. doi: 10.1136/vr.143.5.136
7. Beltrán-Alcrudo D, Guberti V, de Simone L, de Castro J, Rozstalnyy A, Dietze K, et al. *African Swine Fever Spread in the Russian Federation and the Risk for the Region*. EMPRES watch. Food and Agriculture Organization of the United Nations, Rome (2009).
8. Jori F, Bastos AD. Role of wild suids in the epidemiology of African swine fever. *Eco Health.* (2009) 6:296–310. doi: 10.1007/s10393-009-0248-7
9. Mur L, Boadella M, Martínez-López B, Gallardo C, Gortazar C, Sánchez-Vizcaíno JM. Monitoring of African swine fever in the wild boar population of the most recent endemic area of Spain. *Transbound Emerg Dis.* (2012) 59:526–31. doi: 10.1111/j.1865-1682.2012.01308.x
10. Gallardo C, Fernández-Pinero J, Pelayo V, Gazaev I, Markowska-Daniel I, Pridotkas G, et al. Genetic variation among African swine fever genotype II viruses, eastern and central Europe. *Emerg Infect Dis.* (2014) 20:1544–7. doi: 10.3201/eid2009.140554
11. De la Torre A, Bosch J, Iglesias I, Munoz MJ, Mur L, Martínez-López B, et al. Assessing the risk of African swine fever introduction into the European Union by wild boar. *Transbound Emerg Dis.* (2015) 62:272–9. doi: 10.1111/tbed.12129
12. Bosch J, Rodríguez A, Iglesias I, Munoz MJ, Jurado C, Sánchez-Vizcaíno JM, et al. Update on the risk of introduction of African Swine fever by wild boar into disease-free European Union countries. *Trans Bound Emerg Dis.* (2016) 64:1424–32. doi: 10.1111/tbed.12527
13. Costard S, Jones BA, Martínez-López B, Mur L, de la Torre A, Martinez M, et al. Introduction of African swine fever into the European Union through illegal importation of pork and pork products. *PLoS ONE.* (2013) 8:e61104. doi: 10.1371/journal.pone.0061104
14. Galindo-Cardiel I, Ballester M, Solanes M, Nofrarías M, López-Soria S, Argilaguet JM, et al. Standardization of pathological investigations in the framework of experimental ASFV infections. *Virus Res.* (2013) 173:180–90. doi: 10.1016/j.virusres.2012.12.018
15. Gogin A, Gerasimov V, Malogolovkin A, Kolbasov D. African swine fever in the North Caucasus region and the Russian Federation in years 2007–2012. *Virus Res.* (2013) 173:198–203. doi: 10.1016/j.virusres.2012.12.007
16. Oura CAL, Edwards L, Batten CA. Virological diagnosis of African swine fever—Comparative study of available tests. *Virus Res.* (2013) 173:150–8. doi: 10.1016/j.virusres.2012.10.022
17. Cwynar R, Stojkov J, Wlazlak K. African Swine Fever Status in Europe. *Viruses.* (2019) 11. doi: 10.3390/v11040310
18. Penrith ML, Vosloo W, Jori F, Bastos ADS. African swine fever virus eradication in Africa. *Virus Res.* (2013) 173:228–46. doi: 10.1016/j.virusres.2012.10.011
19. Gallardo C, Nieto R, Soler A, Pelayo V, Fernández-Pinero J, Markowska-Daniel I, et al. Assessment of African Swine Fever Diagnostic techniques As A Response To The Epidemic Outbreaks In Eastern European Union countries: how to improve surveillance and control programs. *J Clin Microbiol.* (2015) 53:2555–65. doi: 10.1128/JCM.00857-15
20. Danzetta ML, Marenzoni ML, Iannetti S, Tizzani P, Calistri P, Feliziani F. African Swine fever: lessons to learn from past eradication experiences. a systematic review. *Front Vet Sci.* (2020) 7:296. doi: 10.3389/fvets.2020.00296
21. Berthe F. *The Global Economic Impact of ASF*. Washington, DC: World Organization For Animal Health (OIE) (2020). doi: 10.20506/bull.2020.1.3119
22. Kukielka EA, Martínez-López B, Beltrán-Alcrudo D. Modeling the live-pig trade network in Georgia: implications for disease prevention and control. *PLoS ONE.* (2017) 12:e0178904. doi: 10.1371/journal.pone.0178904
23. Beltrán-Alcrudo D, Kukielka EA, de Groot N, Dietze K, Sokhadze M, Martínez-López B. Descriptive and multivariate analysis of the pig sector in Georgia and its implications for disease transmission. *PLoS ONE.* (2018) 13:e0202800. doi: 10.1371/journal.pone.0202800
24. Aanensen D, Huntley D, Feil EJ, al-Own F, Spratt BG. (2009). EpiCollect: linking smartphones to web applications for epidemiology, ecology and community data collection. *PLoS ONE.* 4:e6968. doi: 10.1371/journal.pone.0006968
25. RStudio Team. *RStudio: Integrated Development for R* (2015). Available online at: http://www.rstudio.com/ (accessed April 28, 2021).
26. Silverman BW. *Density Estimation for Statistics and Data Analysis*. New York, NY: Chapman and Hall New York (1986).
27. Abdi H, Williams L. Principal component analysis. *WIREs Comp Stat.* (2010) 2:433–59. doi: 10.1002/wics.101
28. Husson F, Le S, Pagès J. *Exploratory Multivariate Analysis by Example Using R*. Boca Rato, FL: Hall/CRC (2017). doi: 10.1201/b21874
29. Kassambara A. *MCA - Multiple Correspondence Analysis in R: Essentials* (2017). Available online http://www.sthda.com/english/articles/31-principal-component-methods-in-r-practical-guide/114-mca-multiple-correspondence-analysis-in-r-essentials/ (accessed Oct 4, 2020).
30. Argüelles M, Benavides C, Fernández I. A new approach to the identification of regional clusters: hierarchical clustering on principal components. *Appl Econ.* (2014) 46:2511–9. doi: 10.1080/00036846.2014.904491
31. Le S, Josse J, Husson F. FactoMineR: a package for multivariate analysis. *J Stat Softw.* (2008) 25:1–18. doi: 10.18637/jss.v025.i01
32. Kassambra A, Mundt F. *factoextra: Extract and Visualize the Results of Multivariate Data Analyses* (2017). Available online at: https://CRAN.R-project.org/package=factoextra (accessed October 1, 2021).
33. Jurado C, Martínez-Avilés M, De La Torre A, Štukelj M, de Carvolho Ferreira HC, Cerioli M, et al. Relevant Measures To Prevent The Spread Of African Swine Fever In The European Union Domestic Pig Sector. *Front Vet Sci.* (2018) 16:77. doi: 10.3389/fvets.2018.00077
34. Nielsen SS, Alvarez J, Bicout D, Calistri P, Depner K, Drewe JA, et al. Risk assessment of African swine fever in the south-eastern countries of Europe. *EFSA J.* (2019) 17:5861. doi: 10.2903/j.efsa.2019.5861
35. Martínez-López B, Ivorra B, Ramos AM, Fernández-Carrión E, Alexandrov T, Sánchez-Vizcaíno JM. Evaluation of the risk of classical swine fever (CSF) spread from backyard pigs to other domestic pigs by using the spatial stochastic disease spread model Be-FAST: the example of Bulgaria. *Vet Microbiol.* (2013) 165:79–85. doi: 10.1016/j.vetmic.2013.01.045
36. Amass SF, Vyverberg BD, Ragland D, Dowell CA, Anderson CD, Stover JH, et al. Evaluating the efficacy of boot baths in biosecurity protocols. *J Swine Health Prod Swine Health Prod.* (2000) 8:169–73.
37. Amass SF, Ragland D, Spicer P. Evaluation of the efficacy of a peroxygen compound, Virkon(R)S, as a boot bath disinfectant. *Swine Health Prod.* (2001) 9:121–3.
38. Dee S, Deen J, Pijoan C. Evaluation of 4 intervention strategies to prevent the mechanical transmission of porcine reproductive and respiratory syndrome virus. *Can J Vet Res.* (2004) 68:19–26.
39. Zani L, Dietze K, Dimova Z, Forth JH, Denev D, Depner K, et al. African swine fever in a Bulgarian backyard farm-a case report. *Vet Sci.* (2019) 6:94. doi: 10.3390/vetsci6040094
40. Boklund A, Dhollander S, Vasile TC, Abrahantes JC, Bøtner A, Gogin A, et al. Risk factors for African swine fever incursion in Romanian domestic farms during 2019. *Sci Rep.* (2020) 10:10215. doi: 10.1038/s41598-020-66381-3
41. Taylor RA, Condoleo R, Simons RRL, Gale P, Kelly LA, Snary EL. The risk of infection by African swine fever virus in European swine through boar movement and legal trade of pigs and pig meat. *Front Vet Sci.* (2020) 9:486. doi: 10.3389/fvets.2019.00486

42. Vergne T, Guinat C, Petkova P, Gogin A, Kolbasov D, Blome S, et al. 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. *Trans Bound Emerg Dis.* (2016) 63:e194–204. doi: 10.1111/tbed.12254

Author Disclaimer: The views expressed in this paper are those of the author(s) and do not necessarily reflect the views or policies of FAO.

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

The reviewer EK declared a past co-authorship with one of the authors BM-L to the handling editor.

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

Frontiers Media SA remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Copyright © 2021 O'Hara, Beltrán-Alcrudo, Hovari, Tabakovski and Martínez-López. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.

frontiers in Veterinary Science

ORIGINAL RESEARCH
published: 13 January 2022
doi: 10.3389/fvets.2021.707819

Prevention and Control of African Swine Fever in the Smallholder Pig Value Chain in Northern Uganda: Thematic Analysis of Stakeholders' Perceptions

T. Aliro[1†], *E. Chenais*[2*†], *W. Odongo*[1], *D. M. Okello*[1], *C. Masembe*[3] *and K. Ståhl*[2]

[1] *Faculty of Agriculture and Environment, Gulu University, Gulu, Uganda,* [2] *Department of Disease Control and Epidemiology, National Veterinary Institute, Uppsala, Sweden,* [3] *Department of Zoology, Entomology and Fisheries Science, College of Natural Sciences, Makerere University, Kampala, Uganda*

OPEN ACCESS

Edited by:
*Barbara Wieland,
University of Bern, Switzerland*

Reviewed by:
*Jenny-Ann Toribio,
The University of Sydney, Australia
Polly Compston,
Royal Veterinary College (RVC),
United Kingdom*

***Correspondence:**
*E. Chenais
erika.chenais@sva.se*

† *These authors have contributed equally to this work*

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

Received: *10 May 2021*
Accepted: *06 December 2021*
Published: *13 January 2022*

Citation:
Aliro T, Chenais E, Odongo W, Okello DM, Masembe C and Ståhl K (2022) Prevention and Control of African Swine Fever in the Smallholder Pig Value Chain in Northern Uganda: Thematic Analysis of Stakeholders' Perceptions. Front. Vet. Sci. 8:707819. doi: 10.3389/fvets.2021.707819

African swine fever (ASF) is endemic in Uganda and considered a major constraint to pig production. In the absence of a vaccine, biosecurity is key for ASF prevention and control. To improve prevention and control on farm and community level there is need for more knowledge on current application of biosecurity practises, and better understanding of how pig value chain actors perceive prevention and control. To achieve this, a qualitative interview study involving focus group discussions (FGD) was conducted with actors from the smallholder pig value chain in northern Uganda. Six villages were purposively selected based on previous outbreaks of ASF, preliminary perceived willingness to control ASF, and the representation of several different value chain actors in the village. Results indicated that biosecurity practises such as basic hygiene routines including safe carcass handling, minimising direct and indirect contacts between pigs or between pigs and people, trade restrictions and sharing of disease information were implemented in some of the villages. Thematic analysis based on grounded theory revealed six categories of data relating to ASF prevention and control. Together these categories form a logical framework including both enablers and hindrances for ASF prevention and control. In summary participants mostly had *positive perceptions of ASF biosecurity, describing measures as effective.* Participants further possessed *knowledge* of ASF and its transmission, some of which was in line with known scientific knowledge and some not. Nevertheless, participants were hindered from preventing and controlling ASF due to *biosecurity costs* and a need to *prioritise family livelihood* over disease transmission risks, incompatibility of current biosecurity practises with *local culture, traditions and social contexts* and finally lack of *access to veterinarians or, occasionally, low-quality veterinary services*. The constraints could be addressed by applying participatory processes in designing biosecurity measures to ensure better adaptation to local cultural and social contexts.

Keywords: African swine fever, disease control, focus group discussion, pork, prevention, northern Uganda

INTRODUCTION

Pig production in Uganda involves predominantly very small herds kept under free-range management, tethered or more rarely, housed (1–3). More than 80% of herds consist of one to five pigs (4). Despite the small average herd size, the Ugandan pig population increased from 3,184,0000 in 2008 to 4,037,000 in 2016 (5). Uganda is reported to have the highest pork consumption in East Africa with an estimated annual per capita pork consumption of 3.4 kg (6, 7). Pig production in Africa is frequently associated with outbreaks of African swine fever (ASF) (8), endemic in Uganda (9). ASF is a viral disease of domestic pigs and European wild boar caused by African swine fever virus (ASFV), the sole member of the genus *Asfiviridae* (10). The disease is typically associated with high case fatality rates and clinical presentations such as high fever, anorexia, cyanosis, incoordination of movements and recumbency (11–13). Outbreaks of ASF are generally attributed to reducing the potential of pig production to contribute to income generation and poverty reduction (8). In Uganda outbreaks have been shown to have negative impact for smallholder farmers, with economic consequences increasing with the herd size and social effects such as failure to pay for school or public health fees being reported (3, 14–16). Transmission of ASF mainly occurs through direct and indirect contacts between naïve and infected pigs or products in the domestic pig-to-pig epidemiological cycle (8). In this cycle transmission further depends on the activities of people along the value chain (farmers, traders or middlemen, slaughter slab operators, butchers, pork restaurant operators and consumers), and thus all these actors are important for achieving disease control (17, 18). In the absence of vaccines, consistent application of biosecurity measures remains the only tool for preventing and controlling ASF (19, 20). In typical smallholder systems farm biosecurity is however generally limited or non-existent (21–24).

Previous studies in northern Uganda revealed that smallholder farmers have mostly positive attitudes towards the protective potential of biosecurity (3, 25), but invest very little of their pig farming income into it (14). Studies from both this and other contexts have further shown that smallholder farmers have complex livelihood situations with biosecurity representing just one of numerous concerns in their livestock production (25, 26). To prevent and control ASF, more information is needed about how implementation of biosecurity can be improved throughout the value chains. As a first step, this study aimed to explore biosecurity measures currently in use in the smallholder pig value chain in northern Uganda with a particular focus on the stakeholders' perceptions towards ASF prevention and control.

MATERIALS AND METHODS

Study Area

The study was conducted in the Acholi subregion of northern Uganda. The subregion is among the poorest Uganda, partly due to a period of civil unrest between 1986 and 2006 (27). The Acholi people traditionally keep domestic animals both for livelihood requirement and as a part of their cultural identity (28). According to the Acholi cultural tradition, lack of respect for spirits is the major cause of "*gemo*" (epidemics). Many of the Acholi were internally displaced and lost their domestic animals during the period of civil unrest. Since 2006 the sub-region is under a government recovery program including restocking and promoting of pig farming. Despite frequent ASF outbreaks sustenance smallholder pig farming has become a major economic activity in the sub-region (9).

Study Design and Participant Selection

In a qualitative interview study performed in October 2019 focus group discussions (FGD) were conducted to assess biosecurity measures currently in use, and elicit stakeholders' perception of ASF prevention and control. In the context of this study the term "perceptions" included aspects such as the practical feasibility, factors enabling or hindering implementation, and perceived protective effect of prevention and control measures.

Three districts were purposively selected based on the relative importance of pig business and from each of these two villages were included (Unyama-A and Cwero in Gulu district, Pabala and Kalamomiya in Omoro distrct, Toncwiny and Kal-A in Amuru district) (**Figure 1**). Inclusion of villages was primarily based on field information of suspected ASF occurrence and farmers' preliminary perceived interest in ASF control. Field information of ASF occurrence consisted of outbreak reports from district veterinary officers consistent with ASF based on clinical signs and local epidemiology. Reports were not confirmed with biological testing: based on previous participatory diseases surveillance and absence of main differential diagnoses for ASF the diagnostic accuracy of the reports was deemed sufficient for the purpose of this study (9). Participants preliminary perceived interest in ASF control was based on information from district veterinary officer and confirmed or refuted during the recruitment process. Further, the availability of a suitable number (8–12) of pig farmers for the purpose of a group discussion and known presence of several different actors along the value chain such as middlemen, slaughter slab operators, butchers, and pork-joint[1] owners were considered in the selection. Farm or herd size was not among the inclusion criteria. Previous studies in the area show that pig production is almost exclusively performed by smallholder farmers with herd sizes ranging from 0 to 39 with an average of 3.7 pigs including piglets (14). Villages were selected by the first author in consultation with the district veterinary officers of each district. One FGD was held in each of the selected villages, hereafter identified as FGD 1 in Unyama-A village, FGD 2 in Kalamomiya village, FGD 3 in Pabala village, FGD 4 in Cwero village, FGD 5 in Kal-A village, and FGD 6 in Toncwiny village. The number of villages selected was based on the presumed number of FGDs needed to reach saturation. Participants for each FGD were further purposively selected with the intention to include as many different value chain actors as possible, and to have an equitable gender representation (**Table 1**). The purpose of the aspired group heterogeneity was to include a wide array of different experiences and perspectives. Participants were invited by the community animal health workers in the selected

[1] "Pork-joints" are small kiosk-like restaurants serving only pork.

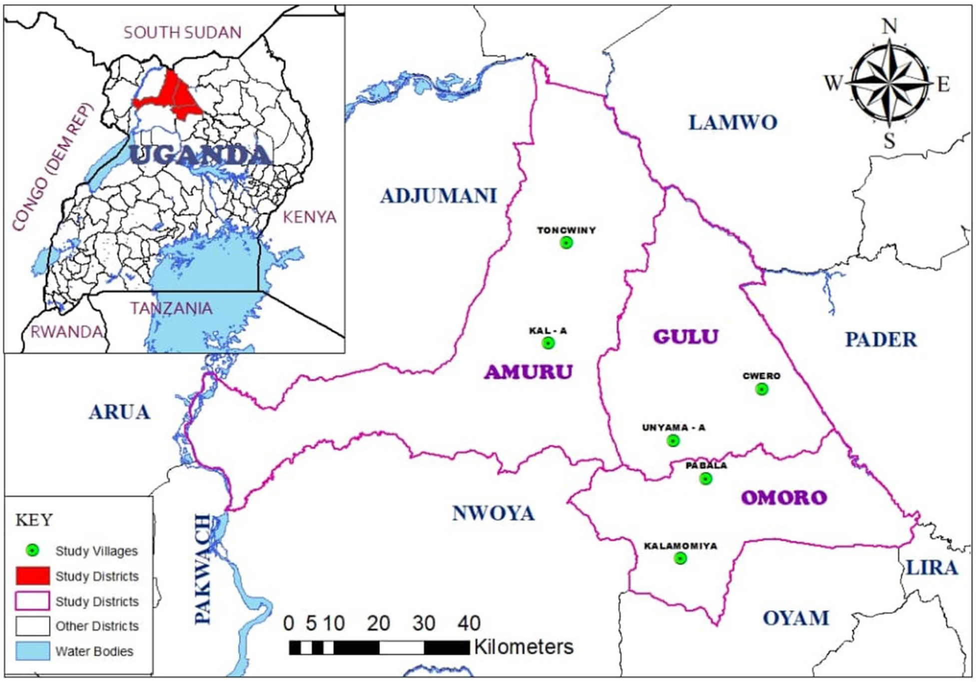


FIGURE 1 | Map of Amuru, Gulu and Omoro districts where a study was conducted in northern Uganda in October 2019. Variations in geographical locations of these districts include; 02045'N, 80 32000'E (Gulu), 02035'N, 32022'E (Omoro) and 02050'N, 33005'E (Amuru).

villages based on the mentioned inclusion criteria. The FGDs were conducted at venues that were convenient for participants, such as in community trading centres, sub-county headquarters, schools, health centres or the home of one of the participants. There were on average 11 participants per FGD. FGDs lasted on average 5 h 13 min (ranging from 4 h 20 min to 5 h 50 min), including a lunch break. Participants were compensated for their transport costs and lunch was provided in connexion with the interview.

Data Collection

The research team was composed of a facilitator (TA), a senior researcher (EC), and a translator proficient in both the local language (Acholi) and English. Both the facilitator and the translator had been trained in qualitative research approaches and the procedure for data collection prior to the study. The FGDs started with the facilitator introducing the purpose of the study, specifically emphasising that it was research and not a needs assessment or similar with possible immediate benefits for participants. It was explained that participation was voluntarily. Confidentiality was assured and permission sought to take photographs and make voice recordings, and participants signed a written consent form to this effect. The discussions which started with farmers' experience of ASF outbreaks (**Table 2**) were conducted in Acholi and simultaneously translated and recorded. Detailed notes were taken during the FGDs, and the recordings were subsequently transcribed verbatim. Discussions followed a topic guide (see **Appendix 1**) centred on the measures participants had implemented to prevent ASF outbreaks and control the spread of ASF during outbreaks. The facilitator guided the discussion according to the topic guide, while letting participants lead the discussion to subjects that were important to them.

Data Analysis

The field notes and transcripts of the audiotapes were merged to form one master set of notes for each FGD. In a first step, all mentions concerning biosecurity were identified (**Table 3**). Secondly, thematic analysis was applied to the master notes (29). This was done independently by two of the authors (TA and DMO). In this step, every segment of the data relevant to perceptions of prevention and control were coded to represent the initial stage in the conceptualisation of the transcribed data. These primary codes were allowed to emerge inductively through repeated reading of the data, while forming hypotheses about the data that were subsequently refined in repeated rounds of analysis, comparing and merging the two sets of codes (30). Applying axial coding, TA and DMO together sorted the primary codes into common themes (31) (see **Appendix 2**). Finally, TA combined themes associated with others to form six categories. The themes and categories are summarised in a matrix (**Table 4**) for ease of traceability back to the original data, to provide the relationship between the themes and the FGDs and to illustrate the frequency of mentions (32). The emerging categories, their internal relation, additive inference for ASF prevention and control, and a suggestion for improving implementation of biosecurity was visualised in a logical framework (**Figure 2**).

TABLE 1 | Distribution of focus group discussions (FGDs) participants' value chain roles and gender from a study in northern Uganda in October 2019. Traders are buyers of live pigs.

FGD /value chain role	Value chain roles[1]														Total No. of participants
	Purely farmer		Trader and butcher		Trader, butcher, and pork joint-owner		Trader, and pork joint-owner		Farmer, butcher and pork joint-owner		Farmer, trader, butcher, and pork joint-owner		Purely pork joint-owner		
Gender	M	F	M	F	M	F	M	F	M	F	M	F	M	F	
FGD-1	4	4							1						9
FGD-2	4	4							3				1		12
FGD-3	7	2			1						1	1			12
FGD-4	5	3							1	1					10
FGD-5	6	2	2				1								11
FGD-6	5	3	1			3									12
Total	31	18	3		1	3	1		5	1	1	1	1		66

[1]*Some participants were involved in several activities in the value chain.*

RESULTS

Participant Characteristics

A total of 65 participants (between nine and twelve per FGD) were included in the six FGDs (**Table 1**). Out of these, 48 were purely pig farmers and 17 were involved in different business along the value chain (some of these participants also kept pigs but did not consider pig farming their main occupation). Pig farmers had between three and six pigs each.

Experience of ASF Outbreaks

Recent ASF outbreaks were mentioned to have occurred in the months of April, May, June, August and October 2019, during both dry and wet season (**Table 2**). Sudden death, change in body colour displayed as red ears and hooves, reduced appetite, difficulty in walking and dullness were each mentioned by at least two FGDs as clinical signs suggestive of ASF. FGDS 2, 4, and 5 reported massive pig deaths as the determinant sign of ASF.

ASF Biosecurity Measures

During the FGDs, 20 different biosecurity measures were mentioned. Many of these were similar and seven groups of more general biosecurity or husbandry measures could be identified (**Table 3**).

Thematic Analysis of Perceptions of ASF Prevention and Control

During the thematic analysis, 39 themes were identified from the emerging primary codes. The themes were summarised into six categories (**Table 4** and **Appendix 2**). The categories included "ASF biosecurity measures perceived as effective," "local knowledge of ASF transmission," "implementation of biosecurity is partially hindered by its cost," "priority given to livelihoods," "local culture and traditions," and "access and quality of veterinary services." Narrative details of themes and categories are explored below.

ASF Biosecurity Measures Perceived as Effective

Biosecurity measures were generally perceived positively by participants. Construction of pigsties or fences were often mentioned as helpful for preventing contact between confined and free-range pigs, and with people. Participants in all FGDs stated that confined pigs are protected from coming into contact with infective materials (e.g., bone and pork) or contaminated water in the environment: *"Pigs confined in the pigsty survived; pigs that were released to be on free range contracted ASF and all died"* (FGD 3). Sharing information about ASF outbreaks was also seen as helpful, serving to alert farmers to improve biosecurity measures and to take protective measures if, for example, pork was brought home for consumption. Farm-gate buying and selling of live pigs was mentioned as a common practise. Participants in one FGD said that they would welcome stricter implementation of punitive measures set locally to improve biosecurity, such as obligatory confinement of pigs and trade restrictions concerning live pigs and pork if outbreaks have been recorded in the area. In this regard, participants said that

TABLE 2 | Details of recent African swine fever outbreak from a study in northern Uganda in October 2019.

Groups	Last occurrence	Participants' comments
FGD-1	April 2019	Common during cold weather, dry spell and beginning of rain.
FGD-2	June 2019	Serious during sunshine, and heavy rain season
FGD-3	May 2019, October 2019	Common during bad hot weather and rainy season
FGD-4	May/June 2019	During dry spell and in December when it is hot. When it's hot and a lot of wind
FGD-5	April/May 2019	When the rain starts every year. Comes during dry spell with sunshine and dust
FGD-6	April/June/Aug/2019	Outbreaks are always during dry season

FGD, focus group discussion.

people did not fully comply with existing by-laws: "*Some people follow the rules, but others don't*" (FGD 1).

Local Knowledge of ASF Transmission

Participants in all FGDs perceived that airborne transmission of ASFV could occur if the virus from infective tissues or ashes from burned carcasses was carried by wind. Similarly, participants stated that flies can be contaminated with ASFV while feeding on infective materials and then transmit the virus to feed or water, which in turn can infect healthy pigs. In all FGDs, participants mentioned that vegetables and water could be contaminated with saliva, faeces or urine from infected stray pigs and serve as a source of infection if served to healthy, confined pigs. Participants further said that faecal matter and urine excreted by infected confined pigs could contaminate feed left on the floor or in the feed trough. It was mentioned that infective remains of partly burned carcasses could be eaten by free-range pigs. In this regard, participants also said that pigs could dig up carcasses if they were not properly buried. In some FGDs, participants said that people who buy and bring pork home could infect healthy free-roaming pigs if bones were not discarded out of the pigs' reach.

Participants in all FGDs mentioned that confined pigs could become infected if butchers and middlemen wearing blood-stained clothes were allowed to enter the pigsty and touch pigs before purchase: *"Farmers would see money and just let the butcher enter the pigsty"* (FGD 2). Participants further said that stray boars that enter pigsties (either on their own or being driven into the house) to mate with sows could transmit ASFV. In some FGDs participants said that ASF transmission could occur if people who had handled infected pork subsequently handled pig feeds without first washing their hands. Likewise, they said that saucepans used to carry pork from the market and subsequently used to water pigs without prior washing could transmit ASF. They also described how ASF could be transmitted if the same wheelbarrow was used to carry contaminated maize from the fields and for pig feeds. Having clothes, gumboots and wheelbarrows strictly for use in the pigsty was mentioned as a good practise that could stop the spread of ASF. The practise of disinfecting shoes at the door and washing hands before entering the pigsty would still leave other body parts contaminated: *"Chemicals will kill the virus on gumboots and shoes, but not on hair or clothes"* (FGD 3).

Avoiding purchasing pigs during ASF outbreaks was mentioned as a way of preventing disease transmission because sick or in-contact pigs are frequently marketed: *"Farmers sell sick pigs cheaply without disclosing their health status to buyers"* and *"Buyers know sick pigs by their low price"* (both FGD 3).

TABLE 3 | African swine fever biosecurity measures mentioned in a study in northern Uganda in October 2019.

Mentions of biosecurity
General hygiene practises: Good hygiene practises, use of disinfectant, do not use the same equipment for pigs and at home
Minimising indirect contacts: Few attendants allowed in the pig house, non-attendants do not enter the pig house
Minimising direct pig-to-pig contacts: Build pig house, fence pig house, confinement of free-range pigs, tether pigs, stray pigs should not enter the pig house, do not borrow boars
Feed and water of good quality and sufficient quantity: Provide feed, avoid swill feeding, provide enough water
Safe carcass handling: Bury or burn carcasses
Restriction of trade in pigs and products: Don't bring pork home, stop buying pigs during outbreaks
Sharing of pig health information: Alert neighbours during outbreak, call veterinary personnel
Other: Remain close to pigs all the time

Participants mentioned "cool temperature" as one factor that could influence ASF transmission. According to their described experience, healthy pigs that were relocated to swampy areas during an ASF outbreak would not die. Meanwhile, sick pigs left on the farm would die of the fever, accelerated in their view, by high temperatures in the pig house. They further described how the wind would not transmit ASFV from carcasses if they were dumped in swampy areas: *"It is better to throw it in the water so that the virus is not blown by the wind"* (FGD 5). Farmers noted that staying close to pigs to immediately remove faeces could serve to maintain good hygiene, and that this could prevent the spread of ASF. Participants in one FGD mentioned that adoption of indigenous microorganism (IMO) technology for floor bedding (using rice bran) in the pigsty could decompose faeces and urine, serving the same purpose. Participants also said that the isolation of sick pigs prevented healthy pigs from succumbing to ASF. Among the different modes of isolation, participants mentioned transferring/relocating healthy pigs to disease-free villages. Provision of good-quality feeds in sufficient quantity was mentioned as boosting the immunity of pigs

TABLE 4 | Perceptions of African swine fever (ASF) prevention and control among pig value chain actors from a study conducted in northern Uganda in October 2019.

Categories and themes/FGD/Number of mentions	*FGD 1*	*FGD 2*	*FGD 3*	*FGD 4*	*FGD 5*	*FGD 6*	Total no. mentions
ASF biosecurity measures perceived as effective							
Pig can be confined in houses or by fences, and these can be constructed in different ways	✓	✓	✓	x	x	x	3
Confining pigs prevent contact with other pigs and people	✓	✓	✓	x	x	x	3
Restrict pigs' movement to control what the pigs eat and avoid contact with sick stray pigs and contaminated items	✓	✓	✓	✓	✓	✓	6
Disclosing animal health status	x	x	x	✓	✓	x	2
Implementation of local punitive measure	✓	x	x	x	x	x	1
Local knowledge of ASF transmission							
ASFV can be transmitted by the wind	✓	✓	✓	✓	✓	✓	6
Damp ASFV cannot be blown from carcasses dumped in the swamp	✓	✓	x	x	x	x	2
Flies and wind can carry infective materials	✓	✓	✓	✓	✓	✓	6
Dogs, pigs and people can bring contaminated pork or bone	✓	✓	✓	✓	✓	✓	6
Feed and water contaminated with urine, faeces and saliva	✓	✓	✓	✓	✓	✓	6
People contaminated with faeces and blood	✓	✓	✓	✓	✓	✓	6
Borrowing breeding boars for mating	x	x	✓	✓	✓	✓	4
Contaminated unwashed hands handling feed and pigs	x	x	✓	x	✓	x	2
Use of contaminated utensils, farm tools and protective gear	x	x	x	✓	✓	x	2
Middlemen and slaughterers can transmit disease	✓	✓	✓	✓	✓	✓	6
Trade in live pigs can transmit disease	✓	✓	✓	✓	✓	✓	6
Vets can transmit disease	x	x	x	✓	x	x	1
Cool temperatures protect pigs, heat kills ASFV	✓	✓	x	x	x	x	2
Disinfection using ash and "Jik"[1].	x	x	✓	✓	✓	x	3
Basic hygiene	x	x	✓	x	✓	x	2
IMO technology adoption[2].	x	x	x	x	✓	x	1
Leaving farm tools and protective gear at the pigsty	x	✓	✓	x	✓	x	3
Isolating sick or relocating healthy pigs	x	✓	x	x	✓	✓	3
Feed quality and quantity is important for good health and fast growth	x	✓	✓	x	x	x	2
Implementation of biosecurity is partially hindered by cost							
Disinfectants, cleaning materials, building materials, fuel and feeds are unaffordable	✓	✓	✓	✓	✓	✓	6
Priority given to livelihoods							
Carcasses are consumed at home or sold to raise some money and avoid total losses	✓	✓	✓	✓	✓	✓	6
Trade in live pigs to protect healthy ones, raise some money and avoid total losses	x	✓	✓	x	✓	✓	4

(Continued)

TABLE 4 | Continued

Categories and themes/FGD/Number of mentions	***FGD 1***	***FGD 2***	***FGD 3***	***FGD 4***	***FGD 5***	***FGD 6***	**Total no. mentions**
People bring pork home to eat	✓	✓	✓	✓	✓	✓	6
Butchers and middlemen make a profit during outbreaks	✓	✓	✓	✓	✓	✓	6
Selling sick pigs poses risk of ASF spread	✓	✓	✓	✓	✓	✓	6
Local culture and traditions							
Burial of animals is forbidden in the Acholi culture and tradition	x	x	✓	✓	✓	✓	4
It is hard work to dig a grave	x	x	x	x	✓	x	1
It is psychologically painful because it reminds you of burying loved ones	x	x	x	✓	x	✓	2
People can throw bones, pork, and intestine in the pigsty to intentionally infect healthy pigs	x	✓	✓	✓	✓	✓	5
Access and quality of veterinary services							
Smallholder farmers have access to veterinarians	✓	x	✓	✓	✓	✓	5
Smallholder farmers do not have access to veterinarians	✓	✓	✓	✓	x	x	4
Veterinary treatments are helping	✓	x	✓	✓	x	✓	4
Veterinary treatments are not helping	✓	✓	✓	✓	✓	x	6
There is no medicine or vaccine for ASF	x	✓	✓	✓	✓	✓	5

ASFV, African swine fever virus; FGD, focus group discussion; IMO, indigenous microorganisms.
Categories are written in bold on a grey background, themes belonging to each category are listed underneath.

✓ = *theme was present in this focus group*

✗ = *theme was not present in this focus group*

[1]*Ash (residue after burning materials) are poured at door entrance to replace footbath. "Jik" is the trade name of a detergent.*
[2]*Indigenous microorganism e.g. "lactic acid bacteria" trapped in a solution are poured on floor of pigsty to decompose pig faeces.*

and stimulating fast growth. The latter was specifically said to be useful for getting pigs to market size before the onset of anticipated ASF outbreaks. ASF outbreaks was mentioned to occur throughout the year: *"We believe that it is brought by hot weather"* and *"If it is serious sunshine, the outbreaks get serious"* (both FGD 2).

Implementation of Biosecurity Is Partially Hindered by Its Cost

Participants revealed that many community members could not afford to buy pig feeds or disinfectants. In addition, commercial feeds (e.g., maize and rice bran) were mentioned as being difficult to access. Farmers who could not afford to buy feed said that they let pigs roam free to scavenge, and that supplementary feeding was done using swill collected for free from restaurants or home kitchens. Participants frequently mentioned that it would be too costly to use fuel to burn carcasses, and that dead pigs need to be marketed (and not destroyed) to recover as much of the incurred losses as possible. Some farmers mentioned that they manage to prioritise investing in biosecurity and buying materials for constructing and cleaning the pigsty.

Priority Given to Livelihoods

Participants said that they slaughtered sick pigs for home consumption, sold pork from pigs that had died to neighbouring communities to raise money, and used pork to barter for other food items as a way of coping with the hardship experienced during ASF outbreaks: "*When you have a pig sick with ASF and don't want others to know, you slaughter it and sell it quickly, and say that the pig was strangled by the tethering rope*" (FGD 4). Participants also said that sick pigs were sold to protect the health of the remaining pigs, to raise money and to avoid the total loss of investments that would occur if the pigs succumbed to ASF. Healthy pigs that had been in contact with suspected ASF cases were reportedly sold for the same reasons and with the aim to use the earnings to restock pigs after the outbreak. As pork is cheaper than usual during outbreaks, participants said that people would take these opportunities to buy pork and bring it home for family consumption or go to eat at places such as pork joints and hotels[2]. Participants further reported that whenever pigs are slaughtered, neighbours not rearing pigs might buy pork and take it home to eat. Farmers reported that middlemen and butchers would buy pigs (sick and healthy) at a low price during ASF outbreaks, but maintain the regular sale price for both fresh and cooked/roasted pork, thus taking advantage of a low buying price to make a profit.

Local Culture and Traditions

Participants in several FGDs mentioned that, according to the Acholi culture and tradition, the burial of animals is forbidden. They said that if animals were buried, other animals would die. In some FGDs, participants said that all animals except dogs could be buried without there being bad consequences, whereas burying dogs would be associated with the disappearance of rain for a year. Apart from the cultural taboo related to the actual act of burying animal carcasses, frequent mention was made of contextual constraints regarding throwing away food, and in particular meat, in the poor study communities. Repeated mention was also made of people possibly digging up buried carcasses to get access to the meat. In addition, they said that burying animals is painful because it reminds them of burying loved ones. The hard work required to dig a hole deep enough to prevent carcasses being exhumed by animals or people was mentioned as discouraging the implementation of this practise for safe carcass disposal. All FGDs mentioned that people (in most cases neighbours) sometimes threw bones, pork or intestine in other peoples' compounds to infect pigs deliberately out of jealousy. This was exemplified as follows: *"Poisoning of pigs in our area by people who are jealous has become a culture"* (FGD 4) and *"When I saw somebody dropping pig bones in my pigsty, I was furious. I immediately let all the pigs out, and they all ran to the swampy area. Some pigs died, others survived"* (FGD 3).

Access and Quality of Veterinary Services

Smallholder farmers in four FGDs expressed their trust in local veterinarians for the diagnosis of ASF as well as for giving advice on disinfection procedures and other prevention practises. In the study area, veterinarians qualified to diagnose and treat animals can be either employed by the government or private. Participants mentioned that veterinarians were generally available, and they were praised for giving advice to farmers on how to manage pig health during outbreaks. However, three FGDs had generally negative accounts, mentioning that veterinarians frequently either did not respond to farmers' calls, or responded so late that all the pigs they treated ended up dying: "*Veterinarians say there are no drugs, so won't respond to farmers' calls*" (FGD 4). The negative accounts further included mention of veterinarians offering generally bad services and giving false expectations about the survival possibilities of ASF-infected pigs if treated: *"Veterinarians injected pigs, the medicine didn't work, all the treated pigs died"* (FGD 5). In this regard they also mentioned some veterinarians asking for payment from farmers for treatment, even if there is no hope of saving the pigs. In one FGD, farmers noted that veterinarians could play a role in transmitting ASF as they reuse needles between different herds. These accounts also included complaints about veterinarians not making farmers aware of the dangers of ASF.

Participants in five FGDs mentioned that they had no hope of saving the lives of pigs infected with ASF, and that the disease has no treatment or vaccine, unlike other pig diseases that can be cured if sick pigs are treated: *"Farmers vaccinate[3] against other diseases such as flu and worms" (FGD 4), "The vaccination has no effect on ASF"* (FGD 2). Farmers said that they do not call veterinarians to treat pigs for ASF as there is no cure for it: *"Veterinarians would say there is no drug for ASF, so they would not come to treat it"* and *"It's not easy, some pigs could still die even if the vet treated them"* (FGD 3).

[2]"Hotel" is the name used in Ugandan English for restaurants serving different sorts of meat.

[3]It should be noted that in the local context "vaccinate" might refer to both preventive and curative injections. This was not further investigated here.

Logical Framework

The emerging categories encompassed both "enablers" and "hindrances" for ASF prevention and control (**Figure 2**). Participants mostly had positive perceptions of ASF biosecurity, describing many measures as feasible to implement and effective for preventing or controlling ASF outbreaks. Together with rich local knowledge of ASF transmission this enabled prevention and control of ASF. Some of the knowledge corresponded to current scientific understanding and practises and some not. Misbeliefs regarding aerial (air-borne) transmission or virus survival in ash might hamper effective implementation of biosecurity, whereas knowledge regarding transmission *via* direct and indirect contacts facilitated achieving control. Four categories were seen as hindrances. Participants' efforts to implement ASF prevention and control measures were limited by: biosecurity costs such as building material and pig feeds that is necessary if pigs are to be confined; the need to prioritise family livelihood over known disease transmission risks connected to for example trade in sick pigs or carcasses from pigs that have died from disease that could be ASF; local culture, traditions and social factors that e.g., complicated safe destruction of carcasses; and finally lack of access to veterinarians or, occasionally, due to low-quality veterinary services. Together this often resulted in failed biosecurity, with the main hindrances seemingly being the cost of the measures, and to some extent the incompatibility of current biosecurity practises with local traditions, context and culture. Both these constraints could be addressed by adapting biosecurity measures to local cultural, social and economic contexts in a participatory process involving the concerned end users.

DISCUSSION

This study showed that perceptions of biosecurity in the smallholder pig value chain in northern Uganda were mostly positive, especially regarding the preventive effect of rather simple measures such as confining pigs and not buying pork during outbreaks. The study did not seek to assess participants' knowledge of ASF, but still captured rich accounts of local knowledge about ASF transmission. It therefore appeared as if neither participants' perception of biosecurity nor their knowledge were the main limiting factors for implementation of ASF biosecurity, in accordance with previous studies from similar settings in Uganda (3, 33).

Health behaviour models have been used to describe and increase the understanding of people's behaviour and decision making in relation to their own or their animals health or disease risks (34). Many such models refer to social cognitive behavioural theory to explain behaviour and decision making, in short attributing the factors determining behaviour to the characteristics of the individuals and their social networks (35–38). The categories emerging as enablers of implementation of biosecurity in this study ("ASF biosecurity measures perceived as effective" and "local knowledge of ASF transmission") could be considered as social cognitive factors, relating to beliefs, attitudes or knowledge (39). Categories hindering implementation of biosecurity ("implementation of biosecurity is partially hindered by its cost," "priority given to livelihoods," "local culture and traditions," and "access and quality of veterinary services") however, were linked to contextual and social factors (40). Ebata et al. (40) describe how such contextual factors can make compliance difficult or even impossible for local people. According to the results, costs of constructing houses or enclosures and providing feed if pigs are prevented from scavenging were in many cases perceived as unaffordable, and could thus not be implemented despite the positive perceptions of these measures. Similar reasons for the failure to implement the most basic biosecurity measures necessary for minimising direct and indirect contacts have previously been reported (16, 33, 41). Likewise, minimal investments in pig feeds have previously been reported from the same area (14), with pig diets consisting of vegetables, cassava peelings and swill, or pigs scavenging for food. Swill feeding, which is continuously practised as a way of reducing feed costs, is a risk factor for ASF management, especially in endemic areas (3, 22, 42). Affordability of inputs and measures that are developed and adapted with end users, thus ensuring suitability and local acceptance, have been suggested as key to achieving functional biosecurity (43). The term "functional biosecurity" is used here to indicate that it is the operational end-result of the total biosecurity efforts, that sufficient biosecurity is always implemented at all risk activities, that is the most important aspect of biosecurity. The opposite, failed biosecurity, have been attributed to lack of biosecurity routines or equipment (biosecurity hardware), or routines that are prescribed but not implemented (biosecurity software) (44).

Providing for the family livelihood and sustaining income were clear priorities for the participants, overriding other concerns such as the risk of transmitting disease or not complying with regulations such as trade restrictions in connexion with ASF outbreaks. The high poverty levels in the study area, among the highest in Uganda (45), most probably contribute to the priority given to sustaining income. In the study area, pigs are mostly not kept for household consumption, but mainly to provide money for school fees or unforeseen healthcare events, and to barter for agricultural labour (14). Consequently, the sale and slaughter of clinically sick or in-contact pigs is practised (14, 40, 46) in order to retain the benefits from this resource, support household livelihoods and avoid financial loss. This coping mechanism was reported in this study. Participants also described how traders and butchers buy pigs at lower prices during ASF outbreaks but sell at normal prices, hence making greater profits and possibly contributing to ASF transmission while travelling to affected villages in search of cheap pigs.

The study noted how the lack of adaption of biosecurity measures to local culture and traditions resulted in failed implementation. Specifically, this concerned the disposal of carcasses from pigs that have died from the disease as a taboo linked to misfortunes, which were frequently reported in connexion with the burial of animal carcasses. In addition to being an important protein source in the food-insecure study area, the local communities considered meat a delicacy and, as such, it is unacceptable to bury or dispose of meat by burning. Consequently, a willingness to buy or barter pork from dead pigs

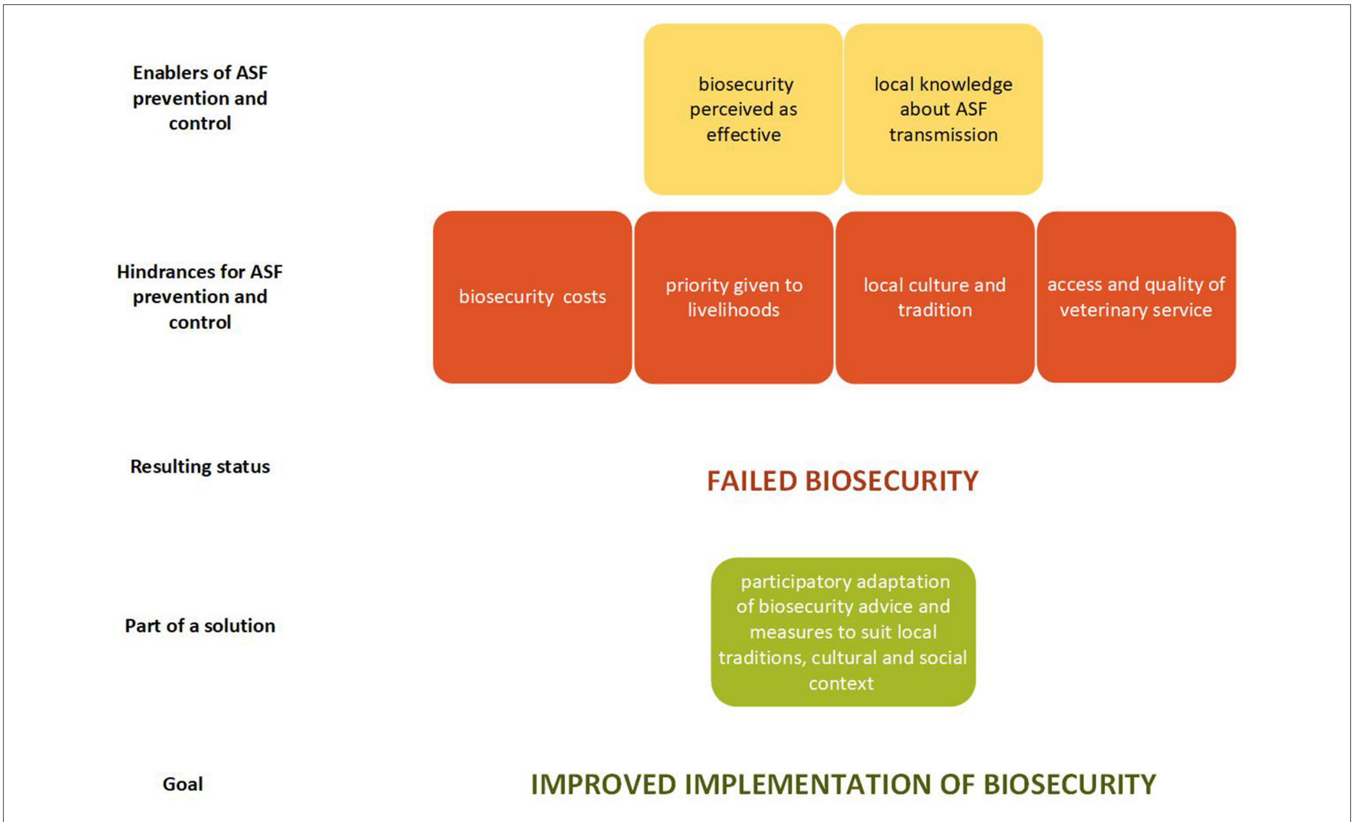


FIGURE 2 | Logical framework illustrating the results from a study in northern Uganda in October 2019.

was reported. The opportunity to make money from diseased or dead pigs serves as a disincentive to dispose of carcasses (3, 14, 47). Additionally, gathering to buy or barter pork from dead pigs allows community members to maintain social capital around an otherwise mere catastrophic event. In both these examples, pork serves as a social and economic resource that concurrently carries the negative attribute of possible ASF transmission. It was reported that carcasses disposed of by burial were exhumed for consumption. Other means of carcass disposal or virus inactivation that fitted better with local culture and traditions (such as heating or drying out of the reach of pigs) are thus needed to achieve functional biosecurity in this context. (40) Ebata et al. (40) discuss how farmers are hindered from investing in biosecurity by contextual or structural factors such as poverty. Likewise, in this study, resource constraints as well as cultural and traditional factors seemed to influence participants' opportunities to improve implementation of biosecurity. As an example of how implementation of biosecurity can be improved in resource poor settings and in agreement with local culture and traditions, a study from Timor-Leste report that participatory adaptation of biosecurity measures to the local context and applying methods inspiring community commitment motivated changes in pig management preventing ASF outbreak in study villages (48, 49).

Finally, the results suggested that access to veterinary health care was limited and hindered ASF prevention and control for some participants. In addition, the professional relationship between local veterinarians and farmers was complicated by suspicions that veterinarians' lack of clinical hygiene might contribute to the spread of ASF. Wesonga et al. (50) conclude that animal disease management in Uganda is ineffective, and that this is associated with inadequate and inefficient delivery of even the most basic, mandatory veterinary services.

There is no evidence supporting aerial (air-borne) transmissions of ASFV for more than a few metres inside and around pig pens (51, 52). According to local knowledge, however, ASFV was frequently mentioned to be transmitted aerially, and ashes of burnt pig carcasses mentioned as a risk factor for transmission. Farmers who perceive ASF as air-borne are unlikely to implement biosecurity measures that could prevent introduction of ASF, as these will not be perceived as effective if the virus "flies in the air." Likewise, an effective way of eliminating ASFV by burning carcasses at temperatures higher than 60°C (53, 54) will not be performed if the ashes are considered infective. In this regard education actions targeting specific epidemiological subjects of concern might improve implementation of biosecurity.

The study design included purposive selection of study sites and participants. This ensures that the results are important for the local context but limits how the results can be extrapolated to other contexts. In this regard the selected farmers were considered to provide a fair representation of the study population in terms of herd size and pig management.

Recent ASF outbreaks was reported from all villages, no further information regarding these outbreaks was however collected meaning that associations between individual responses regarding perceptions of ASF prevention and control and experiences of ASF outbreak could not be investigated. Equal gender representation was not achieved in this study. Although men make most decisions concerning resource allocation for biosecurity, pigs are mostly managed by women (4). The underrepresentation of women could thus have led to selection bias in this regard. FGDs were held in Acholi but the analysis was made from transcripts translated to English. This could have led to loss of information depth (55). In this study this risk was reduced as the first author speaks both Acholi and English. Aspects of hidden and open power dynamics affecting how people can express their opinion and share experiences are present in all groups and will impact on study results (56, 57). Common ways to minimise this bias is to aspire that groups are as homogenous as possible regarding i.e. gender, occupation or poverty level, and not seek consensus but encourage diversity (58). In this study efforts were made to record all opinions and consensus were not sought. Frequency of mentions were however recorded, with themes that were more present than others in the data given more weight in the final (qualitative) analysis.

In conclusion this study demonstrated that despite mostly positive perceptions of biosecurity, biosecurity measures were not being implemented due to costs of feed and housing, and the fact that family livelihood had to be prioritised over investments in disease control. Other hindrances were limitation in veterinary access and quality of services, and biosecurity measures that were not adapted to local culture and traditions. Achieving functional ASF prevention and control thus seems to require careful adaption of biosecurity advice in participation with end users, taking local traditions, culture and the socioeconomic context into consideration. Access to pig feed and quality veterinary services are aspects that need attention in this regard. The inclusion of local veterinarians in participatory discussions on biosecurity and herd health could strengthen the client-veterinary link and improve veterinary access.

DATA AVAILABILITY STATEMENT

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

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by School of Health Sciences Research and Ethics Committee, Makerere University Ref. No. 2019-062. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

This study was designed by EC and KS. EC and TA performed the fieldwork. TA and DMO conducted the thematic analysis. TA drafted the manuscript. EC interpreted and conceptualised the results. All authors revised and approved the final manuscript.

FUNDING

This study was carried out with financial support from the Swedish Research Council VR (ASF-Implement: contract no. 2017-05518), African Union research grants (ASF-RESIST: contract no. AURG II-1-196-2016) and Gulu University (ADB-HEST: contract no. P-UG-IAD-001).

ACKNOWLEDGMENTS

We thank Kioko Robert and Mwaka David for providing a conducive reading environment and internet access. We would like to thank the smallholder pig farmers and pig traders who gave their time and openly shared their experiences and will make sure that results are made accessible for their benefit during the course of the ASF-Implement-project. We thank our translator Onen Christopher, Ocen Zedekiah for drawing the map, and Nyeko Bonny, Opio Richard, Amuge Felicity, Okongo Ronald, Ocheng Michael and Kibwola Andrew for mobilising participants.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fvets.2021.707819/full#supplementary-material

REFERENCES

1. Kungu JM, Masembe C, Apamaku M, Akol J, Amia WC, Dione M. Pig farming systems and cysticercosis in Northern Uganda. *Revue d'élevage et de Médecine Vétérinaire Des Pays Tropicaux.* (2019) 72:115. doi: 10.19182/remvt.31254
2. Dione, Michel M, Ouma EA, Roesel K, Kungu J, Lule P, Pezo D. Participatory assessment of animal health and husbandry practices in smallholder pig production systems in three high poverty districts in Uganda. *Prev Vet Med.* (2014) 117:565–76. doi: 10.1016/j.prevetmed.2014.10.012
3. Chenais E, Boqvist S, Sternberg-Lewerin S, Emanuelson U, Ouma E, Dione M, et al. Knowledge, Attitudes and Practices Related to African Swine Fever Within Smallholder Pig Production in Northern Uganda. *Transbound Emerg Dis.* (2017) 64:101–15. doi: 10.1111/tbed.12347
4. Ouma E, Dione M, Lule P, Pezo D, Marshall K, Roesel K, et al. *Smallholder Pig Valuechain Assessment in Uganda: Results from Producer Focus Group Discussions and Key Informant Interviews.* ILRI Project Report. Nairobi: ILRI (2015). Available Online at: https://cgspace.cgiar.org/bitstream/handle/10568/68011/PR_Uganda_vca_web.pdf?sequence=6&isAllowed=y.
5. UBOS. Uganda Bureau of Statistics 2017 Statistical Abstract. Kampala: Uganda Bureau of Statistics (2017). Available Online at: https://www.ubos.org/wp-content/uploads/publications/03_20182017_Statistical_Abstract.pdf.
6. FAOSTAT. *Food and Agricultural Organization of the United Nations, Statistics Division* (2012). Available online at: http://faostat3.fao.org/download/Q/QL/E (accessed October 10, 2020).
7. FAO, "*Food and Agriculture Organization of the United Nations. Pigmeat supply quantity (kg/capita/yr) in Uganda [WWW Document]. FAOSTAT. Food*

Supply - Livest. Fish Prim. Equiv. Available online at: http://www.fao.org/faostat/en/#data/CL/visualize (accessed 23 May 2018).
8. Penrith M, Vosloo W, Jori F, Bastos ADS. African swine fever virus eradication in Africa. *Virus Res.* (2013) 173:228–46. doi: 10.1016/j.virusres.2012.10.011
9. Chenais E, Sternberg-Lewerin S, Boqvist S, Emanuelson U, Aliro T, Tejler E. African Swine fever in Uganda: qualitative evaluation of three surveillance methods with implications for other resource-poor settings. *Front Vet Sci.* (2015) 2:51. doi: 10.3389/fvets.2015.00051
10. Dixon LK, Alonso C, Escribano JM, Martins C, Revilla Y, Salas M, et al. *Virus Taxonomy. Classification and Nomenclature of Viruses. Ninth Report of the International Committee on Taxonomy of Viruses*. Amsterdam, the Netherlands: Elsevier/Academic Press. (2005). pp. 154–63.
11. Sánchez-Vizcaíno JM, Mur L, Gomez-Villamandos JC. Carrasco, L. *An update on the epidemiology and pathology of African swine fever J Comp Pathol.* (2015) 152:9–21. doi: 10.1016/j.jcpa.2014.09.003
12. Gallardo C, Soler A, Nieto R, Cano C, Pelayo V, Sánchez MA, et al. Experimental infection of domestic pigs with African swine fever virus Lithuania 2014 Genotype II field isolate. *Transbound Emerg Dis.* (2017) 64:300–4. doi: 10.1111/tbed.12346
13. Blome S, Gabriel C. Beer, M. Pathogenesis of African swine fever in domestic pigs and European wild boar. *Virus Res.* (2013) 173:122–30. doi: 10.1016/j.virusres.2012.10.026
14. Chenais E, Boqvist S, Emanuelson U, Brömssen, Claudia V, Ouma E, et al. Quantitative assessment of social and economic impact of African swine fever outbreaks in northern Uganda. *Prev Vet Med.* (2017) 144:134–48. doi: 10.1016/j.prevetmed.2017.06.002
15. Kabuuka T, Kasaija PD, Mulindwa H, Shittu A, Bastos ADS, Fasin FO. Drivers and risk factors for circulating African swine fever virus in Uganda, 2012-2013. *Res Vet Sci.* (2014) 97: 218–25. doi: 10.1016/j.rvsc.2014.07.001
16. Ouma E, Dione M, Birungi R, Lule P, Mayega, L. African swine fever control and market integration in Ugandan peri-urban smallholder pig value chains : An ex-ante impact assessment of interventions and their interaction. *Prev Vet Med.* (2018) 151:29–39. doi: 10.1016/j.prevetmed.2017.12.010
17. Muhangi D, Masembe C, Berg M, Ståhl K, Ocaido M. *Practices in the Pig Value Chain in Uganda; Implications to African Swine Fever Transmission, Vol. 26.* Livestock Research for Rural Development, (2014). Available Online at: http://www.lrrd.org/lrrd26/5/muha26094.htm
18. Rich KM, Perry BD. The economic and poverty impacts of animal diseases in developing countries : New roles, new demands for economics and epidemiology. *Pre Vet Med.* (2011) 101:133–47. doi: 10.1016/j.prevetmed.2010.08.002
19. FAO. FAO takes a close look at the pig sector in Eastern Europe to better understand the threats of African Swine Fever. *Empres Watch*, *2010*(May 2010), p. 1–6. Available online at: http://www.fao.org/docrep/012/ak755e/ak755e00.pdf
20. Penrith ML. Current status of African swine fever. *CABI Agric Biosci*. (2020) 1:11. doi: 10.1186/s43170-020-00011-w
21. Costard S, Porphyre V, Messad S, Rakotondrahanta S, Vidon H. Multivariate analysis of management and biosecurity practices in smallholder pig farms in Madagascar. *Prev Vet Med.* (2009) 92:199–209. doi: 10.1016/j.prevetmed.2009.08.010
22. Fasina FO, Agbaje M, Ajani FL, Talabi OA, Lazarus DD, Gallardo C, et al. Risk factors for farm-level African swine fever infection in major pig-producing areas in Nigeria, 1997–2011. *Prev Vet Med.* (2012) 107:65–75. doi: 10.1016/j.prevetmed.2012.05.011
23. Dione MM, Akol J, Roesel K, Kungu J, Ouma EA, Wieland B, Pezo D. Risk Factors for African Swine Fever in Smallholder Pig Production Systems in Uganda. *Transbound Emerg Dis*. (2015) 64:872–882. doi: 10.1111/tbed.12452
24. Leslie EEC, Christley RM, Geong M, Ward MP, Toribio JA LML. Analysis of pig movements across eastern Indonesia, 2009-2010. *Prev Vet Med.* (2015) 118: 293–305. doi: 10.1016/j.prevetmed.2014.12.002
25. Chenais E, Lewerin SS, Boqvist S, Ståhl K, Alike S, Nokorach, B. Smallholders ' perceptions on biosecurity and disease control in relation to African swine fever in an endemically infected area in Northern Uganda. *BMC Vet Res.* (2019) 15:279. doi: 10.1186/s12917-019-2005-7
26. Chenais E, Wennström P, Kartskhia N, Fischer K, Risatti G, Chaligava T, et al. Perceptions of pastoralist problems: a participatory study on animal management, disease spectrum and animal health priorities of small ruminant pastoralists in Georgia. *Prev Vet Med.* (2021) 193:105412. doi: 10.1016/j.prevetmed.2021.105412
27. Branch A. Gulu in War and Peace? The Town as Camp in Northern Uganda. *Urban Studies*. (2013) 50:3152–67. doi: 10.1177/0042098013487777
28. Hewlett BS, Hewlett BL. Ebola, *Culture and Politics: The Anthropology of an Emerging Disease.* Belmont, CA: Thomson Higher Education (2008). p. 283.
29. Braun V, Clarke V, Braun V, Clarke V. Using thematic analysis in psychology. *Qual Res Psychol*. (2006) 3:77–101. doi: 10.1191/1478088706qp063oa
30. LeCompte MD. Analyzing qualitative data. *Theory Pract.* (2000) 39:146–54. doi: 10.1207/s15430421tip3903_5
31. Moghaddam A. Coding issues in grounded theory. Issues In Educational Research, (2006) 16. p. 52-66. *Issues In Educational Research*, 15.
32. Goulding C, Goulding C. *Grounded theory : some reflections on paradigm, procedures and misconceptions*. University of Wolveampton (1999) 44.
33. Dione MM, Dohoo I, Ndiwa N, Poole J, Ouma E, Amia WC, et al. Impact of participatory training of smallholder pig farmers on knowledge, attitudes and practices regarding biosecurity for the control of African swine fever in Uganda. *Transbound Emerg Dis.* (2020) 67:2482–93. doi: 10.1111/tbed.13587
34. Corner M, Norman P. Protection motivation theory. In: Corner M, Norman P, editors. *Predicting Health Behaviour*.2nd ed. New York: McGraw-Hill Education (2009). pp. 81–126.
35. Conner M, Norman P. *Predicting health behaviour: a social cognition approach. In: Conner M, Norman P. Predicting Health Behaviour*. 2nd ed. Berkshire, UK: Open University Press (2005)
36. Conner M, Sparks P. Theory of planned behaviour and health behaviour. In: Conner M, Norman P. editors. *Predicting Health Behaviour*. 2nd ed. pp. 170–222. New York, NY: McGraw-Hill Education (2009).
37. Schemann K, Firestone SM, Taylor MR, Toribio JA, Ward MP, Dhand NK. Perceptions of vulnerability to a future outbreak: a study of horse managers affected by the first Australian equine influenza outbreak. *BMC Vet Res.* (2013) 9:152. doi: 10.1186/1746-6148-9-152
38. Schemann K, Firestone SM, Taylor MR, Toribio JA, Ward MP, Dhand NK. Horse owners '/ managers ' perceptions about effectiveness of biosecurity measures based on their experiences during the 2007 equine influenza outbreak in Australia. *Prev Vet Med.* (2012) 106:97–107. doi: 10.1016/j.prevetmed.2012.01.013
39. Michael Cummings K, Becker MH, Maile MC. Bringing the models together: an empirical approach to combining variables used to explain health actions. *J Behav Med.* (1980) 3:123–45. doi: 10.1007/BF00844986
40. Ebata A, Macgregor H, Loevinsohn M, Su K. Why behaviours do not change : structural constraints that influence household decisions to control pig diseases in Myanmar. *Prev Vet Med.* (2020) 183:105138. doi: 10.1016/j.prevetmed.2020.105138
41. Fasina FO, Lazarus DD, Spencer BT, Makinde AA, Bastos ADS. Cost Implications of African Swine fever in smallholder farrow-to-finish units : economic benefits of disease prevention through biosecurity. *Transbound Emerg Dis.* (2012) 59:244–55. doi: 10.1111/j.1865-1682.2011.01261.x
42. Nantima N, Ocaido M, Ouma E, Davies J, Dione M, Okoth E, et al. Risk factors associated with occurrence of African swine fever outbreaks in smallholder pig farms in four districts along the Uganda-Kenya border. *Trop Anim Health Prod.* (2015) 47:589–95. doi: 10.1007/s11250-015-0768-9
43. Penrith M, Bastos A, Chenais E. With or without a vaccine — a review of complementary and alternative approaches to managing african swine fever in resource-constrained smallholder settings. *Vaccines*. (2021) 9:116. doi: 10.3390/vaccines9020116
44. Chenais E, Depner K, Guberti V, Dietze K, Viltrop A, Ståhl, K. Epidemiological considerations on African swine fever in Europe 2014 – 2018. *Porcine Health Manage*. (2019) 5:1–10. doi: 10.1186/s40813-018-0109-2
45. UBOS. *Poverty Maps of Uganda: Mapping the Spatial Distribution of Poor Households and Child Poverty Based on Data from the 2016/17 Uganda* (2019).
46. Nantima N, Davies J, Dione M, Ocaido M, Okoth E, Mugisha A, et al. Enhancing knowledge and awareness of biosecurity practices for control of African swine fever among smallholder pig farmers in four districts along the Kenya–Uganda border. *Trop Anim Health Prod.* (2016) 48:727–34. doi: 10.1007/s11250-016-1015-8

47. Dione M, Ouma E, Opio F, Kawuma B, Pezo D. Qualitative analysis of the risks and practices associated with the spread of African swine fever within the smallholder pig value chains in Uganda. *Prev Vet Med.* (2016) 135:102–12. doi: 10.1016/j.prevetmed.2016.11.001
48. Hunter CL, Millar J, LML Toribio, J.-A. More than meat: the role of pigs in Timorese culture and the household economy. *Int J Agri Sustain.* (2021) 1–15. doi: 10.1080/14735903.2021.1923285
49. Barnes TS, Morais O, Cargill C, Parke CR, Urlings, A. First steps in managing the challenge of African Swine Fever in Timor-Leste. *One Health*. (2020) 10:100151. doi: 10.1016/j.onehlt.2020.100151
50. Wesonga WSN, Madasi B, Nambo E. Factors associated with a low veterinary regulatory compliance in Uganda, their impact and quality management approaches to improve performance. *Open J Vet Med.* (2018) 8:89051. doi: 10.4236/ojvm.2018.812019
51. De Carvalho F, Weesendorp E, Elbers ARW, Bouma A, Quak S, Stegeman JA,. African swine fever virus excretion patterns in persistently infected animals : a quantitative approach. *Vet Microbiol*. (2012) 160:327–40. doi: 10.1016/j.vetmic.2012.06.025
52. Sofie A, Lohse L, Boklund A, Halasa T, Gallardo C, Pejsak Z, et al. Transmission of African swine fever virus from infected pigs by direct contact and aerosol routes. *Vet Microbiol.* (2017) 211:92–102. doi: 10.1016/j.vetmic.2017.10.004
53. Plowright W, Parker J. The stability of African swine fever virus with particular reference to heat and pH inactivation. *Archiv Für Die Gesamte Virusforschung*. (1967) 21:383–402. doi: 10.1007/BF01241738
54. Panasiuk NM, Zmudzki J, Wozniakowski G. African swine fever virus – persistence in different environmental conditions and the possibility of its indirect transmission (2019). *J Vet Res*. 28:303–10. doi: 10.2478/jvetres-2019-0058
55. Clark L, Birkhead AS, Fernandez C, Egger MJA Transcription and Translation Protocol for Sensitive Cross-Cultural Team Research. *Qual Health Res*. (2017) 27:1751–64. doi: 10.1177/1049732317726761
56. Fischer K, Katja S, Erika C. "Can we agree on that"? Plurality, power and language in participatory research. *Prev Vet Med*. (2020) 180:104991. doi: 10.1016/j.prevetmed.2020.104991
57. Chenais E, Fischer K. Increasing the local relevance of epidemiological research : situated knowledge of cattle disease among basongora pastoralists in Uganda. (2018) 5:1–12. doi: 10.3389/fvets.2018.00119
58. Campbell SM, Braspenning J, Hutchinson A, Marshall M. Research methods used in developing and applying quality indicators in primary care. *Qual Saf Health Care*. (2002) 11:358–64. doi: 10.1136/qhc.11.4.358

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

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

Copyright © 2022 Aliro, Chenais, Odongo, Okello, Masembe and Ståhl. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.

frontiers in Veterinary Science

ORIGINAL RESEARCH
published: 10 February 2022
doi: 10.3389/fvets.2021.734236

Beyond Numbers: Determining the Socioeconomic and Livelihood Impacts of African Swine Fever and Its Control in the Philippines

Tarni L. Cooper[1,2,3*†], *Dominic Smith*[1,3†], *Mark Jaypee C. Gonzales*[4], *Marlon T. Maghanay*[5], *Sunny Sanderson*[1], *Marie Rachelle Jane C. Cornejo*[4], *Lohreihleih L. Pineda*[5], *Rose Ann A. Sagun*[5] and *Oliver P. Salvacion*[4]

[1] School of Agriculture and Food Sciences, The University of Queensland, Brisbane, QLD, Australia, [2] School of Veterinary Science, The University of Queensland, Brisbane, QLD, Australia, [3] Griffith Asia Institute, Griffith University, Brisbane, QLD, Australia, [4] College of Veterinary Medicine, Central Bicol State University of Agriculture, Pili, Philippines, [5] College of Veterinary Science and Medicine, Central Luzon State University, City of Munoz, Philippines

OPEN ACCESS

Edited by:
Michel Dione, International Livestock Research Institute (ILRI), Kenya

Reviewed by:
Walter Odongo, Gulu University, Uganda
Folorunso Oludayo Fasina, University of Pretoria, South Africa

***Correspondence:**
Tarni L. Cooper
t.cooper@uq.edu.au

†*These authors share first authorship*

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

Received: *30 June 2021*
Accepted: *24 December 2021*
Published: *10 February 2022*

Citation:
Cooper TL, Smith D, Gonzales MJC, Maghanay MT, Sanderson S, Cornejo MRJC, Pineda LL, Sagun RAA and Salvacion OP (2022) Beyond Numbers: Determining the Socioeconomic and Livelihood Impacts of African Swine Fever and Its Control in the Philippines. Front. Vet. Sci. 8:734236. doi: 10.3389/fvets.2021.734236

The impacts of African Swine Fever (ASF) have most frequently been described quantitatively though it is increasingly acknowledged these impacts extend well beyond numbers. During 2020, a multidisciplinary team of researchers developed a framework for Socioeconomic and Livelihood Impact Assessment (SELIA) of livestock diseases in smallholder communities. Two key innovations within this SELIA framework are the integration of sustainable livelihoods concepts to capture rich information beyond financial impacts, and the inclusion of stakeholders across the value chain, beyond farmers. This paper focuses on the findings from one of the first applications of the SELIA framework. In late 2020 the research team applied participatory tools from the SELIA Framework (8 focus group discussions, 14 key informant interviews, and 2 network mapping activities) to gather data to describe the impact of ASF in backyard pig-farming communities and value chains. This was undertaken across two locations in the Philippines, in turn highlighting potential leverage points for intervention. Owing to COVID-19 travel restrictions and risks, modifications to training and field activities were made. Findings from focus groups and interviews revealed the deep, emotional impacts of ASF and the associated control measures. Pigs were considered pets by many farmers and some women described them as being like their children. Animal health-workers (AHWs) also recognised the emotional toll on farmers and were sometimes strongly criticised by community members due to their involvement in depopulation campaigns. Misinformation early in the epidemic also led farmers to hide their animals from AHWs, and to dispose of them inappropriately. While the overall impact of ASF on society was negative, the impacts across different communities, scales of production and different value chain actors varied. The losses experienced by backyard farmers resulted in significant losses to linked value chain actors, such as input suppliers. This trial application of the SELIA framework revealed some complex and varied impacts of ASF. This included significant differences in livelihood and socio-economic impacts amongst different actors within value chains and also among different categories of actors (for example small, medium and large-scale traders). Repeated themes and triangulated findings suggest two leverage points for further consideration. Firstly, it is recommended a One Welfare approach to ASF control in the Philippines is explored. Emphasising careful communication between animal health-workers and farmers, and humane and sensitive pig depopulation practices. Secondly, consideration of ASF support programs tailored to sectoral and specific communities is recommended.

Keywords: African Swine Fever, participatory research, Philippines, value chain, livelihoods, smallholders, socioeconomics

INTRODUCTION

African Swine Fever (ASF) was first reported in the Philippines in July 2019, starting with seven outbreaks in the province of Rizal, Region IV-A, adjacent to Metro Manila (National Capital Region) in the Philippines (1). As of 21st September 2020, ASF had been reported in 31 provinces across eight regions. A further nine provinces where ASF was not reported by the 21st September 2020 were classified as buffer, surveillance or protected zones (2) (**Figure 1**). The outbreak of ASF resulted in a 9.8% drop in pig production in the last quarter of 2019 (3). The Government of the Philippines continued to collect quantitative data throughout the outbreak for both larger-scale commercial holdings and smaller farms (2). What have been less-well understood are the broader impacts of ASF on tangible and intangible, qualitative aspects of livelihoods, both within farming households and the broader value chains. There has been expressed a need by governments and international non-government organisations for this sort of information across Southeast Asia and the Pacific (1).

In response, from early 2020, university and government partners in Australia, Timor-Leste and the Philippines developed a Socioeconomic and Livelihood Impact Assessment (SELIA) Framework for livestock diseases (**Figure 2**) with an initial focus on ASF (4). The SELIA Framework is modular in design with both an overarching process of participatory prioritisation with decision-makers, such as government or donors, followed by data gathering, analysis and creation of useful outputs. In addition to this linear process there is a continual feedback component, where the researchers use formative evaluation to improve the assessment process in dialogue with the decision-makers. The SELIA Framework is designed to be adaptable to different decision-maker priorities, research needs and resource availabilities, and so each assessment is likely to look very different. The SELIA Framework's first trial applications have been this study and another in Timor-Leste during late 2020 (5).

The term "livelihood" is interpreted in many ways, from a synonym for "income," to a mixed tangible and intangible phenomenon. This has led to a multiplicity of livelihood-associated frameworks, methods and tools. In the SELIA context, livelihood impact assessment is based around the Sustainable Livelihoods Framework (SLF) as proposed by the Department for International Development (DFID) (6) and widely adopted since the 1990s. The SLF includes many components of a livelihood for interrogation, such as the vulnerability context in which a livelihood is set, livelihoods capitals (social, human, natural, physical, and financial) used to create this livelihood and transforming structures and processes influencing the way these capitals can be utilised, such as laws, policies, culture, institutions and gender dimensions. The SLF is further based on the key principals that any interventions must be participatory and responsive; multi-level; conducted in partnership with the private and public sector; sustainable and dynamic (7). The SELIA framework may have future applications in framing discussion, planning of interventions, implementation and monitoring and therefore, and could hold utility in examining how communities might use their resources to address livestock biosecurity threats.

The risks posed by livestock diseases such as ASF extend well beyond production losses (8). Agricultural diseases often have significant indirect and sometimes direct impacts on human health and wellbeing, both tangible and intangible, with ripple effects through communities. The speed and severity of the ASF epidemic in the pig sectors of Southeast Asia and the Pacific Region has left stakeholders scrambling to determine appropriate management and/or control measures. ASF has been a shock to pig raising systems that has resulted in both tangible and intangible impacts due to the personal and cultural significance of pigs in many regions. Further, communities, households and individuals have different vulnerability to the impact of ASF, and as such, an understanding of relative vulnerability is critical for effective decision-making in at-risk countries. The original motivation for the development of the SELIA Framework was to evaluate the impacts of livestock disease on the livelihoods of those often most vulnerable, smallholder farmers. The Framework was soon expanded to include impacts along the value chains, as the impacts of ASF extend well beyond the farmgate.

Value chain analysis takes a systems approach to analysis and enables an understanding of the overall market system and context. Taking a systemic approach allows for any challenges, problems, and bottlenecks at various points within the value chain to be identified (9). Taking a systemic approach is very important for impact assessment frameworks like SELIA, as this enables the identification of flow-on impacts of shocks to producers across different levels of the value chain.

This paper describes the trial application of a set of core data gathering tools from the SELIA Framework in two locations in the Philippines, to better understand the impact of ASF in smaller-scale pig-pork value chains (**Figure 3**).

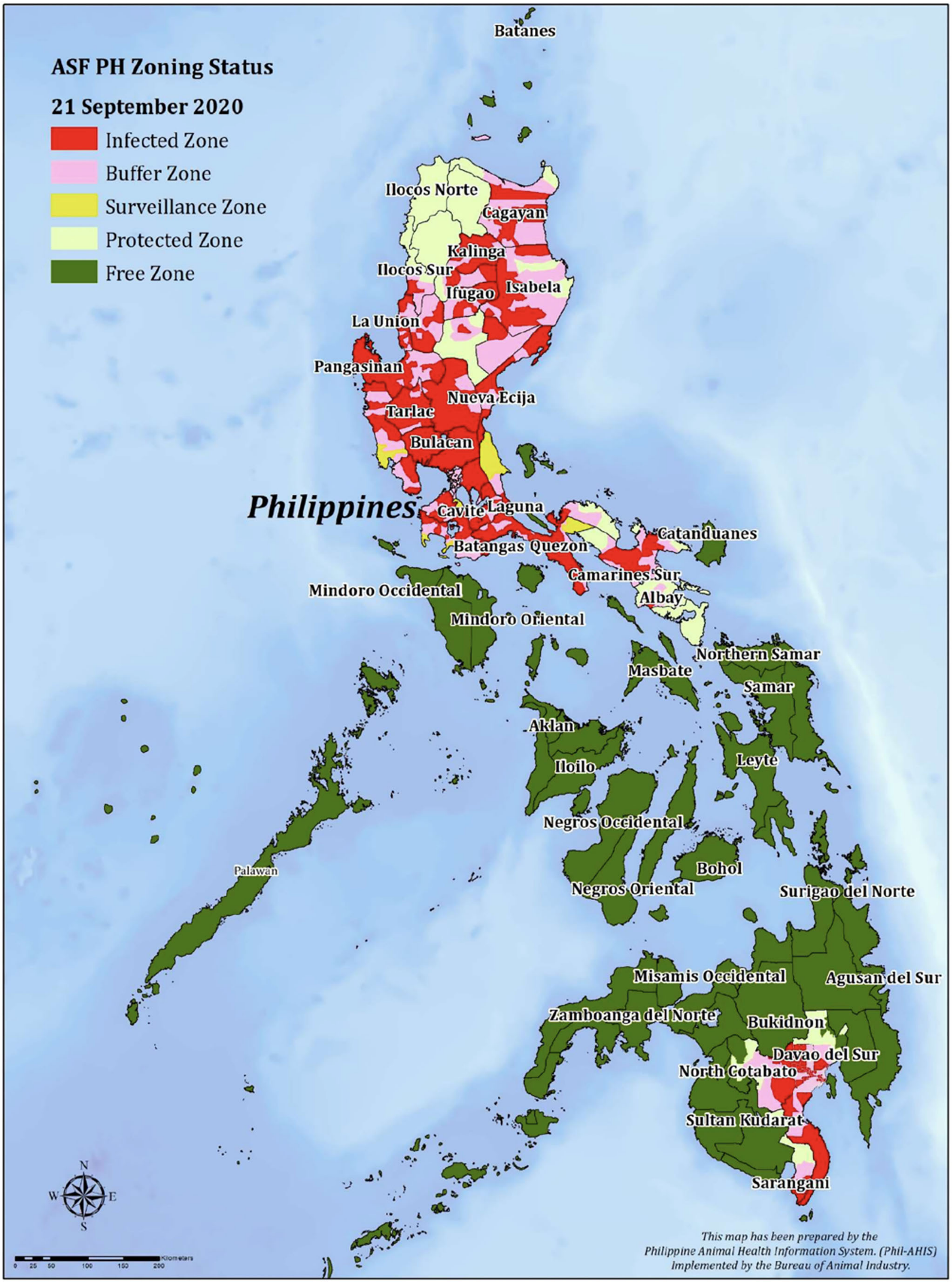


FIGURE 1 | ASF zoning status in Philippines, September 2020.

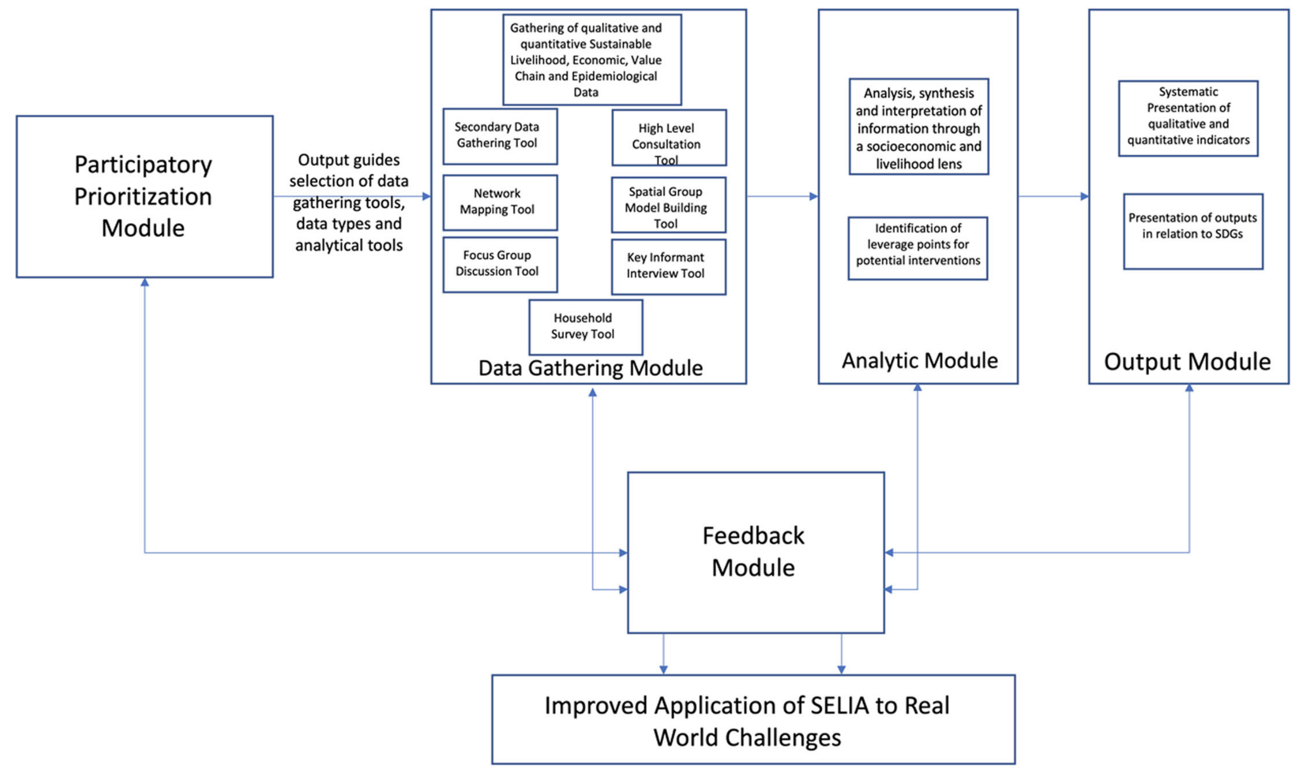


FIGURE 2 | Schematic representation of the Socioeconomic and Livelihood Impact Assessment (SELIA) Framework for livestock diseases.

MATERIALS AND METHODS

The Philippines Country Context and Site Selection

The Philippines is an archipelago in Southeast Asia that has a population of 106.7 million people (10), over half of whom live in rural areas (52.85%) (11). In 2019, approximately one in five of the total population lived in poverty (20.8%) (12). Furthermore, from 2017 to 2019, on average 17.6% of the population suffered severe food insecurity (13). Agriculture is of crucial importance in the Philippines, and closely linked to food security and poverty reduction (14). As the country was already grappling with the large-scale outbreak of ASF in 2020, the impact of COVID-19 delivered an additional blow to livelihoods and poverty reduction efforts in the Philippines.

Philippine partners for this research included the Department of Agriculture's Bureau of Animal Industry (BAI), Department of Science and Technology's Philippine Council for Agriculture, Aquatic, and Natural Resources Research and Development (PCAARRD), Central Luzon State University (CLSU) and Central Bicol State University of Agriculture (CBSUA). Two sites were chosen for field research with one key inclusion criterion, that the communities studied had been impacted by ASF. Other than meeting this criterion, sites were chosen to mitigate COVID-19 risk by reducing travel for researchers. The two locations chosen were Camarines Sur province, Bicol Region and Nueva Ecija province, Central Luzon Region, focusing on San Jose City.

Camarines Sur has 35 municipalities and two cities. The province's first ASF outbreak was in Barangay Sto. Domingo, Bombon on February 21, 2020. The situation quickly spread to nearby municipalities such as Canaman, Calabanga, Magarao and Naga City (Bicol's Centre of Commerce and Industry). The ASF situation in Camarines Sur is still evolving; as at 18th of August 2020 ASF was reported in 17 municipalities and one city[1], but as of September 21, ASF was active in 18 municipalities and both cities.

In San Jose City, Nueva Ecija, ASF first emerged in Barangay Santo Nino on January 3, 2020, and since, there have been a total of 18 outbreaks in San Jose City[2] In Nueva Ecija province, 29 of the 32 cities and municipalities are infected with ASF (red zones) and three remain as buffer zones.

Prioritisation and Instruments Tested

Firstly, the research team held discussions with BAI and PCAARRD to establish research needs and priorities. National

[1]Domingo (2020) 18th August 2020 Update on Zoning Status of Regions in Relation to The Implementation of The National Zoning and Movement Plan for African Swine Fever (ASF), Memo from Office of the Director, BAI (https://www.bai.gov.ph/index.php/regulatory/item/477-asf-portal).

[2]Available online at: BAI ASF Portal https://www.bai.gov.ph/index.php/regulatory/item/477-asf-portal.

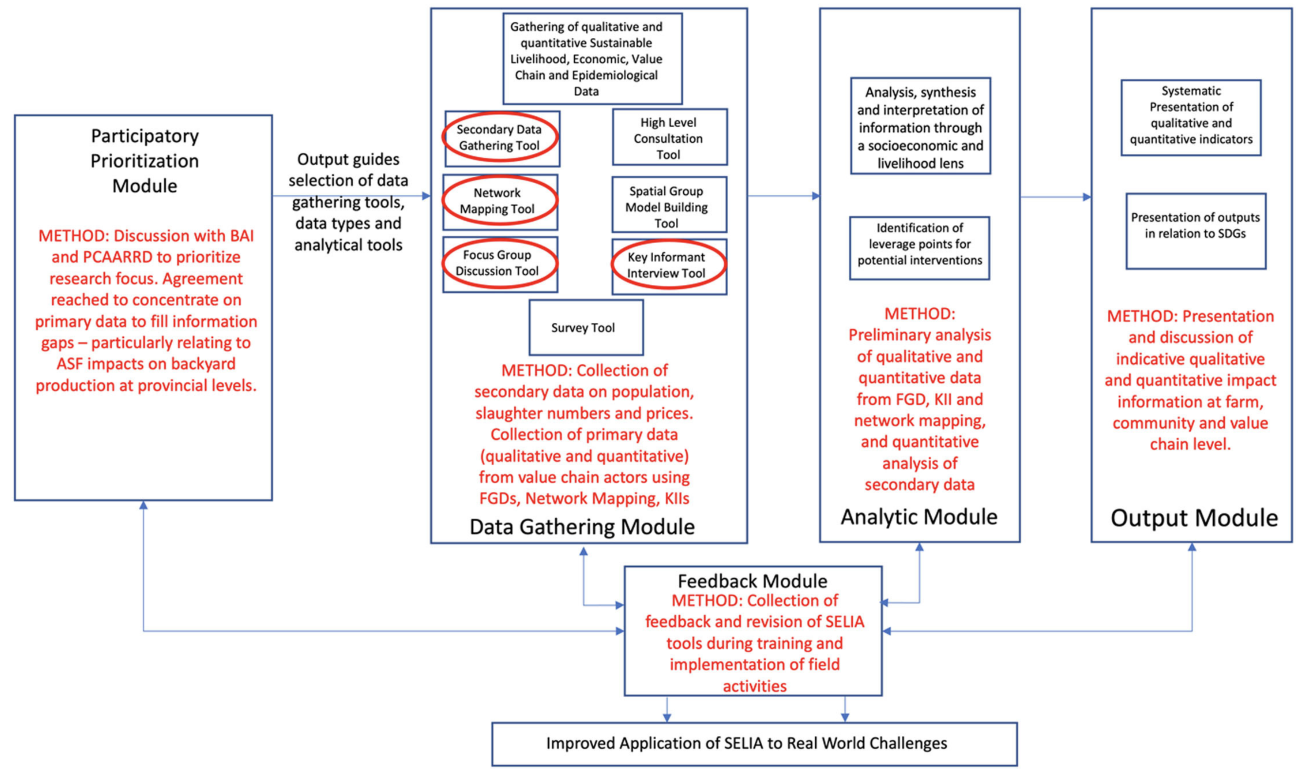


FIGURE 3 | Pilot implementation of the SELIA Framework in the Philippines (selected tools and applications in red).

and regional level data to base these rapid estimations on were readily available online from the Philippine Statistics Authority (PSA) (https://psa.gov.ph/pages/survey). However, government partners explained it had been difficult to assess the full impacts and extent of ASF due to the additional resources required to gather detailed information at the local level, and the impact of COVID-19 on resourcing and movement restrictions. Analysis of secondary data confirmed these gaps in information. Details of the secondary data analysis are included in the **Supplementary Materials**.

Given the gaps in knowledge in how ASF was affecting smallholders, their communities and connected value chain actors, and owing to resource, time and COVID-safety constraints for the pilot activities, the following primary data collection methods were chosen: Focus Group Discussions (FGDs) (with farmers), Network Mapping (with mixed value chain actors) and Key Informant Interviews (KIIs). Details of COVID-19 safe measures adopted for these data collection methods are given in section COVID-19 Risk Mitigation. Details of the instruments used to guide these methods are included as attachments and described briefly below. A total of eight FGDs, two Network Mapping sessions and 14 KIIs were conducted across the two sites (see **Table 1**).

Network Mapping

Mapping the value chain processes and key actors and product flows gives an overview of the key stakeholders within a sector (15), enabling decisions about the bounds of the analysis, and which actors are most usefully included within an impact assessment (16), i.e., it informs subsequent research design and sampling. In this study, a qualitative and semi-quantitative value chain mapping exercise concentrated on product flow, coordination, governance and linkages aspects. Mapping techniques were utilised to build up an accurate picture of actor types, numbers of actors, flow volumes, values, prices, costs and benefits and the participation of the poor. Governance and linkages were incorporated into the analysis with a concentration on analysing social capital and coordination and cooperation inside and outside the value chains based on the inclusive value chain analysis methodology outlined in (9). The mapping process is outlined in detail in the **Supplementary Material**.

The mapping served to build up a picture of the key categories of actors, the volume of flow of products between actors, the value of products at each level of the chain, the costs and benefits to different actors, the number of actors at each level of the chain and the linkages between the actors. This provided the foundation for an in-depth and contextually embedded initial estimation of impacts on upstream and downstream actors of ASF at producer level in terms of value and volumes of product.

Focus Group Discussions

Focus Group Discussions were designed to gather contextual, community-level data on the impacts of ASF on pig farmers.

TABLE 1 | Activities conducted and details of participants in each study location.

Activity	Nueva Ecija, Central Luzon	Camarines Sur, Bicol
Key informant interviews	1. Livestock Inspector at City Veterinary Office (male) 2. Animal handler and ASF response team at City Veterinary Office (female) 3. Agri-supply business owner (female) 4. Agri-supply business owner (female) 5. City Veterinarian, meat inspector and regulator (male) 6. City Slaughterhouse Master (female) 7. Pig trader (male) 8. Pig trader/meat vendor (female)	1. Meat Inspector at City Veterinary Office/Animal Health Worker (female) 2. Pig trader and pork seller (male) 3. Meat inspector at locally registered meat establishment (male) 4. Team Leader (feed monitoring) at a private company 5. Senior Meat Control Officer (male) 6. Piggery utility worker, backyard pig raiser, butcher, private livestock technician (male)
Focus Group Discussions	1. Female part time pig farmers, women, (average age 50yo) 2. Male part-time pig farmers, men (average age 53yo) 3. Female full time (commercial) pig farmers, women (average age 55yo) 4. Male full time (commercial) pig farmers, men (average age 41yo)	1. Female pig farmers with 10 or fewer pigs, 5 women, (average age 45yo) 2. Male pig farmers with 10 or fewer pigs, 5 men (average age 45yo) 3. Female pig farmers with >10 pigs, 6 women (average age 50yo) 4. Male pig farmers with >10 pigs, 7 men (average age 57yo)
Network Mapping	One group of participants (9 men, 7 women, average age 45yo): i. Veterinary Officer/Animal Health Worker x 2 ii. Housewife/pig farmer x 4 iii. Farmer/pig farmer x 7 iv. Call centre agent/pig farmer x 1 v. Poultry supply owner/agri-input supplier x 1 iv. Meat stall owner/pig trader x 1	One group of participants (4 men, 1 woman, average age 26yo): i. Meat Inspector at City Veterinary Office/Animal Health Worker ii. Self-employed, feed retailer, pig farmer iii. LGU veterinarian iv. Animal technician/livestock inspector LU v. Student, son of pig farmer

Participatory activities included community timelines, seasonal calendars, and collection of epidemiological information through proportional piling, ranking, tabulation and open discussion. Participatory epidemiological methods policies (17, 18) are more sensitive than surveys for capturing local, contextual information and hold great utility for rapid assessments of disease impact in the field. To understand the vulnerability context of the community, seasonal calendars were developed to study disease and risk factors, population structures, disease features, biosecurity, disease timeline—historical data, disease impacts, strategies employed, plans for the future, indicative farm budget information, and responses to disease at community level.

Gathering farmers together for discussion aimed to first explore the role of pigs in the livelihoods of communities in the context of whole, usually very complex livelihoods. In SELIA, the FGD guide includes all elements of the SLF, either explicitly or in the discussion probed by the facilitator. This gives the researchers an understanding of the underlying vulnerability context and potential resilience of the community to the livestock disease. Following on from this, the FGD zooms in on this disease to better understand how the disease has and is impacting the livelihoods of the farming community. The FGD finishes with a discussion of the livelihood strategies the farmers are employing and plan to employ in the future, to mitigate the impacts of the disease.

Key Informant Interviews

Semi-structured, key informant interviews are usually the main method for primary data collection of actors beyond the farm. Semi-structured interviews are not based on a rigid sequence of short and precise quantitative questions as is the case with structured interviews. Instead, they consist of a series of exchanges and discussions around pre-determined questions and topics following a flexible interviewing format.

Targets for KIIs were identified through high-level consultations, review of secondary data and the FGD and network mapping exercises, and with assistance from the Local Government Units in the study sites. Two broad categories of key informants were targeted:

i. Direct or indirect market participants ($n = 5$ in Central Luzon and $n = 3$ in Central Bicol): These are either involved in the marketing, and processing of the agricultural commodity under analysis (e.g., traders and processing firms) or engaged in the delivery of commercial services to value chain participants (e.g., input suppliers and transporters). These value chain actors are able to give detailed information about prices, costs, flows and linkages between actors and narratives of personal impacts. In particular, KIIs with direct value chain participants concentrated on: (i) the respondent's role in the value chain; (ii) the characteristics of purchasing products; (iii) characteristics of product selling; (iv) understanding costs and profits; (v) impact of animal disease on the business of the interviewee; (vi) opinion of impact of animal disease on other value chain actors; and (vii) hopes for the future.
ii. Knowledgeable observers ($n = 3$ in Central Luzon and $n = 3$ in Central Bicol): These people do not participate in the production and marketing of the commodity in question but may offer important information and insights. In general, academics, researchers, retired food industry managers, policy makers, other government officials, extension officers, and staff from donor agencies, NGOs, or projects all fall under this category. The knowledgeable observers targeted in this study were limited to those associated with animal health. Animal Health Workers (AHWs) can give a rich description of disease context and impacts on a population-health level.

The checklist topics for these interviews included: (i) the respondent's role in animal health; (ii) fees for services; (iii) disease timeline; (iv) strengths/successes in disease response; (v) weaknesses/challenges in disease response; (vi) disease impact on farmers and other value chain actors; (vii) disease impact on themselves; and (viii) hopes for the future.

Training and Roles of Field Researchers

Field researchers were trained by the lead institution using a combination of interactive Zoom sessions, practice activities, and trainer and peer feedback. Three training sessions of 3-3.5 h were structured around PowerPoint presentations, which were also provided in advance of the sessions for printing. The first session was dedicated to Key Informant Interviews and Foundational Principles, such as the overview and aims of the project, roles and responsibilities and research ethics. The remaining two sessions covered Focus Group Discussions and Network Mapping, and were mostly hands-on. The outputs from the two field teams for every activity were reviewed by the training team who provided feedback both during Zoom sessions and in between each session. Following the sessions, university teams practiced using the tools and provided further practice outputs for review.

The team size was kept to a minimum (three people) for COVID-19 risk mitigation. The three major roles for each team were a lead facilitator, a note-taker and an observer, with the latter two supporting the lead facilitator as needed. The note-taker plays a very important role as they capture discussions that would not be captured by the other activity outputs. As the research was a pilot, the observer role was responsible for observing what worked and didn't work during the research process and suggesting improvements. The team gathered after each activity to reflect on the process and supplement notes taken. The team later transcribed and translated all materials with one person taking the lead and the others checking the outputs.

Materials

The field teams were required to source materials for training and field research. The materials were basic, cheap and readily available to the teams: blank A0 paper ("flipchart paper"), markers, coloured paper, legumes, a measuring jug and paper for note taking. To reduce sharing of pens for hygiene reasons, the teams also bought a stack of post-it notes for each participant to write on and stick on the shared A0 paper. For COVID-19 risk mitigation during face-to-face activities, materials included face masks, face shields, liquid soap, gloves, hand sanitiser, alcohol with foot dispenser, foot bath with rugs for drying, a temperature scanner, a health declaration logbook and health declaration check list. Refreshments for these meetings included snacks (biscuits, bread, spaghetti, *palabok*, *pancit*, and beverages) and meals (prepared by a local person or fast food).

Human Research Ethics

The research proposal and tools underwent review and were approved by The University of Queensland Human Research Ethics Committee (approval #2020001543).

Participant Recruitment

The teams were responsible for seeking consent from gatekeepers at the Local Government Unit (LGU) level before approaching and seeking consent from prospective participants. The teams translated research information sheets and provided these to gatekeepers and participants before seeking free and informed consent.

Sampling for Key Informant Interviews was purposive; the interviewees were selected to ensure each of the four stakeholder-specific interview guides could be piloted. Sampling for Network Mapping was also purposive, aiming to bring together voices across the pig-pork value chain.

For FGDs, the aim was to include two different scales of smallholder enterprise. In each location, the proposed FGD group classifications were slightly different; in Nueva Ecija, researchers defined smaller scale as "part-time" pig raisers (where income streams are heavily mixed) and slightly larger as "full-time" pig raisers. In Camarines Sur the research team used the number of pigs kept as the defining feature as they explained, it is common even for larger scale farmers to have mixed livelihoods. The research team divided participants on whether they owned 10 or fewer pigs, or 11 or more as provided by the Municipal Agriculture Office of Pamplona, which was based on their latest list and depopulation report.

The total number of participants were 33 in Camarines Sur and 39 in Nueva Ecija. The details of these are listed in **Table 1**.

Data Analysis

Once all primary data from KIIs and participatory group activities (FGDs, Network Mapping) were collected, a thematic analysis was used to analyse interview transcripts, field notes and other participatory group activity outputs. Initially, a deductive approach was taken, using sustainable livelihood themes based on the SLF and associated codes. In addition, as additional themes emerged, inductive coding was used, adding additional codes to the pre-determined list. Relationships between codes and themes were then identified and the findings were interpreted within the wider context of the research. The findings were discussed and agreed upon by the research team and reported to government partners for their feedback. Primary quantitative data underwent descriptive analysis.

COVID-19 Risk Mitigation

No researchers travelled internationally, and all training and collaboration occurred online. Six field researchers from two remote institutions were trained online and worked closely with the local Departments of Health (DoH) to ensure the research was implemented safely. Precautions included screening of field researchers for COVID-19, the use of personal protective equipment and social distancing. Where there was a greater prevalence of COVID-19 in the community, activities were conducted online or via telephone.

RESULTS

The results below are organised according to the major socioeconomic and livelihood themes identified. They include

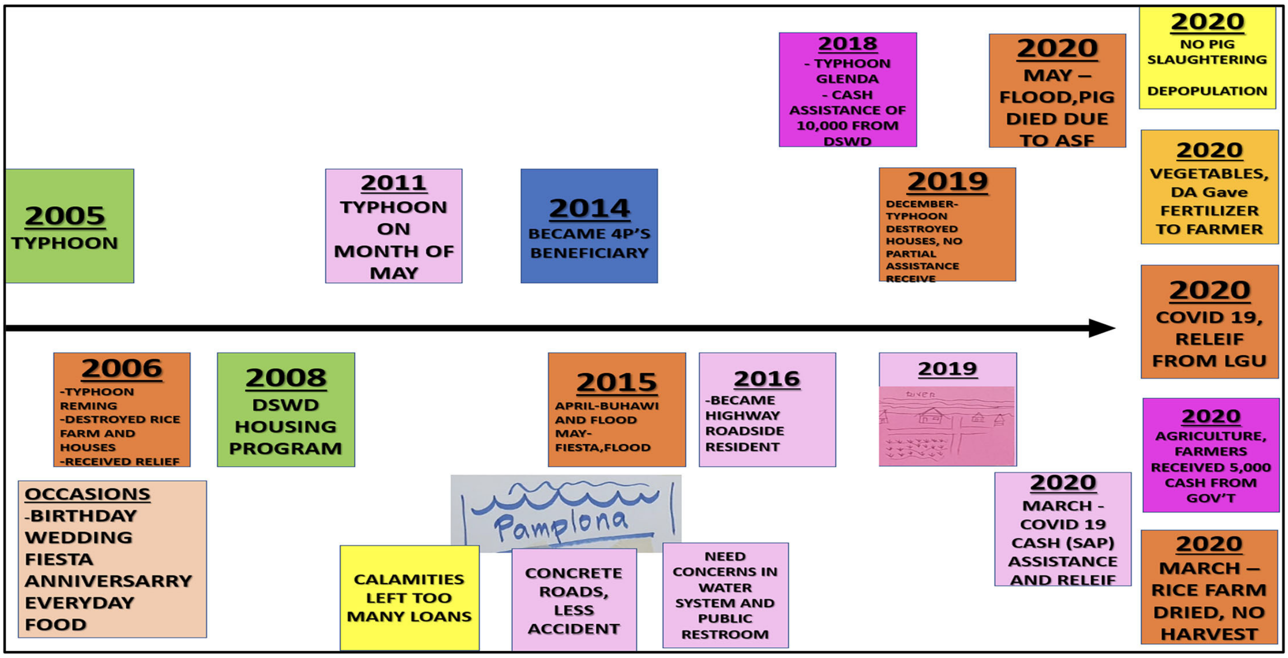


FIGURE 4 | Community timeline developed by women farmers during focus group discussion—CSFGD1.

both the ways in which livelihoods characteristics augment the impacts of ASF and the ways ASF impact upon livelihood characteristics. Findings are drawn from all field notes, transcripts and other research activity outputs.

Vulnerability Context

Communities differed in their underlying vulnerability to livelihood stressors. In Camarines Sur, an overriding vulnerability and cause of perpetual community anxiety was typhoons, occurring with seasonal regularity. As revealed in the FGD community timelines (**Figure 4**) and described by the note-taker:

> *The participants started with talking about typhoons, which stimulated discussion of fear. One always feared for her children. Another exclaimed that typhoons would always cause floods, and she fears for the pigs during floods – CSFGD3 women.*

The seasonal calendar activity in FGDs provided information on how livelihood vulnerabilities change over a year. As well as weather events and income-generating activities, cultural events may result in seasonal variation in income. In Camarines Sur, Graduation Month (in March, at the end of the school year) brings slaughter and consumption of beef (for wealthier households) and pork (**Figure 5**). Losses to ASF during this period are particularly profound.

In August, participants in all Camarines Sur FGDs mentioned the word *Tingating* to describe it as a period of financial difficulty. There was also a seasonal component to common pig diseases described by the communities.

> *August is a season of hardships. This is also usually the planting season which means no income for the farmers. To be able to get money for their daily expenses, the males in the family usually work as construction workers. The males also help in making nipas (traditional huts) and carrying them. The females make the tiklad (nipa thatch). Other than nipa making, the females also apply for jobs as nannies and salesladies in Naga City. Other females also sell different things such as vegetables or put up sari-sari stores and karenderia (eatery serving mostly Filipino dishes) – (CSFGD1 women).*

Also contributing to vulnerability context, farmers faced additional, ongoing challenges in pig production including high feed prices, no or limited informal credits provided by the input suppliers, low live weight prices from traders, disease, and high vaccine prices.

Social Capital

Relationships between animal health workers and farmers were important for communicating ASF risk mitigation messages.

> *The strength in the Animal Health Worker response was communication. The ASF outbreak in San Jose City was contained immediately because they communicated personally to the pig raisers from commercial to backyard farms – Interview with Animal Health Worker in Nueva Ecija.*

In Camarines Sur, animal health workers said they visited farms daily and covered all farms for which they were responsible every week. These relationships between animal health workers and farmers were credited with the advances in ASF control. The

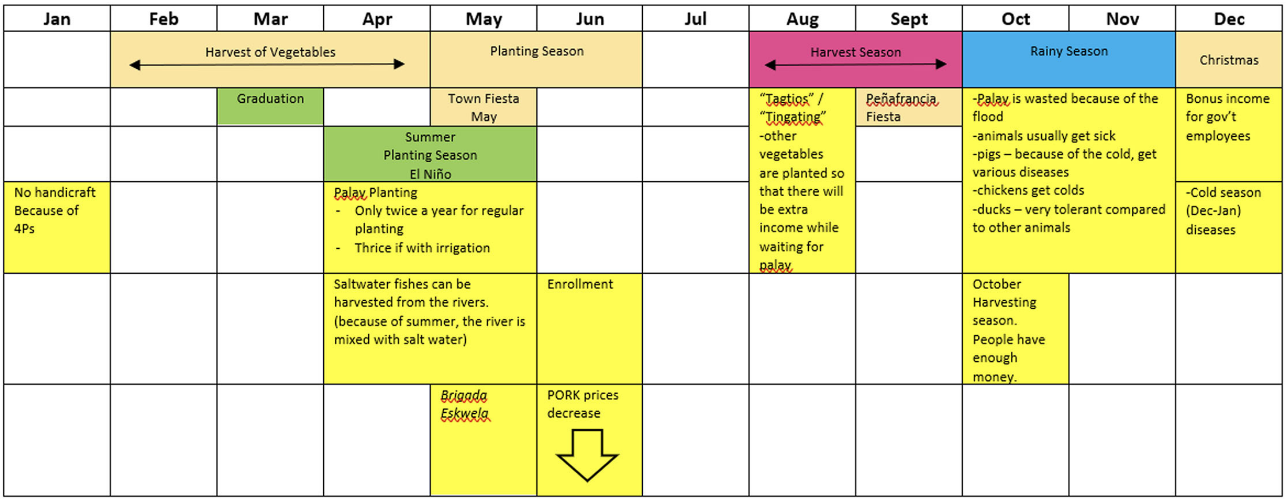


FIGURE 5 | Seasonal calendar constructed by male participants during a focus group discussion in Camarines Sur—Male farmers of 10 pigs or fewer CSFGD2.

relationships were, however, put under significant strain during depopulation campaigns (see psychosocial impacts below).

During the Network Mapping activity, social inclusion mapping of the value chain was undertaken to highlight the heterogeneous nature of actors at various stages of the value chain and to explore the differing characteristics of production, power relations and the differential impact of disease between different groups within a value chain actor category (**Figure 6**).

No farmer networks or groups were mentioned by farmers. However, the collaborative nature of social inclusion matrix development also served to stimulate discussions about potential further collaboration and support between various actors in the value chain in order to respond to the challenges of ASF:

> *They also discussed the need for organized pig farmer's associations or cooperatives in which they can enjoy privileges such as access to discounted inputs and have a voice in crafting political policy in their sector that the LGU will pass. NE 002 also added in their conversation, an organized barangay ASF response team [is needed] comprised of volunteer pig farmers, who are responsible for information dissemination and surveillance in their community. The social inclusion mapping for the participants became an eye-opener to them to unite together for one common goal of helping one another, for their sector to survive – NENM.*

Financial Capital

Farmer livelihoods were complex, consisting of on-farm and off-farm activities and remittances. Proportional piling in the FGD placed pig farming within the context of an overall livelihood, hinting at the potential impact of pig production losses. While this was only intended to be a semi-quantitative, descriptive exercise, the triangulation of this activity with male and female groups repeatedly supported its accuracy; for example, males and females raising more than 10 pigs in Camarines Sur each said pigs made up 21% of their income. In Nueva Ecija, farmers described their province as "the rice granary of the Philippines" but pig farming was their second-most important income-generating activity. Male, commercial pig farmers said they contributed 30 percent, and this income was used for the education of their children and other necessities.

When reflecting on the pig production budgets they had made together in the FGDs, farmers described the impacts of ASF, including difficulties repaying debts:

> *According to NE 031 the impact of ASF in each production budget line is really devastating to her, she cites with about the feeds that she has now an informal credit with his input supplier and very problematic on paying it. NE 032 discussed the effect of ASF in the price of the live weight of pigs which she stated to be on the range of 50 to 70 Php [USD1-USD1.40]/kg which really affected her income. Most member of FGDS discussed how ASF make their pig raising livelihood broke and had a negative income. And also, the pigs that died and buried which contribute to their loss income (NEFGD1).*

Similar stories were shared during production of the process matrix in the Network Mapping activity. One participant had taken a loan from the bank to start his pig farm with his house serving as collateral and he could no longer service the loan.

Though the number of pigs on each smallholder farm was small, the losses to the sector overall and therefore to the associated value chains, were large. The losses were felt acutely by input suppliers and this gave them a vested interest in supporting farmers in biosecurity efforts:

> *A lot of backyard farms were gone because of biosecurity, he said. He emphasised that the totality of all these small backyard pig raisers had a bigger impact on his targets than the larger farms. Thus, the lack of consumers caused their sales volumes to plummet. He also said, with a sigh, that some areas are only able to sell 20,000 bags in the month (instead of the usual 50,000)" – Interview with input supplier (CS004).*

	BACKYARD FARMS (PART TIME PIG FARMER MEN AND WOMEN)
Characteristics of Production	• Small Scale Production (1-20 Sows) • Other sources of income • Buyers are mostly small-scale traders • No or loose biosecurity • Adulterated feeding practices "swill feeding"
Power relations	• Mostly have no or limited access to training on pig keeping • No or limited voice in associations or cooperatives • No leverage in dictating pig price
Impact of ASF on each group	• Severely affected by ASF outbreak • Loss of other sources of income • Most of the backyard farm have stopped raising pigs or lack motivation to continue pig keeping • Backyard producers shift livelihood activities from pig keeping to poultry goat, cattle, rice and vegetable farming • Psychological and mental stress (Traumatic experience) During depopulation pigs are being shot in broad daylight

FIGURE 6 | Farmers create a social inclusion matrix during a network mapping exercise in Nueva Ecija (photo top and digitised extract bottom).

Network mapping allowed some quantification of losses across the value chain and comparison between production levels. Findings were triangulated with KIIs. Larger-scale farms tended to have a financial buffer to absorb some of the shock from ASF. Also, it became apparent that different value chain actors were impacted to varying degrees and some pig traders even benefited from ASF in the short term, taking advantage of panic selling of healthy pigs:

"In terms of financial, she did not have losses during the ASF issue, instead her sales increased. Of course, she is not thankful that ASF hit their city that affected many especially the backyard farmers,

but during those times, her business boomed... Her sales increased by at least 50% and that lasted for 3 months" – Interview with Pig trader (NE-008).

In his opinion, the backyard farmers lost their livelihood and had credit from their feed supplier that up until now, they cannot repay. In that case, it was a domino effect on the feed supplier because pig raisers were not able to pay their debt. Then they had losses and were probably considered as bad debtors. Lastly, for traders like him, they won in this battle because some traders took the opportunity to have high sales – NE-007.

FGD participants were not the only people with mixed livelihoods. All KII respondents had mixed livelihoods. No fees were charged for the government's veterinary services, they received a wage. However, animal health workers also had mixed livelihood activities. All were involved in the government ASF response, but one was also a pig farmer and two were engaged in some informal veterinary work on the side of their government jobs. One had a side business of artificial insemination providing him with around 8000Php (USD160) per month and another conducted pet vaccination and emergency care for about 2000Php (USD40).

Input suppliers also maintained side businesses as technicians which were impacted by ASF:

Company technicians, to increase their sales volume and suki, would [usually] also act as livestock technicians. He mentions that it is very difficult today to utilize this side job because there are no backyard farms. Larger farms, on the other hand, do not need livestock technicians, he says, since these farms employ veterinarians – Input supplier (CS-004).

The fees charged for slaughtering within government establishments was inexpensive before and since ASF. In the example of small-scale slaughterhouses, the hot meat (informal, unregistered) butcher estimated he spent Php1200 on equipment and his rate for slaughtering was Php300/head. An LRME meat inspector described how they only charged Php105/head:

The interviewers commented that it was cheap, to which CS-003 agrees and states, this is the reason why most people in Pamplona prefer their service than backyard slaughterers. He says that hiring a backyard slaughterer would cost Php300 (sometimes double, if you need two of them), and you have to consider them as guests. You offer food, cigarettes, and sometimes alcoholic drinks. He also mentions that this [the LRME] price did not change even after ASF and even they would get compliments that it is cheap (he would even joke to them, "Would you like us to increase cost?") – Researcher notes on interview with meat inspector (CS-003).

While government slaughterhouse workers were largely protected from financial ASF impacts, one respondent noted that some butcher assistants, *saluyot*'s lost their jobs. Researchers interviewing the hot meat butcher noted the sadness in his eyes when he said that during 2020, he did not have a single customer for butchering or for his other business as a technician.

Human Capital and Psychosocial Impacts

Smallholder farmers used the sale of pigs for important expenses such as education and ASF compromised this. As well as this more tangible impact of ASF, an emergent theme was the psychosocial impacts of ASF. Findings from focus groups and interviews revealed the deep, emotional impacts of ASF and associated control measures.

Open discussion with farmers revealed the intangible significance of pigs in their lives:

"Pigs are like (our) children. (We) would often talk with them and would even cry when they are being sold. Even the youngest considers their pigs as family members" – Female participant, CSFGD3.

The researchers described the tears of participants as they talked about the toll of ASF; they frequently spoke of the trauma of watching or hearing their pigs being shot under the depopulation effort. The note-taker in Nueva Ecija described varying degrees of "emotional shock," "stress," "depression," and "sadness" across all groups:

A participant recounted that she was crying while her pigs and piglets were starting to be culled during the depopulation because she witnessed from afar how the gunshot sounds pierced her ears and watched her pigs die simultaneously. She was in shock knowing that the proceeds from the sale of her pigs were intended for the schooling of her family, University Students in CLSU. She also recounted how she became heartbroken to see how her pigs suffered and was in shock and distress knowing that she would be economically on the brink due to an informal credit she got from her 'Suking Agri Supply' (their input supplier trusted partner) – Female part-time pig farmer, 62yo (NE032, NEFGD1).

The participant NE 011 recounted that he was furious at first while his pigs and piglets were starting to be depopulated because from afar, the gunshots pierced his ears. He was in shock knowing that the proceeds from the sale of his pigs, intended as his household income was already gone... You can see in the eyes of the participants how badly they were affected by the outbreak and how hard for them to bury their pigs seeing [the devastation] with their own eyes... - Male part-time pig farmers (NEFGD2).

A participant shared her experiences when the City veterinary office depopulated their pigs. She cried and begged, "Ako na lang sana ang idamay nyo wag na ang aking mga alaga" (Please don't hurt my animals, hurt me instead). When depopulating she did not even look at her pigs. Instead, she went to other places to breathe. In addition, their investment [in the pigs should have helped] them to pay for their debt and additional income too. The owner was in turmoil physically and mentally especially when they remembered their everyday routine in working at their piggery, feeding, bathing, giving vitamins to their pigs. They considered them as their pets – Female full-time pig farmer (NE019, NEFGD3).

Animal health workers, when asked to comment on the impact of ASF upon value chain actors all spoke of the emotional toll of depopulation on farmers. While job security and satisfaction were noted by many animal health workers, there were also situations where these workers were vilified as "pig killers" by their communities and felt their personal safety was threatened.

At the height of depopulation, she would sometimes search her name on Facebook and would find many public posts where she was being labelled as paragadan orig or "pig-killer... The height of the security risk was during the time of depopulation: I was invited inside the farmer's home to sit and talk. I then noticed an itak (bolo knife) below the farmer's chair and recognized it as a threat. This happened three times - one time, the farmer was even holding the itak!"

– Interview with animal healthcare worker.

Physical Capital

Infrastructure is important for protecting livelihoods from the impacts of infectious diseases. Early on in the epidemic in Camarines Sur, a significant challenge for ASF control was the inability of the local laboratory equipment to test samples, so delaying the receipt of test results. This resulted in depopulation being stalled because they needed a positive result first. This has since been overcome with the laboratory now having the resources for testing.

Beyond laboratory equipment, pigs were an important form of physical capital. While compensation classically involves cash payments, some farmers in this study explained that if their pigs were culled by the government they would prefer replacement pigs of good genetic value. This is because in locations where entire areas are depopulated, high quality pigs may be scarce and cash may be insufficient to assist farmers in recovering from ASF.

Natural Capital

There were narrative accounts of where community members feared compensation would be insufficient and therefore hid their pigs from government staff until they succumbed to ASF. Carcasses were then discarded in the rivers and elsewhere, polluting the environment. Conversely, following the outbreak of ASF there were some improvements in the management of waterways. The illegal dumping practices exposed underlying mismanagement of waterways by pig farmers. These farmers were banned from keeping pigs beside waterways and some community members celebrated this.

Transforming Structures and Processes

Laws, regulations and cultural characteristics mediated the impacts of ASF. These were all touched on by a pig trader interviewed in Camarines Sur:

"He stated that the situation of ASF limited the movement of pigs in Pamplona and increased the supply within the municipality. This is because all the pigs in Pamplona can only be sold to people within the municipality... He also stated that both buying and selling feel very weak because of the ASF situation, and his business was way stronger before. COVID-19 has also made it more challenging since large gatherings are now prohibited by the government. He reminisced that back then, customers would approach him on every special occasion (weddings and fiestas, for example) and they would order three sows! Now, he said, there is no more market for sows – Interview with pig trader (CS-002).

The depopulation program, including compensation and the program's weaknesses was a topic of passionate discussion. FGD participants included ASF-related information on their community timelines. Participants offered information on deviant behaviour, such as hiding pigs from depopulation teams due to poor communication and resulting fear of insufficient government assistance (**Figure 7**).

For slaughter, all pigs need a veterinary health certificate (VHC) but according to respondents, regulation was not always successful. In Camarines Sur, the animal health worker believed private veterinarians were issuing VHCs at their clinics without inspecting herds:

She thinks the poor coordination between private veterinarians and government veterinarians was a challenge. She recalls a story where a pig trader requested Veterinary Health Certificates (six pigs) from a private veterinarian through the phone. This trader told the veterinarian that his pigs came from Milaor (but came from San Fernando where pig mortality was high) and was issued a VHC. This was recognized by the meat inspector (non-veterinarian) in the Naga City Abattoir for slaughter since the raiser presented complete documents signed by a veterinarian. Around 11 pm on that day, one of the pigs died. The remaining five were isolated, and some manifested signs of ASF.

So, [the respondent] thinks it is imperative to unite the private veterinarians, government veterinarians, and the consuming public – CS-001.

This problem was partly addressed by the City Veterinary Office charging much less than private veterinarians (50Php/pig vs. 300Php/pig, respectively) for VHC's which the respondent felt also helped to build relationships between themselves and farmers.

Livelihood Strategies

Farmers in FGDs discussed possible community responses to ASF and potential livelihood strategies using a community timeline projected into the future. In Camarines Sur, rather than offering specific dates, participants divided their discussion into two scenarios, one where ASF remains and one where it is eliminated (**Figure 8**). The discussion was captured by the note-taker, in brief:

If ASF remains, they hope to receive cash assistance from the government. They will also consider raising carabaos, ducks, and goats instead of pigs. But once ASF is gone, which they pray to happen soon, they would love to return to pig raising. They also wish that liveweight pricing would be uniformed throughout Pamplona and the price of feeds be lowered – Male farmer FGD (CSFGD2).

Demonstrations of resilience were captured in the community timelines and open discussions; farmers moved to other livestock species and alternative activities while hoping a vaccine would become available and ASF would be eliminated.

As well as legal practices, animal health workers described deviant behaviour by farmers to counter the personal costs of ASF:

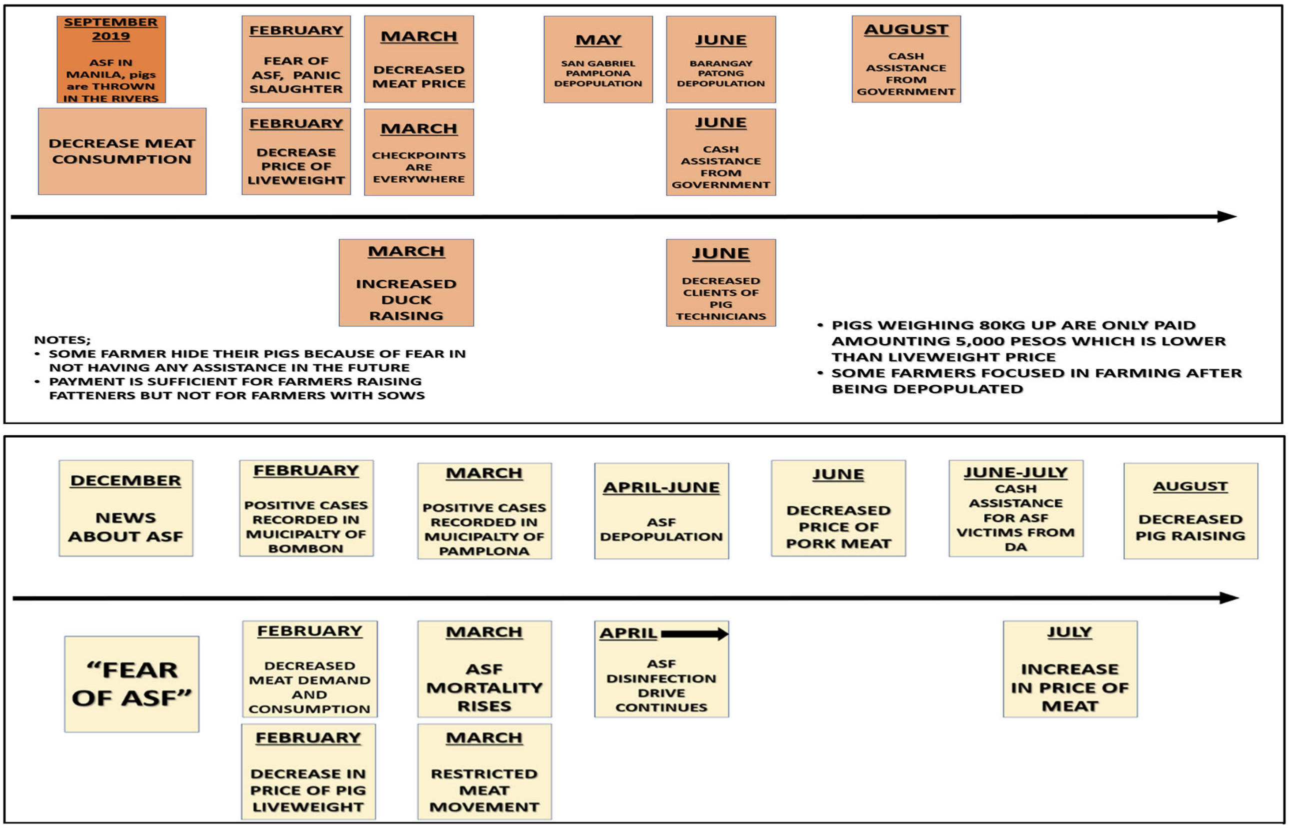


FIGURE 7 | Timelines for African Swine Fever disease events beginning in December 2019, produced during two focus group discussions in Camarines Sur by male (top) and female (bottom) farmers of fewer than 10 pigs.

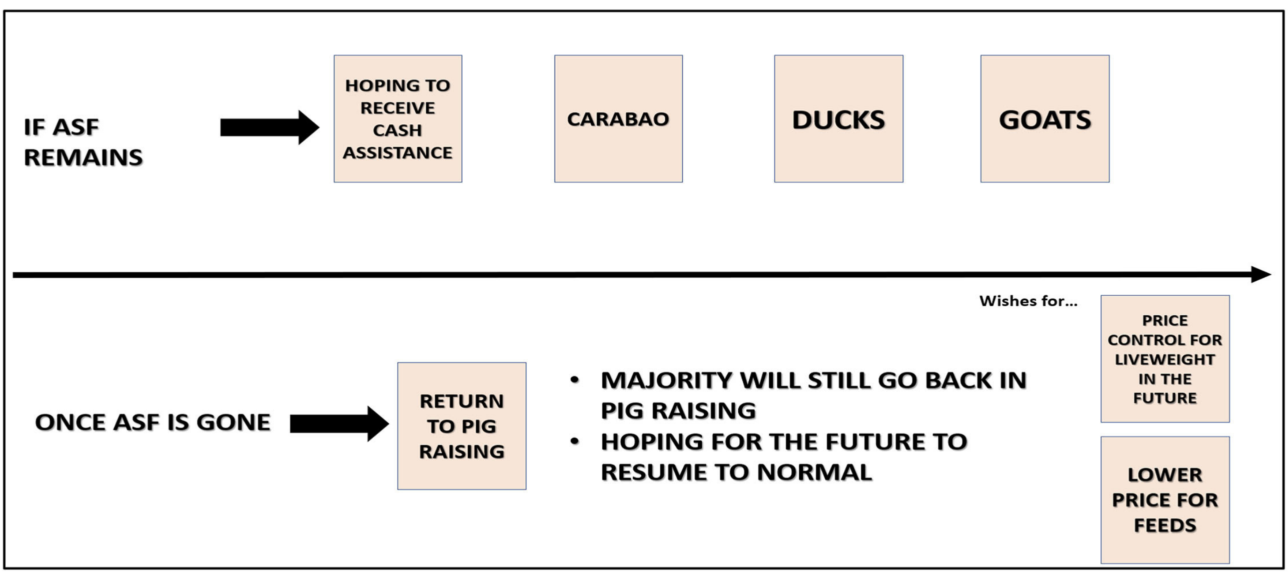


FIGURE 8 | Extension of community timeline into the future to stimulate focus group discussion on planned community responses to African Swine Fever (CSFGD2).

... some pig raisers would try to secretly slaughter their pigs and even sell to other adjacent barangays. This was possibly influenced by the national campaign stating that ASF-positive pigs are safe to eat since ASF is not zoonotic – CS-001.

From the first reported ground zero case at Barangay Santo Niño 1st, there were a total of 166 pigs depopulated. However, there were still some backyard farm owners who transported their herd for slaughter and meat processing despite the *policy given by the authority since it was also reported that the ASF virus was not a zoonotic disease. These instances led to the spread of the virus to other barangays in the municipality – NE-001.*

Other value chain actors also adapted livelihood activities. One input supplier started to produce broiler chickens, another began to sell products online and another cut her business expenses. Generally, input suppliers felt optimistic about a return to normal levels of business in the future.

DISCUSSION

This study describes the broad socioeconomic and livelihood impacts of ASF and the measures used to control it. The study includes findings that can be used to inform future studies and policy measures. All farmers in this study, from small and larger properties experienced financial losses from the ASF epidemic. The financial impacts of ASF on farmers have been described in detail in Africa (19–23); reviewed in (24) and Asia (25, 26). The negative impacts on broader pig value chain players have been described but not quantified in Cameroon (27) and Tanzania (28). Recently the global consequences of a major ASF outbreak in China have been modelled, including knock-on effects on other commodities (29). The impact of ASF on pigmeat markets in Europe has also been recently examined (30). While these numbers provide an important overview of the impact of ASF on agricultural goods, there are fewer published studies on the qualitative impacts of ASF.

In Vietnam, a mixed methods approach was recently used to identify impacts of ASF at value chain, sector and national level and to evaluate the effectiveness of the ASF compensation scheme implemented by the national government (31). Both this study and the Vietnam study mapped impacts along the value chain, but this study placed greater emphasis on qualitative research than the Vietnam study. In addition, this study provides greater detail of the broader livelihoods context of farmers, consistent with the Sustainable Livelihoods Framework (9). This is important because the spread of ASF among smallholder communities in Southeast Asia and the Pacific is superimposed over a complex vulnerability context. Seasonal adverse weather events and corresponding pig disease outbreaks as described in this study are also experienced in other countries inflicted with the disease (26, 32) and these events are only expected to increase with climate change (33). Further, the seasonal peaks and troughs in demand for pork coinciding with ceremonies and cultural events in the Philippines are also seen in other affected countries (32, 34, 35). In these countries, the timing of ASF outbreaks and depopulation programs will influence their impact.

In addition to seasonal vulnerabilities, biosecurity remains a major challenge for smallholder farming systems globally, rendering them more vulnerable to infectious diseases than more biosecure, large-scale production systems. The scale of this disparity has been evidenced with the spread of ASF through Southeast Asia. In China, the proportional rate of outbreaks in smaller farms has been much greater than in medium or large farms (36). The resultant collapse of the smallholder farming sector, which produces more than 80 percent of China's pork, has created big "winners" from the crisis in the form of large pig production firms (35). The shift towards large-scale pig production has also occurred due to ASF in Vietnam (31). As explained by an input supplier in this study, when the millions of smallholders go out of business, the loss of their collective contribution means enormous losses for many associated value chain actors. As the sector becomes dominated by large-scale production there will be concentration of value chain actors, potentially putting many thousands of small-scale input suppliers, buyers, traders, butchers and meat sellers out of business. As observed in this study and as described in peri-urban pig value chains in Uganda (37), biosecurity interventions themselves may also have significant positive and negative impacts on various value chain actors.

Biosecurity challenges extend beyond the farms themselves. In this study, there were accounts of community members hiding sick pigs to avoid their herd being culled. When these pigs died, farmers disposed of the carcasses in rivers. In the Philippines, there is very real concern for the impact of ASF on a native boar species making proper disposal of carcasses a pressing issue (38). The problem of ASF-contaminated carcasses being dumped and contaminating water and waterways has been described in several other countries (27, 39, 40). One of the great challenges of biosecurity and disease control is education. In this study, animal health workers in both sites emphasised the importance of personal communication with farmers. In Camarines Sur, animal health workers described regular contact with every farming household. Given the 1991 devolution of veterinary services in the Philippines (41) and the resource intensity of such a strategy, this may not be replicated in each local government unit.

While a study with a limited sample size of 72 people across two study sites is an insufficient base from which to make policy recommendations, the study findings correspond to several promising interventions warranting further consideration. These were around changes to the ASF control practices and tailoring any support packages to particular needs. The ASF control effort was enormous with all interviewed animal health workers having been recruited to it. The need to consider improvements to the process on the ground became clear. Depopulation campaigns were a dominant theme in discussions, eliciting intense emotion and strong opinions. Farmers had been traumatised by the sounds and vision of their pigs being shot. Pigs were described as pets and even family members by farmers and animal health workers were aware of this, putting them under strain. Many participants were still bearing emotional scars following the loss of their herds and found it difficult to see a future for their livelihood. Human trauma resulting from animal disease control measures appears to be infrequently considered by authorities and academics. Findings in this study echo those described by Mort et al. (42) documenting the psychosocial impacts of the 2001 FMD disaster in the United Kingdom. In their paper, the authors explained that farms are typically places of livestock management and abattoirs the appropriate places for livestock death; depopulation campaigns transgress these boundaries and bring family farmers, who would normally achieve some spatial distancing and emotional detachment into the direct audio and visual experience of the culling. The paper also describes the emotional turmoil of animal health workers and other people on the frontline in the FMD response. This deep and wide-reaching impact of mass depopulation campaigns deserves further attention globally.

As was described as far back as 1985 (27), ASF has the ability to undermine veterinary-farmer relationship, particularly as there is no vaccine or treatment available. In this study, the safety of animal health workers was at risk where depopulation was not supported by the community. While appropriate security measures for animal health workers are important in case of safety breaches, preventative actions, namely improved community engagement processes should be considered. These might also provide an opportunity for delivering information; While biosecurity and prevention measures were not a focus of this study, studies in Timor-Leste (39) and along the Kenya-Uganda border (43) indicate there may be simple interventions such as farmer education, which could be employed to enhance biosecurity and reduce the spread of ASF in smallholder settings.

Improved communication and trust-building with the affected communities will not only improve safety for workers, but it will also likely increase the effectiveness of control programs. Messages around compensation for culled animals need to be timely. In the studied communities, deviant behaviour occurred early in the epidemic before arrangements for compensation were understood by farmers. Information-gathering to determine the most appropriate, desirable form of compensation may also prove useful; Mort et al. (42) echoes the findings in this study, that the loss of a herd of livestock is experienced by some as the loss of their "life's work," with animal genetics often passed down along family farmer lines along with the intimate knowledge of the farm. This deep loss may be why farmers specifically requested that authorities compensate them with good genetic stock, rather than money.

In addition to better communicating the process of depopulation and compensation with farmers, changes to the culling process should be considered to achieve gentler, more humane practices. This is a situation where a One Welfare approach, acknowledging the interconnectedness of human and animal welfare (44) could be taken; improving pig welfare will have significant impacts on human wellbeing. The significant emotional attachment of Filipino farmers to their pigs is underreported in the literature and from the authors' reading, has not been part of the discussion on ASF in the Philippines.

African Swine Fever does not occur in a vacuum; the impacts it has on communities are augmented by existing livelihood vulnerabilities. The results of this study demonstrate how communities with underlying vulnerabilities such as seasonal changes in income, livestock diseases and natural disasters can be impacted particularly heavily by ASF. A rapid situation analysis such as the one conducted in this study to capture and contextualise ASF impacts within the broader vulnerability context could be used to tailor support according to need.

In addition, value chain actors were impacted by ASF in varied ways. While the overall impact of ASF on society was negative, the network mapping, KIIs and FGDs highlighted the fact that within the value chain, actors were impacted very differently. These pilot data reveal, most actors suffered significant losses as a result of ASF but some actors (certain pig traders) were actually able to increase profits and suffered little or no negative qualitative or quantitative impacts of ASF.

Large-scale/commercial farms may have more of a financial buffer to absorb the economic shock of ASF for longer than smallholders. In the short-term, governments could consider focusing support on backyard farmers with the aim of getting them back into pig raising (as the majority of farmers in this study wanted)—It is important for the value chain that backyard farmers return to pig farming. As explained by a respondent, the losses experienced by the very large backyard farming sector amount to significant losses to other VC actors.

Limitations

There was an elevation of community transmission of COVID-19 in one of the study sites, Camarines Sur during the pilot and the Department of Health suggested any face-to-face meetings were postponed. As timelines were tight, the research team was quick to adapt. Telephone and web-based interviews were sufficient, and the interview transcripts were full of rich, detailed information but the research teams noted that they could build greater rapport with those interviewees they were able to meet in person.

For the network mapping exercise, which is usually conducted as an in-person, highly interactive multi-stakeholder group activity, some challenges were faced when moving the exercise online in one site. Firstly, participant recruitment was challenging, with fewer people wishing to participate in the online format. Secondly, recruitment was restricted to people with internet access so there was a bias towards better-resourced participants. Thirdly, even for those with internet access, the connection speeds were often slow, and quality was frequently unreliable creating barriers to full participation. The research team rose to the challenge though, conducting follow up calls to clarify details that were missed and try to maximise participant inclusion.

Owing to time and COVID-19 safety constraints, the value chain actors included in the study were limited and did not include either end of the chain, upstream input producers (such as maize farmers) or downstream pork consumers. To increase the external validity of the findings, this study would provide an excellent foundation for development of empirical survey tools as part of an exploratory, sequential mixed methods design, to capture information from many more participants. Additionally, the classical value chain mapping exercises used in this study are unable to assess *ex*-ante the impacts of alternative control scenarios (45). System dynamics approaches are included as an option within the SELIA Framework (4) for conducting impact assessment and modelling ex-ante policy scenarios at the value chain level. These tools were recently applied in the second ASF SELIA study, in Timor-Leste (Jared 5). The selection of SELIA tools for a given livestock disease impact assessment depend greatly on the type of problem being addressed, the time and resources available.

CONCLUSION

The availability and accessibility of relevant secondary data in the Philippines is greater than in most ASEAN countries.

However, significant gaps exist in the understanding of impact, particularly in qualitative measures. Using multiple participatory tools (network mapping, focus group discussions and key informant interviews), the lived experiences of farmers and other pig/pork value chain actors were captured in rich descriptions. The strength of the qualitative findings was increased using several techniques for triangulation: multiple methods, multiple subjects, comparison with secondary data and semi-quantitative data. These SELIA data provided insights not captured through the use of secondary data and quantitative survey tools. This early application of the SELIA Framework validated the use of classical participatory tools for conducting a rapid socioeconomic and livelihood impact assessment at the community and value chain level. In addition, the network mapping tool showed promise as a first step in a collaborative change-making process, as stakeholders saw the strength in uniting together to help their sector survive ASF.

DATA AVAILABILITY STATEMENT

The datasets presented in this article are not readily available because access is subject to review by the data custodians. Requests to access the datasets should be directed to d.smith1@uq.edu.au.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the University of Queensland Human Research Ethics Committee (Approval Number 2020001543). The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

DS and TC: conceived of and designed the study and contributed equally to drafting and editing the manuscript. DS, TC, and SS: designed the study tools and trained field researchers. MG, MM, MC, LP, RS, and OS: gathered, translated, and transcribed data. All authors contributed to the initial report on which this paper was based and to the paper editing process.

FUNDING

This research was funded by the Australian Centre for International Agricultural Research as a Small Research and Development Activity, *Developing a Regional African Swine Fever Socio-economic and Livelihood Impact Assessment Framework* (LS/2019/187).

ACKNOWLEDGMENTS

The research team gratefully acknowledge the contributions of research participants in Bicol and Central Luzon, the coordinating role of Local Government Units in Camarines Sur and Nueva Ecija provinces and the guidance of the City Health Authorities in the study sites. The team also wish to thank Synan Baguio and Ronilo O. De Castro from the Department of Science and Technology's Philippine Council for Agriculture, Aquatic, and Natural Resources Research and Development (PCAARRD), Samuel Animas, Oscar Cabanayan, and Janice Garcia from the Philippine Government Department of Agriculture's Bureau of Animal Industry (BAI), Van Ibay and Reildrin Morales for their contributions to the research prioritisation process and for providing guidance and feedback. We also acknowledge the administrative role of the Philippine Agriculture and Resources Research Foundation, Incorporated (PARRFI).

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fvets.2021.734236/full#supplementary-material

REFERENCES

1. OIE. 09/09/2019: *African Swine Fever, Philippines (immediate notification).* Manila: OIE (2019).
2. Bureau of Animal Industry RotPDA. *African Swine Fever Portal*. (2020). Available online at: https://www.bai.gov.ph/index.php/regulatory/item/477-asf-portal (accessed November 12, 2020).
3. Corpuz P. *Performance of Philippine Agriculture in 4th Quarter 2019*. (2020). Available online at: https://apps.fas.usda.gov/newgainapi/api/Report/DownloadReportByFileName?fileName=Performance%20of%20Philippine%20Agriculture%20in%204th%20Quarter%202019_Manila_Philippines_01-11-2020 (accessed November 12, 2020).
4. Smith D, Cooper T. *Final Project Report: Developing a Regional African Swine Fever Socioeconomic and Livelihood Impact Assessment Framework*, Canberra: Australian Centre for International Agricultural Research (2021).
5. Berends J, Bendita da Costa Jong J, Cooper TL, Dizyee K, Morais O, Pereira A, et al. Investigating the socio-economic and livelihoods impacts of African Swine Fever in timor-leste: an application of spatial group model building. *Front Vet Sci.* (2021) 8:687708. doi: 10.3389/fvets.2021.687708
6. DFID Department for International Development. *Sustainable Livelihoods Guidance Sheets.* London: DFID Department for International Development (1999).
7. Baumann P. *Improving Access to Natural Resources for the Rural Poor: A Critical Analysis of Central Concepts and Emerging Trends From a Sustainable Livelihoods Perspective*. (2002). Available online at: http://www.fao.org/3/a-ad683e.pdf (accessed November 12, 2020).
8. Binns C, Low WY. Public health implications of African swine fever in Asia. *Asia Pac J Public Health.* (2019) 31:677–8. doi: 10.1177/1010539519889539
9. Smith D, Dyer R, Wandschneider T, (editors). *Making Value Chains Work Better for the Poor: A Toolbook for Value Chain Practitioners.* 4th ed. Canberra: Australian Centre for International Agicultural Research (2020).
10. UNDP. *Philippines: Human Development Indicators.* New York, NY: UNDP (2020).
11. World Bank. *Rural population (% of total population)- Philippines.* Washington, DC: World Bank (2020).
12. World Bank. *East Asia and the Pacific, Macro Poverty Outlook: Country-by-country Analysis and Projections for the Developing World*. Washington, DC: World Bank (2020).

13. FAO. *FAOSTAT- Philippines.* Rome: FAO (2020).
14. World Bank. *Transforming Philippine Agriculture: During COVID-19 and Beyond*. Washington, DC: World Bank (2020).
15. Kaplinsky R, Morris M. *A Handbook for Value Chain Research*. Institute of Development Studies, Univeristy of Sussex, Brighton, United Kingdom (2001). Available online at: http://asiandrivers.open.ac.uk/documents/Value_chain_Handbook_RKMM_Nov_2001.pdf
16. Horton D, Dononan J, Devaux A, Torero M. Innovation for inclusive value-chain development: highlights. In: Devaux A, Torero M, Donovan J, Horton, D, editors. *Innovation for Inclusive Value-Chain Development: Successes And Challenges*. Washington, DC: International Food Policy Research Institute (2016). p. 3-37.
17. Alders RG, Ali SN, Ameri AA, Bagnol B, Cooper TL, Gozali A, et al. Participatory epidemiology: principles, practice, utility, lessons learnt. *Front Vet Sci.* (2020) 7:532763. doi: 10.3389/fvets.2020.532763
18. Catley A, Alders RG, Wood JL. Participatory epidemiology: approaches, methods, experiences. *Vet J.* (2012) 191:151–60. doi: 10.1016/j.tvjl.2011.03.010
19. Babalobi O, Olugasa B, Oluwayelu D, Ijagbone I, Ayoade G, Agbede S. Analysis and evaluation of mortality losses of the 2001 African swine fever outbreak, Ibadan, Nigeria. *Trop Anim Health Prod.* (2007) 39:533. doi: 10.1007/s11250-007-9038-9
20. Brown AA, Penrith M-L, Fasina FO, Beltran-Alcrudo D. The African swine fever epidemic in West Africa, 1996–2002. *Transbound Emerg Dis.* (2018) 65:64–76. doi: 10.1111/tbed.12673
21. Chenais E, Boqvist S, Emanuelson U, Von Brömssen C, Ouma E, Aliro T, et al. Quantitative assessment of social and economic impact of African swine fever outbreaks in northern Uganda. *Prev Vet Med.* (2017) 144:134–48. doi: 10.1016/j.prevetmed.2017.06.002
22. Kivumbi CC, Yona C, Hakizimana JN, Misinzo G. An assessment of the epidemiology and socioeconomic impact of the 2019 African swine fever outbreak in Ngara district, western Tanzania. *Vet Anim Sci.* (2021) 14:100198. doi: 10.1016/j.vas.2021.100198
23. Komba E, Karimuribo E, Kanemanema M. Socio-economic impact of African swine fever outbreak of 2011 and its epidemiology in Isoka District of Zambia. *Tanzania Vet J.* (2014) 29:39–47.
24. Mulumba-Mfumu LK, Saegerman C, Dixon LK, Madimba KC, Kazadi E, Mukalakata NT, et al. African swine fever: update on Eastern, Central and Southern Africa. *Transbound Emerg Dis.* (2019) 66:1462–80. doi: 10.1111/tbed.13187
25. Weaver TRD, Habib N. *Evaluating Losses Associated With African Swine Fever in the People's Republic of China and Neighboring Countries*. Manila: Asian Development Bank (2020).
26. Matsumoto N, Siengsanan-Lamont J, Halasa T, Young JR, Ward MP, Douangngeun B, et al. The impact of African swine fever virus on smallholder village pig production: an outbreak investigation in Lao PDR. *Transbound Emerg Dis.* (2021) 68:2897–908. doi: 10.1111/tbed.14193
27. Nana-Nukechap M, Gibbs E. Socioeconomic effects of African swine fever in Cameroon. *Trop Anim Health Prod.* (1985) 17:183–4. doi: 10.1007/BF02356970
28. Swai E, Lyimo C. Impact of African swine fever epidemics in smallholder pig production units in Rombo district of Kilimanjaro, Tanzania. *Livestock Res Rural Dev.* (2014) 26:32.
29. Mason-D'Croz D, Bogard JR, Herrero M, Robinson S, Sulser TB, Wiebe K, et al. Modelling the global economic consequences of a major African swine fever outbreak in China. *Nat Food.* (2020) 1:221–8. doi: 10.1038/s43016-020-0057-2
30. Niemi JK. Impacts of African swine fever on pigmeat markets in Europe. *Front Vet Sci.* (2020) 7:634. doi: 10.3389/fvets.2020.00634
31. Nguyen-Thi T, Pham-Thi-Ngoc L, Nguyen-Ngoc Q, Dang-Xuan S, Lee HS, Nguyen-Viet H, et al. An assessment of the economic impacts of the 2019 African swine fever outbreaks in Vietnam. *Front Vet Sci.* (2021) 8:686038. doi: 10.3389/fvets.2021.686038
32. Smith D, Cooper T. *Potential Research and Development Support for Smallholder Livestock-Keeping in Timor-Leste*, Canberra: Australian Centre for International Agricultural Research (2020).
33. Forman S, Hungerford N, Yamakawa M, Yanase T, Tsai H, Joo Y, et al. Climate change impacts and risks for animal health in Asia. *Rev Sci Tech Off Int Epiz.* (2008) 27:581–97. doi: 10.20506/rst.27.2.1814
34. Hunter CL, Millar J, Lml Toribio J-A. More than meat: the role of pigs in Timorese culture and the household economy. *Int J Agricult Sustain.* (2021) 19:1-15. doi: 10.1080/14735903.2021.1923285
35. Xiong T, Zhang W, Chen, C.-T. A Fortune from misfortune: Evidence from hog firms' stock price responses to China's African Swine Fever outbreaks. *Food Policy.* (2021) 105:102150. doi: 10.1016/j.foodpol.2021.102150
36. Gao L, Sun X, Yang H, Xu Q, Li J, Kang J, et al. Epidemic situation and control measures of African swine fever outbreaks in China 2018–2020. *Transbound Emerg Dis.* (2021) 68:2676–86. doi: 10.1111/tbed.13968
37. Ouma E, Dione M, Birungi R, Lule P, Mayega L, Dizyee K. African swine fever control and market integration in Ugandan peri-urban smallholder pig value chains: An ex-ante impact assessment of interventions and their interaction. *Prev Vet Med.* (2018) 151:29–39. doi: 10.1016/j.prevetmed.2017.12.010
38. Luskin MS, Meijaard E, Surya S, Sheherazade, Walzer C, Linkie M. African swine fever threatens Southeast Asia's 11 endemic wild pig species. *Conserv Lett.* (2021) 14:e12784. doi: 10.1111/conl.12784
39. Barnes TS, Morais O, Cargill C, Parke CR, Urlings A. First steps in managing the challenge of African Swine Fever in Timor-Leste. *One Health.* (2020) 10:100151. doi: 10.1016/j.onehlt.2020.100151
40. Normile D. African swine fever marches across much of Asia. *Science.* (2019) 364:617–8. doi: 10.1126/science.364.6441.617
41. Government of the Philippines. *Local Government Code of 1991*. Metro Manila: Government of the Philippines (1991).
42. Mort M, Convery I, Baxter J, Bailey C. Animal disease and human trauma: the psychosocial implications of the 2001 UK foot and mouth disease disaster. *J Appl Anim Welfare Sci.* (2008) 11:133–48. doi: 10.1080/10888700801925984
43. Nantima N, Davies J, Dione M, Ocaido M, Okoth E, Mugisha A, et al. Enhancing knowledge and awareness of biosecurity practices for control of African swine fever among smallholder pig farmers in four districts along the Kenya–Uganda border. *Trop Anim Health Prod.* (2016) 48:727–34. doi: 10.1007/s11250-016-1015-8
44. Colonius TJ, Earley RW. One welfare: a call to develop a broader framework of thought and action. *J Am Vet Med Assoc.* (2013) 242:309–10. doi: 10.2460/javma.242.3.309
45. Rich KM, Ross RB, Baker AD, Negassa A. Quantifying value chain analysis in the context of livestock systems in developing countries. *Food Policy.* (2011) 36:214–22. doi: 10.1016/j.foodpol.2010.11.018

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

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

Copyright © 2022 Cooper, Smith, Gonzales, Maghanay, Sanderson, Cornejo, Pineda, Sagun and Salvacion. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.

Advantages of publishing in Frontiers

OPEN ACCESS
Articles are free to read for greatest visibility and readership

FAST PUBLICATION
Around 90 days from submission to decision

HIGH QUALITY PEER-REVIEW
Rigorous, collaborative, and constructive peer-review

TRANSPARENT PEER-REVIEW
Editors and reviewers acknowledged by name on published articles

Frontiers
Avenue du Tribunal-Fédéral 34
1005 Lausanne | Switzerland

Visit us: www.frontiersin.org
Contact us: frontiersin.org/about/contact

REPRODUCIBILITY OF RESEARCH
Support open data and methods to enhance research reproducibility

DIGITAL PUBLISHING
Articles designed for optimal readership across devices

FOLLOW US
@frontiersin

IMPACT METRICS
Advanced article metrics track visibility across digital media

EXTENSIVE PROMOTION
Marketing and promotion of impactful research

LOOP RESEARCH NETWORK
Our network increases your article's readership