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REVIEW

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Risks of introduction and economic consequences associated with African swine fever, classical swine fever and foot-and-mouth disease: A review of the literature

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Abstract

African swine fever (ASF), classical swine fever (CSF) and foot-and-mouth disease (FMD) are considered to be three of the most detrimental animal diseases and are currently foreign to the U.S. Emerging and re-emerging pathogens can have tremendous impacts in terms of livestock morbidity and mortality events, production losses, forced trade restrictions, and costs associated with treatment and control. The United States is the world's top producer of beef for domestic and export use and the world's third-largest producer and consumer of pork and pork products; it has also recently been either the world's largest or second largest exporter of pork and pork products. Understanding the routes of introduction into the United States and the potential economic impact of each pathogen are crucial to (a) allocate resources to prevent routes of introduction that are believed to be more probable, (b) evaluate cost and efficacy of control methods and (c) ensure that protections are enacted to minimize impact to the most vulnerable industries. With two scoping literature reviews, pulled from global data, this study assesses the risk posed by each disease in the event of a viral introduction into the United States and illustrates what is known about the economic costs and losses associated with an outbreak.

KEYWORDS

domestic livestock, economic impact, feral swine, foreign animal diseases, risk assessment

1 | INTRODUCTION

Domestic livestock production plays a vital role in human health and nutrition, food security, rural poverty reduction and overall agronomic health (Randolph et al., 2007; Tomley & Shirley, 2009). The Food and Agriculture Organization (FAO) estimates that 40% of the global value of agricultural output is provided by livestock and 1.3 billion people are dependent on livestock for their livelihoods and food security (FAO, 2019a). Emerging and re-emerging pathogens pose a significant threat to livestock industries across the globe, as they can have serious impacts in terms of livestock morbidity and mortality, production losses, consumer demand and costs associated with treatment and control. Some of the most challenging and economically burdensome diseases are those transmitted between wildlife and domestic animals (Miller et al., 2017). Diseases transmitted at the domestic animal–wildlife interface are increasingly challenging veterinary health systems with African swine fever (ASF), classical swine fever (CSF) and foot-and-mouth disease (FMD) being three of the most concerning among animal diseases (OIE, 2019). Globally, between 1995 and 2005, the number of outbreaks of these three diseases reached all-time maximums (Figure 1) and has continued to be important animal diseases of economic concern (OIE, 2019).

Disease control measures such as movement bans, culling and vaccination (when available) can be used to reduce the frequency of disease already present in a population by eliminating causes of disease or reducing them to levels of little or no consequence. Analysis of the effectiveness of a disease mitigation strategy is difficult because of inherent uncertainties about the likelihood of disease outbreak and spread parameters (Elbakidze et al., 2009). Further, the ideal cost-minimizing strategies (determined in either ex-ante or ex-post analysis) also depend on relative costs, ancillary benefits and effectiveness of mitigation strategies (Elbakidze & McCarl, 2006). For these reasons, 'explicit risk-based investigation' (Elbakidze et al., 2009, p. 932) of mitigation of these three diseases are necessary to inform the possible outbreak costs and benefits of mitigation. Thus, a comprehensive understanding of the risks and consequences associated with a potential outbreak of ASF, CSF and/or FMD is crucial in order to (a) allocate resources to prevent routes of introduction that are believed to be more probable, (b) consider costs and efficacy of control methods and (c) ensure that appropriate mitigation tactics are put in place to minimize impact to the most vulnerable industries. Here, we illustrate the findings of two separate scoping reviews of global literature to identify epidemiological risks, economic measures and scientific gaps for ASF, CSF and FMD.

African swine fever virus (ASFV), a large, double-stranded DNA virus in the Asfarviridae family, is the causative agent of African swine fever. This virus is believed to have evolved in southern and eastern Africa (Penrith, 2009) as a sylvatic cycle exists between warthogs (*Phacochoerus africanus*) and soft ticks (*Ornithodoros*; Bakkes et al., 2018). While asymptomatic in warthogs, ASF is a haemorrhagic disease that can cause mortality nearing 100% in susceptible populations of domestic swine and wild boar (Blome et al., 2013). In 2007, ASFV was introduced to the Caucuses region and subsequently spread throughout Europe and Asia infecting domestic and wild pigs. In the fall of 2018, the virus was introduced to China and has spread rampantly throughout Southeast Asia (FAO, 2019b; Le et al., 2019; Zhou et al., 2018).

Classical swine fever virus (CSFV) is a pestivirus which is the causative agent of classical swine fever. Infection can take several forms (acute, chronic or prenatal) depending on the virus strain and host immune status, which is heavily influenced by age (Moennig, 2000). Clinical signs can range from acute death to non-specific signs, including fever, anorexia, lethargy, respiratory signs, conjunctivitis, diarrhoea and central nervous system involvement (Brown & Bevins, 2018a). Although CSFV is often fatal, death may or may not follow imminently. Neonatal piglets infected with CSFV in utero may be aborted or stillborn or demonstrate congenital signs soon after birth resulting in death, depending on when in utero the foetus was exposed. Classical swine fever was eradicated from the United States in 1976 after an official eradication scheme began in 1961 (Edwards et al., 2000). Presently, the virus is endemic in several countries in South and Central America, Asia, and parts

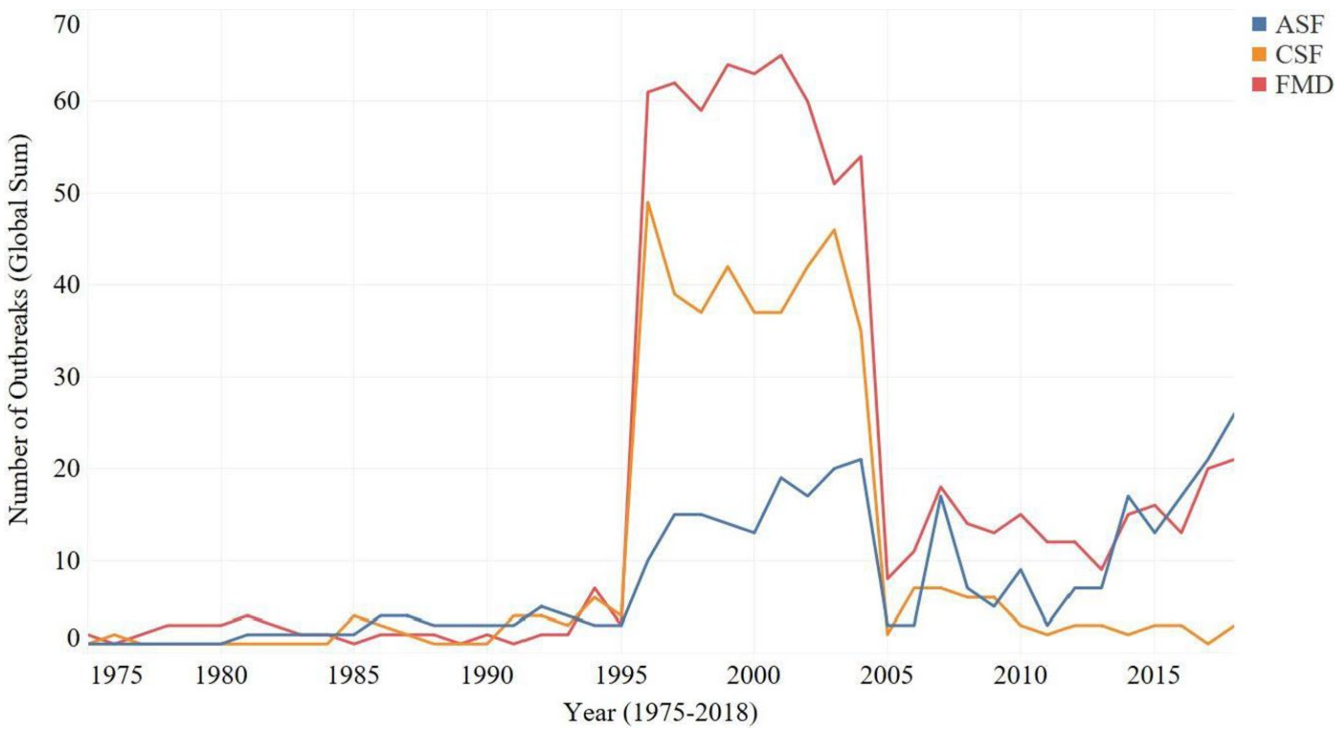

FIGURE 1 Number of ASF, CSF and FMD outbreaks worldwide, by year (OIE, 2019) [Colour figure can be viewed at wileyonlinelibrary.com]

of Eastern Europe and neighbouring countries. The presence of the virus in Africa is unknown (Blome et al., 2017).

Foot-and-mouth disease, caused by foot-and-mouth disease virus (FMDV), is a highly contagious virus that infects cloven-hoofed animals, including cattle, buffaloes, sheep, goats, pigs and various wildlife species (FAO, 2012; Grubman & Baxt, 2004). This virus can be spread both horizontally and vertically and causes low mortality but high morbidity. These disease dynamics contribute to the significant costs associated with an outbreak as affected animals have reduced growth rates and decreased milk production resulting from vesicles that develop in and around the oral cavity and along the hooves (Alexandersen et al., 2003). Foot-and-mouth disease is endemic in large areas of Asia and Africa, and South America had its most recent outbreak in Colombia in 2017. Based on strict trade measures, North America, Europe and Australia have been able to maintain an FMDV-free status in recent years without vaccination (Niedbalski et al., 2019).

Transboundary animal diseases are challenging to manage as the demand for animal protein increases, globalization of international trade increases, and climate change continually threatens ecosystems and agricultural production systems. Given the considerable impact of these three diseases, they have been the focus of a significant number of studies evaluating risks which have sought to provide guidance it mitigate risk, conduct contingency planning and insights to potential economic outcomes (e.g. Boklund et al., 2013; Halasa, Boklund, et al., 2016; Halasa, Bøtner, et al., 2016). The majority of this work has likely resulted from World Organisation for Animal Health (OIE) requirements to conduct risk and economic consequence assessments, resulting in most available assessments being narrowly focused to specific geographic region(s) and often addressing OIE guidelines. Despite the significant amount of work available for ASF, CSF and FMD, there remains a paucity of work to synthesize the literature and identify gaps and needs.

Knowledge about the economic consequences of ASF, CSF and FMD can better inform effective allocation of resources for disease prevention and potential response. Economic analyses have been carried out in regions around the world since at least the late 1970s; however, there has yet to be a rigorous meta-analysis or review of either the economic literature for ASF, CSF and FMD individually or collectively in more than 10 years. Knight-Jones and Rushton (2013) provide an extensive table of existing

TABLE 1 Risk evaluation & economic scoping review, PRISMA steps

		Search terms		Exclusion criteria	
PRISMA step	Text evaluated	Risk	Economic	Risk	Economic
Identification	Primary search terms in title, abstract, index terms	[Disease name] + risk + assessment OR analysis OR pathway	[Disease name] + economic [Disease name] + 'economic damage' economic loss cost	Studies without Identification primary search terms in title, abstract or index terms	Studies without Identification primary search terms in title, abstract or index terms
Screening	NA	NA	NA	Not published in peer-reviewed journal or as government technical report Unable to locate Not in English Does not pertain to (disease OR Risk analysis)	Not published in peer-reviewed journal Unable to locate Not in English Does not pertain to (disease OR economic analysis)
Eligibility	Secondary search terms in full text	Risk Pathway Assessment Analysis	Economic Cost Loss Dollar Total 'Total economic'	Do not present own results	Do not present own results No outbreak cost/ loss analysis
Included	Full text	NA	NA	Not published in peer-reviewed journal or as government technical report Unable to locate	Not published in peer-reviewed journal Unable to locate No outbreak cost/ loss analysis No historic exchange rate available for time of study

cost–benefit analysis studies of FMD control and eradication programs as a part of their original economic analysis (Knight-Jones & Rushton, 2013). However, the paper does not specifically function as a scoping or systematic literature review. Bennett and IJpelaar (2005) also carried out a review of 34 endemic diseases to Great Britain where they outlined new developments in economic analysis and updated disease cost estimates; however, they did not report a table of all findings and briefly summarize results with no mention of FMD (Bennett & IJpelaar, 2005). While acknowledging that many economic evaluations of non-zoonotic animal disease programs have been carried out on an ad hoc basis, Perry & Grace (2009) conclude that the varying diseases, methodologies and results make it difficult to draw general conclusions or compare diseases (Perry & Grace, 2009). It should also be noted that most of these studies have been carried out in developed countries and those from developing counties rarely consider the differential impact on the poor (Perry & Grace, 2009).

The objective of our study is twofold. First, to identify and illustrate potential risks (epidemiological or economic) posed by ASF, CSF and FMD. Second, to identify knowledge gaps and opportunities to better inform policy, risk management and applied research. To accomplish this, we used two separate scoping reviews. We first present the methods and results of these two scoping reviews. We then discuss the risks and economic implications of each of these diseases based on the findings of both reviews. Finally, we conclude by illuminating the most important takeaways from this analysis, and consider the roles invasive feral swine may play in transmission dynamics of these diseases in the United States in the event of an outbreak. We originally anticipated this to be a U.S. focused review; however, the paucity of available data forced us to expand our efforts to a global scale.

2 | METHODS

We used systematic scoping reviews as our primary tool given the large, heterogeneous nature of comparing epidemiological and economic literature. These reviews were based on the methodological guidance outlined by Peters et al. (2015) and utilized the PRISMA methods (Preferred Reporting Items of Systematic Reviews and Meta-Analyses; Moher et al., 2009, 2015) for systematic scoping reviews. Specific text evaluated, search terms and exclusion criteria, based on each PRISMA step, are outlined for the risk evaluation and economic literature reviews (respectively) in Table 1.

2.1 | Scoping review 1: risk evaluation

In the risk evaluation scoping review, we examined the range of studies evaluating risk that have been conducted for ASF, CSF and FMD globally. Risk assessment is a broad area of analysis that can represent quantitative or qualitative analyses and can be limited to just the pathway of introduction or include an analysis of the mechanisms which drive disease spread. Within the OIE framework, risk assessment is a rigorous structured approach that conducts

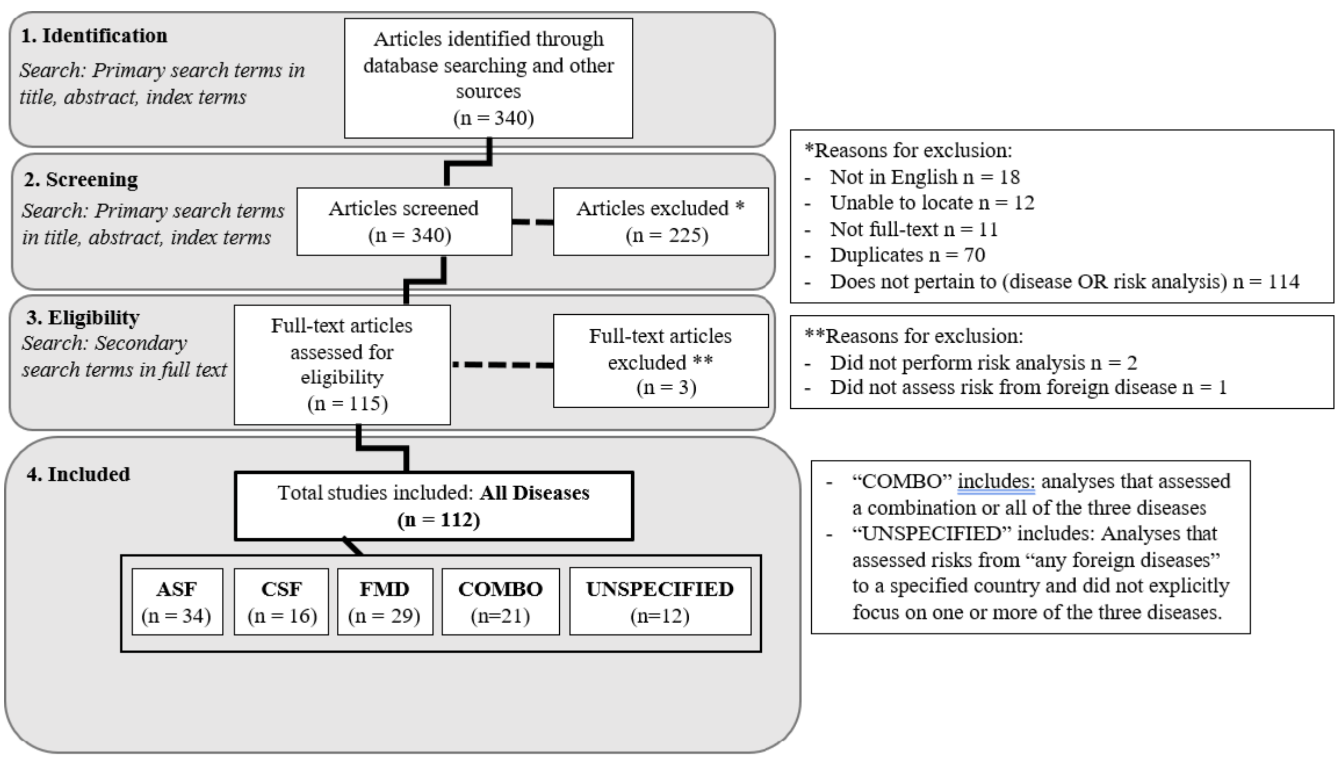

FIGURE 2 Risk evaluation scoping literature review, PRISMA outcomes [Colour figure can be viewed at wileyonlinelibrary.com]

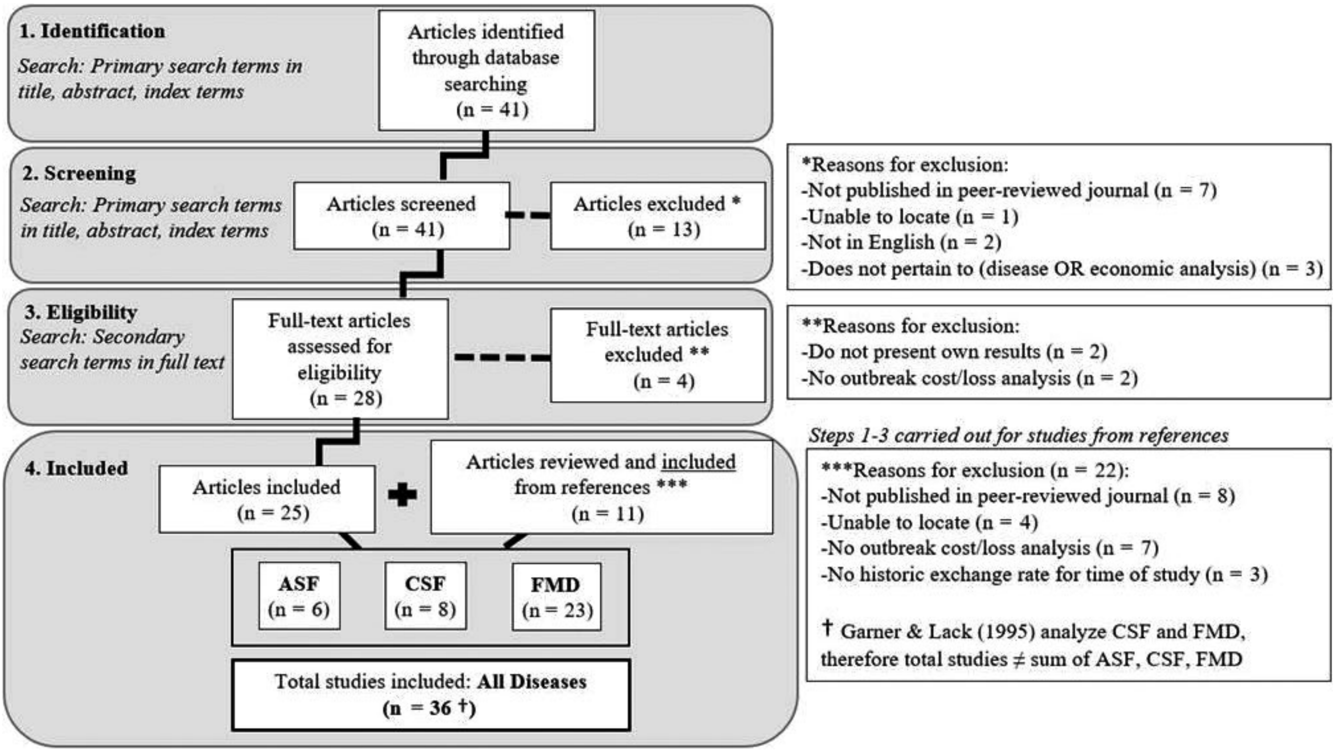

FIGURE 3 Economics scoping literature review, PRISMA outcomes

specific assessments—release assessment, exposure assessment, probability of occurrence—which are used with a consequence assessment to arrive at a final risk estimation (Dufour et al., 2011). To capture the breadth of studies investigating potential risks associated with these pathogens, all literature evaluating risks were considered eligible and are reflected in the use of broad search terms. We did not limit our search to only studies using OIE risk assessment framework as many studies address only a few aspects of the framework. All scientific peer-reviewed literature from journals, edited book volumes, government reports, technical documents or other similar documents were considered eligible, as well as grey literature consisting of mainly unpublished government reports. To identify studies, we used keywords to search four databases (PubMed, Scopus, Web of Science and National Agricultural Library). Studies in English published in any year through 2019 were considered eligible. Once all relevant sources were identified and retrieved, we reviewed each source to ensure relevance and data were extracted. A detailed description of these are included in Appendix Table A1, but in summary, included information pertained to pathogen type, risk evaluation type, pathways of introduction, geographic source (where the virus could come from) and destination (where the virus could end up), models used in the risk evaluation and other pertinent information. Additionally, the associated highest risk variables (i.e. introduction pathway, geographic source and destination, and consequence) were recorded in the database if they were identified by the study evaluating risk. This process is outlined in Figure 2, and a total of 112 literature sources were included in the database.

2.2 | Scoping review 2: economic impact

In the economic impact scoping review, we identified where ASF, CSF and FMD studies have been carried out, compare economic outcomes and identify research gaps. Studies were classified by the pathogen type and sorted by continent and country. Literature included was found through Google Scholar and the PRIMO (Peer-Reviewed Instructional Materials Online) database. Peer-reviewed literature published any year through 2019, in English, was included. Methodological quality was not assessed in this review as it is not a specific criterion for scoping reviews [29]; however, inclusion of only peer-reviewed literature should imply methodological soundness. Grey literature was not considered in this case, and articles were not retained if they only reported results from another source (results were then sought out in their original documentation). A total of 35 sources were reviewed for the economic literature (Figure 3).

3 | RESULTS

3.1 | Scoping review 1: risk evaluation

3.1.1 | Geographic location

Thirty-two (28.6%) of the reviewed documents assessed the risks posed to the United States, and the remaining 80 (71.4%) assessed risks associated with other foreign countries. The overwhelming majority of the foreign risk evaluations (51 (63.7%)) identified risk to

TABLE 2 Descriptive summary of the United States and foreign studies evaluating risk characterized by pathogen(s) evaluated and the type of risk evaluation

	Pathogen evaluated				Type of assessment			
	ASFV	CSFV	FMDV	Combination	Qualitative	Semi-quantitative	Quantitative	Both
U.S. assessments	3	9	10	8	16	1	6	8
Foreign assessments	32	7	19	13	39	10	22	9

[a]One U.S. assessment and 11 foreign assessments did not identify pathogen evaluated.

European countries and regions, and 8 (10.0%) of the foreign risk evaluations did not identify a specific geographic destination but still evaluated possible routes of introduction, and so were considered relevant to our study and included. As for the remaining foreign risk evaluations, 7 (8.7%) assessed risk to countries in Asia, 6 (7.5%) assessed New Zealand, 3 (3.7%) assessed African countries, 2 (2.5%) assessed Canada, 2 (2.5%) assessed Brazil, and 1 (1.2%) assessed the risk to Australia.

3.1.2 | U.S. risk evaluation: highest risk geographic source and destination

Of the 32 documents evaluating risk to the United States, only 6 (18.7%) identified specific countries as being the most likely source of an outbreak. The geographic locations identified were Asia, Canada, Cuba, the Dominican Republic, Germany, Italy, Russia and the United Kingdom. Ten studies evaluating risk (31.2%) identified risks below the national scale, identifying specific locations within the United States as the highest risk for virus introduction. These locations were California, Florida, Iowa, Minnesota, Puerto Rico, Texas, Wisconsin and the southwest region of the U.S, as well as the major airports of Florida, New Jersey, New York, North Carolina, Ohio, Puerto Rico, Rhode Island, Texas and Virginia. Risk factors common among these states included (a) dense livestock populations, (b) large international airports, (c) existing feral swine populations and (d) presence of swine waste feeding operations.

3.1.3 | Pathogens evaluated

Thirty-three (29.5%) of the 112 total studies evaluating risk specifically assessed ASF, 17 (15.2%) assessed CSF, and 29 (25.9%) assessed FMD. Another 21 (18.7%) assessed a combination of two or more diseases, and 12 (10.7%) risk evaluations did not identify a specific disease and so are not included in 'Pathogen Evaluated' section of Table 1. However, these studies evaluating risk were considered relevant as they still evaluated potential pathways of introduction to a country for 'any foreign disease', which while not specifically stated, is assumed to include ASF, CSF and FMD.

3.1.4 | Risk evaluation types and models used

Of the 112 assessments, there were 55 (49.1%) qualitative reviews, 28 (25.0%) quantitative, 11 (9.8%) semi-quantitative analyses, and 18 (16.1%) performed a combination of both qualitative and quantitative analyses. A variety of models were used within the literature, including, but not limited to: net trade, stochastic, multi-level binomial, logistic and linear regression, Monte Carlo simulations, Hierarchal cluster analyses and Scenario trees. Table 2 itemizes the pathogen(s) evaluated and the types of assessments utilized.

3.1.5 | Assessed pathways of introduction

The majority of the studies evaluating risk considered many pathways for pathogens to be introduced to a specific country or continent. The primary pathways of disease introduction assessed by all 112 studies included the following: natural movement of wildlife; legal and illegal imports of animals and animal products including bushmeat and genetic material; by way of commercial, personal, or military planes, ships, vehicles and mail; and bioterrorism. Many risk evaluations then determined which of the assessed pathways of disease introduction could be the highest risk to the country or region being evaluated.

3.1.6 | Foreign assessments: highest risk pathway of introduction

Across all three diseases, 34 (42.5%) of the foreign assessments did not identify a highest risk pathway of introduction, but of the 46 that did, the majority (32 (69.6%)) identified legal and illegal importations of live animals, meat and meat products, animal feed, genetic material and bioterrorism to be the pathways of highest risk. Another 8 (17.4%) identified cross-border movements of livestock or wild boar, 6 (13.0%) identified swill-feeding, 6 (13.0%) identified cross-border movements of livestock trucks, and 2 (4.3%) identified other fomites such as shoes, clothing, supplies and fresh-cut grass from infected areas. It is important to note that some assessments reported multiple pathways of introduction as highest risk.

The only pathway of introduction that varied based on disease within the foreign assessments was returning livestock vehicles and other fomites. This pathway was identified as highest risk primarily by European assessments evaluating the risk posed by ASF. Only two assessments, also European, identified returning livestock trucks specifically as highest risk for CSF, and none of the foreign assessments evaluating FMD reported any fomites as a highest risk pathway of introduction.

3.1.7 | U.S. assessments: highest risk pathway of introduction

Of the 32 U.S. assessments, 17 (53.1%) did not identify a pathway of introduction of highest risk, but 11 assessments (34.4%) identified legal or illegal imports (including bioterrorism) of animals, animal products, animal feed or genetic material, as the highest risk pathway of introduction, most commonly by way of air passenger or air passenger baggage. In addition, 2 U.S. assessments (6.2%) identified swill-feeding as being the highest risk pathway of introduction, 1 (3.1%) identified the importation of diagnostic samples, and 1 (3.1%) identified *Ornithodoros* ticks, as they can be vectors for ASF. Importantly, these ticks were identified to be the highest risk in comparison with all other tick species that can transmit the disease; however, ticks as vectors were not identified as a highest risk pathway of introduction to the United States when compared to all other possible routes of introduction. Unlike the foreign assessments, none of the U.S. assessments identified wild boar or their movements as a highest risk pathway of introduction.

3.2 | Scoping review 2: economic impact

A total of 36 peer-reviewed articles were found, in English, which presented their own economic analysis. One article by Garner and Lack (1995) addressed both a study on CSF and another on FMD. Broken down, we identified six studies for ASF (16.2% of all 37 disease studies), eight for CSF (21.6%), and 23 for FMD (62.2%) (Figure 3) for a total of 37 studies within 36 articles. Eight institutional or government reports were reviewed and not included in the selection because they were not published through the peer-review process. The economic evaluations carried out among the studies included the following: Agricultural sector model (ASM), benefit–cost analysis (BCA), computable general equilibrium (CGE), economic impact assessment (EIA), input–output (I/O), partial equilibrium (PE), partial budget model (PBM), referred to as 'financial costing' (FC) where a more accounting-type approach is taken to quantify economic impacts. Across all studies, a total economic cost or loss (or combination of the two) was estimated, often pertaining to agricultural production loss and epidemic control costs. Costs were often associated as government costs, and loss was most often reported as production loss to the livestock or milk industries. To our knowledge, no studies specifically addressed feral swine as the primary source of disease introduction but several studies suggested with may contribute to establishment and spread if the disease was introduced.

The range of costs and/or losses presented for ASF was from $649,000 to $94,539,870,064 (USD, 2019) which represent the average annual pig production loss from an outbreak in Nigeria (Fasina et al., 2012) and the total economic loss value of swine depopulated from an outbreak in Spain (Bech-Nielsen et al., 1993), respectively. The range of costs and/or losses presented for CSF was from $58,338 to $585,762,061 (USD, 2019) which represent the total direct annual production loss from an outbreak in Australia (Garner et al., 2001) and the maximum median epidemic cost (based on infected herd) of an outbreak in Denmark (Boklund et al., 2009), respectively. Finally, the range of costs and/or losses presented for FMD was between $83 and $84,584,000,000 (USD, 2019) which represent total average economic loss per herd from an outbreak in Ethiopia (Jemberu et al., 2014) and the maximum, median total national loss in agricultural surplus from an outbreak in California in the United States (Carpenter et al., 2011), respectively. These ranges highlight the fact that geospatial information and scale are paramount to compare studies and since that was not uniform, it is nearly impossible to make generalizations about which of these diseases is the most costly.

The economic scoping review affirmed that an outbreak of any of these diseases is expensive and that the economic impact of each disease is driven by a number of factors, including location of outbreak (e.g. Hop et al., 2016; Mahul & Durand, 2000; Pendell et al., 2007), trade implications (e.g. Babalobi et al., 2007; Countryman & Hagerman, 2017; Mangen et al., 2004) and consumer reaction (e.g. Blake et al., 2003; Thompson et al., 2002). The results of the review also implied that disease management and control practices heavily contribute to the economic impact of the disease (e.g. Boklund et al., 2009; Schoenbaum & Disney, 2003). Comparing across studies, analyses were often partial in terms of total impact evaluation (micro and macroeconomic), therefore not capturing the full burden on the economy.

Of the 37 studies, a total of nine peer-reviewed published studies were 'retrospective' studies (25.7%) and the remaining 26 studies

TABLE 3 Count of studies included in literature review, by study type

Study type	Description	# Studies
Retrospective	Ex-post analysis of historical outbreak. Provides an economic impact value based on observed outcomes of the outbreak	9
Forecast	Hypothetical outbreak scenario. Purpose is economic impact evaluation for future outbreak potential	26

TABLE 4 Count of countries with economic analyses, by disease, by 'Retrospective' (Retro.) or 'Forecast' (For.)

Country name	FMD Retro.	FMD For.	ASF Retro.	ASF For.	CSF Retro.	CSF For.	Total Retro.	Total For.	Total analyses[a]
Argentina	1	0	0	0	0	0	1	0	1
Australia	0	1	0	0	0	2	0	3	3
Belgium	0	0	0	0	0	1	0	1	1
Brazil	1	0	0	0	0	0	1	0	1
Colombia	1	0	0	0	0	0	1	0	1
Denmark	0	2	0	1	0	1	0	4	4
Ecuador	1	0	0	0	0	0	1	0	1
Ethiopia	1	0	0	0	0	0	1	0	1
France	0	1	0	0	0	0	0	1	1
Germany	0	0	0	0	0	1	0	1	1
Netherlands	0	1	1	0	2	3	3	4	7
New Zealand	0	1	0	0	0	0	0	1	1
Nigeria	0	0	1	1	0	0	1	1	2
Spain	0	0	0	1	0	0	0	1	1
S. Sudan	1	0	0	0	0	0	1	0	1
Taiwan	1	0	0	0	0	0	1	0	1
Turkey	1	0	0	0	0	0	1	0	1
UK	1	1	0	0	0	0	1	1	2
USA	0	9	0	1	0	0	0	10	10
Uruguay	1	0	0	0	0	0	1	0	1
Venezuela	1	0	0	0	0	0	1	0	1
Total	11	16	2	4	2	8	15	28	43

[a]Totals presented here are not counts of individual studies—they are counts of economic analyses by country.

were categorized as 'forecast' (74.3%; Table 3). We define 'retrospective' as an ex-post analysis of an actual historic outbreak with the purpose of providing an economic impact value based solely on observed outcomes of the outbreak. A retrospective study utilizes data specifically from one historic outbreak (or outbreak period) to determine the economic impact. We define 'forecast' as a study whereby a hypothetical outbreak scenario is created with the purpose of economic impact evaluation. Forecast studies often utilize simulation models based on historic outbreak data to provide insight into the potential economic impacts of varying outbreak sizes and control strategies. Forecast studies often aim to inform future epidemic outbreak management decisions. All studies which used simulation modelling were labelled as 'forecast', but not all forecast studies used simulation modelling.

3.2.1 | Geographic span of analyses

Collectively, economic analysis was carried out in six of the seven global continents. Table 4 lists the 21 countries represented in economic studies and totals the number of analyses carried out by disease and analysis type (retrospective or forecast). Analyses tended to focus on country-wide economic effects of disease outbreaks in one respective country. However, two transcontinental/global FMD studies were also carried out, one being an analysis in Turkey by Senturk and Yalcin (2008) which spans both Asia and Europe and the other from Knight-Jones and Rushton (2013) which is a global economic impact analysis of FMD in countries/regions in Asia, Africa, Europe and South America. Two studies for CSF were multi-country studies, one between the Netherlands and Germany (Hop et al., 2016) and the other between the Netherlands and Belgium (Saatkamp et al., 2000). For FMD in the United States, Carpenter et al. (2011), Pendell et al. (2007) and Bates et al. (2003), respectively, consider outbreaks in the state of California, the state of Kansas (and regions within) and a three-county region in California.

To explore the relationships between the prevalence of peer-reviewed research and outbreak location, we created four bivariate chloropleth world maps (Figures 4, 5, 6 and 7). Figure 4 demonstrates the relationship between the number of outbreaks of ASF, CSF and FMD (1975–2018) and the number of retrospective (ex-post) economic studies. To follow, we considered the relationship between livestock or swine per capita and the number of forecast economic studies in Figures 5, 6 and 7 for FMD, ASF and CSF, respectively. The number of livestock or swine per capita is a proxy for the weight carried by livestock or swine (thus at risk for FMD, ASF or CSF) in a country's economy.

Figure 4 shows the number of outbreaks of ASF, CSF and FMD (1975–2018) on the x-axis, and on the y-axis the number of

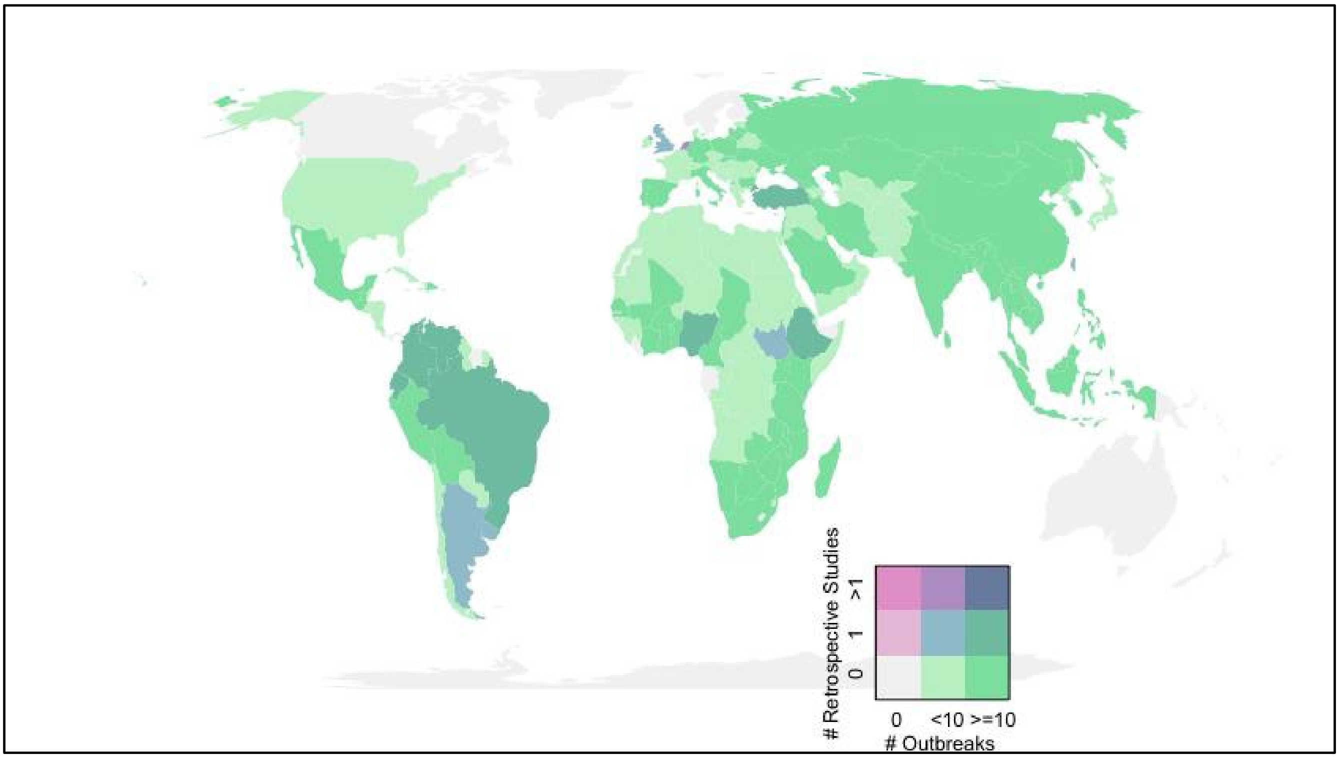

FIGURE 4 Number of outbreaks of ASF, CSF and/or FMD between 1975 and 2018 and number of retrospective economic studies. (1) Data for *x*-axis are publicly available from the World Organisation for Animal Health (OIE) website (OIE, 2020) presented in Table A2 in the Appendix. Range of years was based on year of publication for studies included in the literature review, and availability of OIE data. (2) The 177 countries on the *x*-axis are arbitrarily divided into three groups (terciles) based on the number of ASF, CSF and FMD outbreaks reported 1975–2018. Group 1X (group 1 on far left, *x*-axis) countries reported no outbreaks. Group 2X reported 1–9 respective disease outbreaks. Group 3X experienced 10 outbreaks or more. (3) The *y*-axis is grouped by number of peer-reviewed retrospective studies by country. Group 1Y (group 1 on bottom, *y*-axis) includes countries with zero retrospective studies, Group 2Y with 1 retrospective study, and Group 3Y included with more than one retrospective study. (4) Group 1X (no outbreaks): 31 countries (shaded in light grey) (18% of all reported countries)—incl. Australia, Canada, Norway, South Africa and Sweden. (5) Group 2X (1 to 9 outbreaks): 78 countries (44% of all reported countries)—72 countries did not maintain any retrospective economic analyses including: the United States, over 15 European countries, Chile and Japan (shaded in light green)—Five countries reported 1 (Argentina, South Sudan, Taiwan, the United Kingdom and Uruguay) (shaded in blue)—Only the Netherlands published more than one study (shaded in light purple). (6) Group 3X (10 outbreaks or more): 68 countries (38% of all reported countries). 61 including China, Italy, Russia and Spain (shaded in bright green) did not have ex-post economic analysis [90% of Group 3X]. Seven countries—Brazil, Columbia, Ecuador, Ethiopia, Nigeria, Turkey and Venezuela (shaded in dark green) conducted only one analysis. No country in Group 3X performed more than one economic analysis [Colour figure can be viewed at wileyonlinelibrary.com]

retrospective economic studies. The mean number of outbreaks across all countries was 7.8, and the median was 6. Overall, the results in Figure 4 suggest that despite the important number of outbreaks reported 1975–2018 (1,547 outbreaks of ASF, CSF and FMD, collectively), few (11) retrospective economic studies have been published. The results also suggest that there is no correlation between the frequency of disease outbreaks and number of ex-post, retrospective economic studies published. In particular, the top five countries with the most total reported outbreaks (ASF, CSF, FMD combined) were Russia (49), China (45), Italy (43), South Africa (32) and Zambia (29). Based on this literature review, there are no published economic (retrospective or forecast) studies for these leading five countries for total outbreaks.

Figure 5 represents the relationship between hooved livestock (cattle, goats, sheep and pigs) per capita in 2018 on the *x*-axis (in terciles), and the number of forecast economic studies published for FMD on the *y*-axis, for 175 countries for which data were available. The number of livestock per capita is a proxy for the weight carried by livestock (thus at risk for FMD) in a country's economy. In the first tercile (less than 0.23 livestock per capita), none of the 58 countries had any forecast studies. In the second tercile (more than 0.23 and up to 0.56 livestock per capita), only the United Kingdom (shaded in blue) conducted one simulation, and the United States (shaded in light purple) conducted nine studies. The remaining 56 countries in that tercile did not conduct any forecast study. Among the third tercile (59 countries, more than 0.56 animals per capita), where the number of livestock per capita is the highest, 54 countries (91.5% of tercile 3)—including Argentina, Canada and Spain—did not conduct any anticipatory economic analysis despite the high potential impact to their economy given the high livestock density per capita. These countries are shaded in bright green. Four countries, Australia, France, the Netherlands and New Zealand (shaded in dark

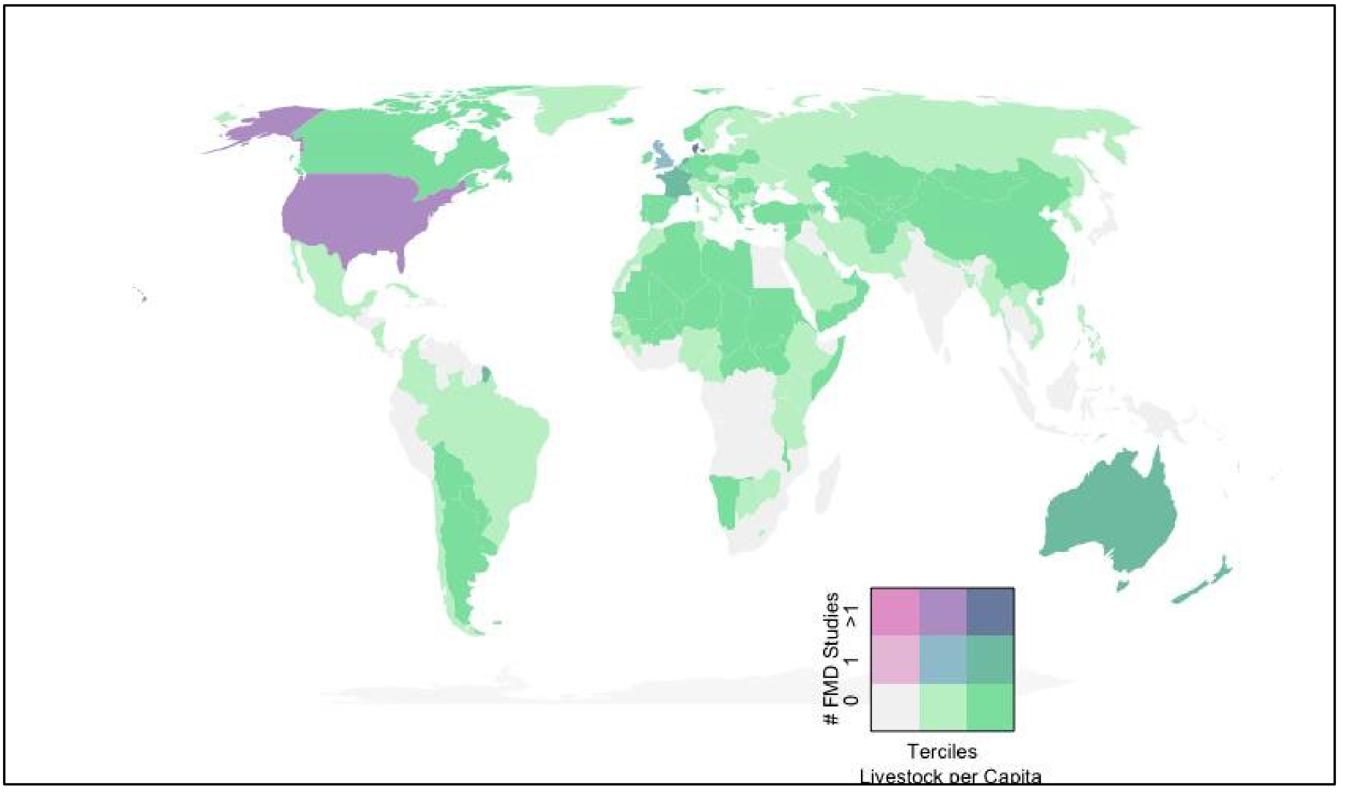

FIGURE 5 Number of head of livestock per capita (in terciles) and number of forecast economic studies for FMD. (1) For the *x*-axis, number of hooved livestock by country is based on publicly available data from the Food and Agriculture Organization of the United Nations (FAO). Livestock production data for 'Livestock Primary' animals (definitions and methodology can be found through the source link provided; FAO, 2019c). Human population by country data was retrieved from the United Nations Department of Economic and Social Affairs Population Dynamics data (United Nations, 2020). These numbers can be found in Table A2 in the Appendix. (2) On the *x*-axis, countries were divided into three groups (terciles) of 58 or 59 countries each based on the number of livestock per capita listed for each country in 2018. Group 1X (group 1, far left on *x*-axis) is livestock per capita less than 0.23. Group 2X represents between 0.23 and 0.56 livestock per capita, and the third represents more than 0.56 animals per capita. Group 3X represents countries with more than 0.56 animals per capita. (3) The *y*-axis is grouped by number of peer-reviewed forecast economic studies for FMD by country. Group 1Y (group 1, bottom of *y*-axis) includes countries with zero studies, Group 2Y had 1 retrospective study, and Group 3Y included more than one forecast study. (4) Group 1X, 1Y countries did not publish any forecast studies for FMD (shaded in grey). (5) Among the 58 2X countries, 56 (including Brazil, Chile, Italy and Russia) did not conducted any simulated economic study (shaded in light green). The United Kingdom (shaded in blue) conducted one simulation, and the United States (shaded in purple) conducted 9 studies. (6) Among the 59 3X countries, 54 countries (shaded in bright green)—including Argentina, Canada and Spain—did not conduct any prospective economic analysis despite the high potential impact to their economy given the high livestock density per capita. Four countries, Australia, France, the Netherlands and New Zealand (shaded in dark green), conducted one forecast study, and only Denmark conducted two [Colour figure can be viewed at wileyonlinelibrary.com]

green), conducted one forecast study, and only Denmark conducted two (8.5% of tercile 3). The results indicate no correlation between the potential impact on the economy of an FMD introduction and the number of forecasting analyses of the economic impact of the disease.

We carried out the same exercise for ASF and CSF, this time using terciles based on swine per capita in 2018 on the *x*-axis, and the number of forecast economic studies published for ASF (Figure 6) or CSF (Figure 7) in three terciles on the *y*-axis. The number of swine per capita is a proxy for the weight carried by swine production in a country's economy, which is at risk in the case of an ASF or CSF introduction. Overall, it was found that regarding ASF studies (Figure 6), no countries in tercile 1 (less than 0.01 swine per capita, 58 countries in light grey) conducted simulated studies, and among tercile 2 studies (between 0.01 and 0.14 swine per capita, also 58 countries), only Nigeria (blue) conducted a forecast study. The remaining 57 countries in tercile 2 (including Brazil, Chile, Italy and Russia) did not conduct any simulated economic studies and are shaded in light green. For tercile 3 (above 0.14 swine per capita), where the number of swine per capita is the highest (57 countries), 54 of those countries (94.7%, including Argentina, Australia, Canada, Russia and most of Europe) did not conduct any prospective economic analysis despite the potential impact to their economy. These countries are shaded in bright green. Three countries (5.3% of tercile 3; Denmark, Spain and the United States), shaded in dark green, conducted one forecast study each, and no country conducted more than one forecast study overall. Again, the results indicate no correlation

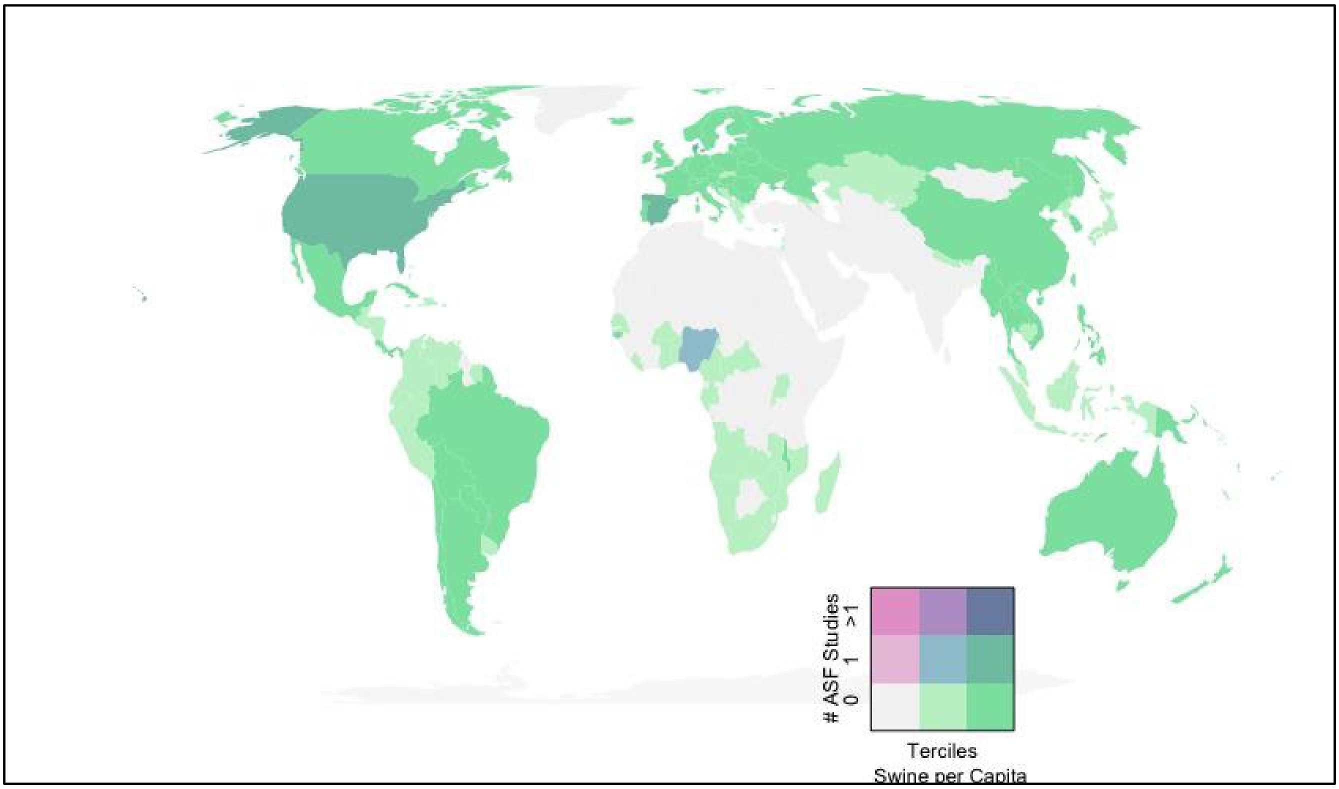

FIGURE 6 Head of livestock per capita (in terciles) and number of simulated economic studies for ASF. (1) For the *x*-axis, the number of swine per capita by country was based on the same publicly available data from the FAO, except only 'pigs' were selected from the 'Livestock Primary' animal data (FAO, 2019c). 171 countries had reported swine per capita data (1975–2018). The data used are presented in Table A5 in the Appendix. (2) On *x*-axis, countries were divided into 3 equally sized tercile groups based on the number of swine per capita where 1X (tercile 1, far left on *x*-axis) is less than 0.01 swine per capita, 2X is between 0.01 and 0.14 swine per capita and 3X is more than 0.14 swine per capita. (3) The *y*-axis is divided in to three groups by number of peer-reviewed forecast economic studies for ASF by country. Group 1Y (tercile 1, bottom of *y*-axis) the *y*-axis includes countries with zero studies, Group 2Y with 1 retrospective study, and Group 3Y included with more than one forecast study. (4) In (1X,1Y) (tercile 1 for x and y axes) in light grey, no forecast studies of the economic impact of an introduction of ASF were conducted. (5) In tercile 2X, only one country, Nigeria (shaded in blue), conducted a forecast study of the economic impact of the introduction of ASF. The remaining 57 countries (including Brazil, Chile, Italy and Russia) did not conduct any simulated economic studies and are shaded in light green. (6) Among tercile 3X (57 countries), 54 (including Argentina, Australia, Canada, Russia and most of Europe) did not conduct any prospective economic analysis and are shaded in bright green. Three countries (Denmark, Spain and the United States), shaded in dark green, conducted one forecast study each, and no country conducted more than one forecast study overall [Colour figure can be viewed at wileyonlinelibrary.com]

between the potential impact on the economy of an ASF introduction and the number of forecasting analyses of the economic impact of the disease.

Finally, regarding swine per capita and CSF forecast studies (Figure 7), among the first and second tercile groups of swine per capita for CSF studies, no forecast studies of the economic impact of an introduction of CSF were conducted. These countries are shaded in light grey and light green, respectively. Fifty-seven countries were classified under tercile 3, where the number of swine per capita is the highest. Of those countries, 52 (91.2% of tercile 3, including Argentina, China, Russia and the United States) conducted no prospective economic analysis despite the potential impact to their economy. These countries are shaded in bright green. Belgium, Denmark and Germany (shaded in dark green) conducted one simulation, and Australia and the Netherlands (dark blue) both conducted two studies. This means that out of the 57 countries with the highest level of swine per capita, 8.8% have conducted forecast studies.

3.2.2 | Other economic review results

Another finding from the economic review was the lack of consistency across studies in terms of the information describing data used in analyses. For example, definitions of economic terms were found to be decidedly variable (see column 'Economic estimation description' in Tables A2, A3 and A4 in the Appendix). To highlight the discrepancies regarding economic definitions, we compared WordCloud visuals (Jin, 2017) as a visual means to compare qualitative definitions of the quantitative studies. We used the definitions of 'total cost' or 'total loss' as provided by each paper (column nine 'Economic estimation description' in Tables A2, A3

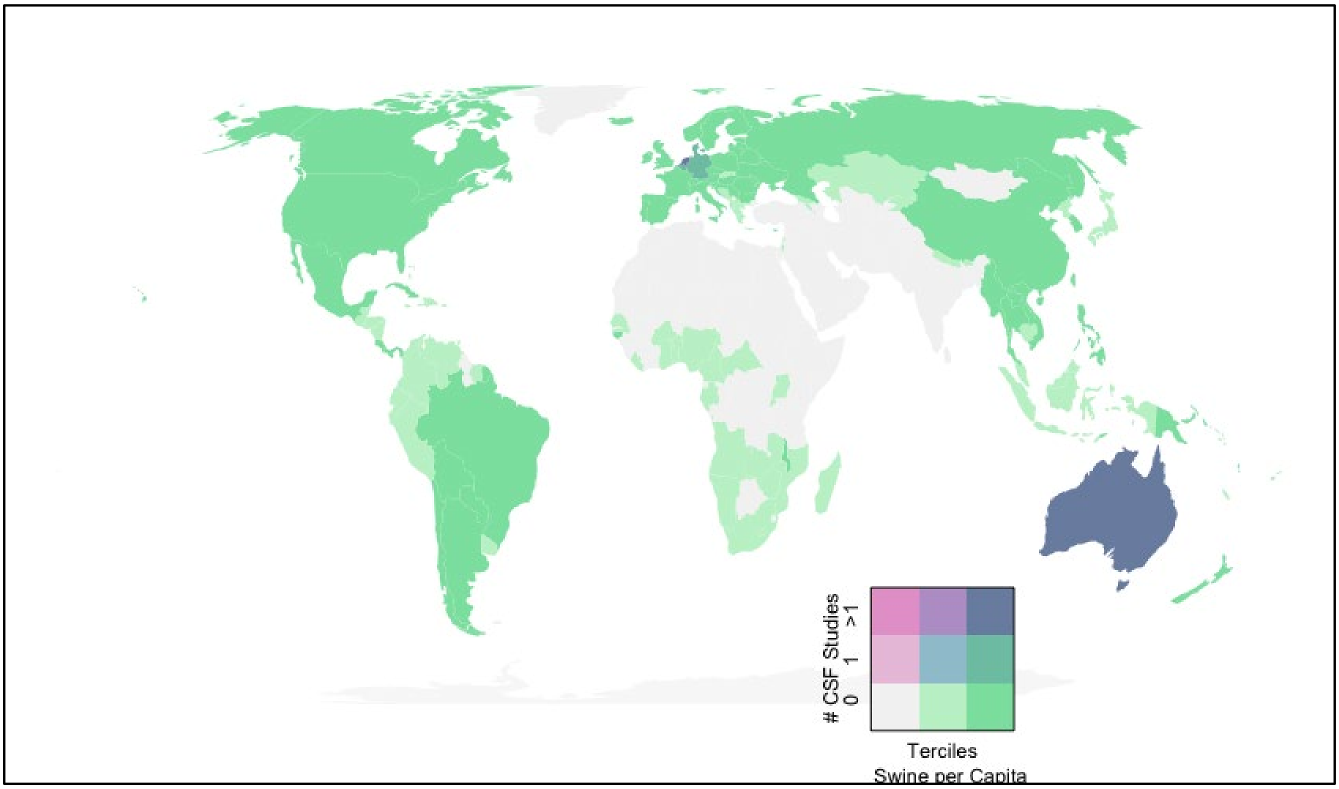

FIGURE 7 Number of head of livestock per capita (in terciles) and number of simulated economic studies for CSF. (1) The *x*-axis is the same as in Figure 6. (2) The *y*-axis is grouped by number of peer-reviewed forecast economic studies for CSF by country. Group 1Y (tercile 1, bottom of *y*-axis) includes countries with zero studies, Group 2Y with 1 retrospective study, and Group 3Y included with more than one forecast study. (3) For 1X and 2X, no forecast studies of the economic impact of an introduction of CSF were conducted. These countries are shaded in light grey and light green, respectively. (4) Among the 3X countries, 54 (including Argentina, China, Russia and the United States) did not conduct any prospective economic analysis. These countries are shaded in bright green. Three countries (Belgium, Denmark and Germany), shaded in dark green, conducted one simulation, and Australia and the Netherlands both conducted two studies and are shaded in dark blue [Colour figure can be viewed at wileyonlinelibrary.com]

and A4 in the Appendix). It was found that not every study included the terms 'costs', 'losses', or an aggregate definition of these two terms. The term 'cost' more often alluded to outbreak response costs (often referred to as 'direct' costs) like 'vaccination', 'cleaning' and 'disinfection'. Other notable descriptors included 'government' and 'compensation' or 'indemnity'. The term 'loss' more often related to agricultural production and included words like, 'milk', 'production', 'death' (related to animal deaths) and 'industry'. Other notable descriptors included 'government', 'economic' and 'financial'. Most obvious was that 'cost' includes losses and 'loss' includes costs, which is to be expected but convolutes the differentiation between cost and losses. Finally, words associated with outbreak response costs like 'disinfection' and 'vaccination' are found in the 'loss' definitions, and words associated with agricultural production such as 'export loss' and 'cattle industry' are found in the 'cost' definitions.

These comparisons qualitatively suggest that there are inconsistencies in the definitions of economic 'cost' and 'loss' across studies. While no statistical analysis was carried out, these figures illustrate the variability in parameters used to define cost and loss measures across studies. These results reiterate Perry & Grace (2009) that varying diseases, methodologies and results make it difficult to draw general conclusions across studies. Lastly, one smaller but decidedly important takeaway from the review of economic literature was that some studies did not explicitly provide the year of reference for the currency values presented. This information is a simple detail which should always be clear in publications for ease of future use such as inflation calculations.

4 | DISCUSSION

These two scoping literature reviews originally aimed at simultaneously elucidating the most likely route of introduction and the associated economic impact associated with ASF, CSF and FMD. We were optimistic that a thorough review of the literature would implicate a 'smoking gun' that could be used as a starting point for further risk analyses and as a policy and decision making tool to prevent and prepare for a foreign animal disease (FAD) introduction. While this was not the outcome, we were able to extrapolate some useful results and develop a guide to key future research endeavours.

In reviewing all risk evaluation literature, we cannot definitively identify the most likely route of introduction by specific region or disease. However, the majority of foreign risk evaluations that identified a specific pathway of introduction specified legal and illegal importations of live animals, animal products, animal feed, genetic material and bioterrorism; these results were reinforced by the U.S.-specific risk evaluations.

Further, our review of the economic literature highlights that there were not any systematic retrospective economic analyses of the historic outbreaks, and too few simulations in the countries that are currently the most at risk for economic harm. This void makes preparation, preparedness and future planning challenging.

Taken together, the synergies of these two reviews tell us more about how any one of these diseases may enter the United States, but still very little about which disease is most likely to cause the greatest economic harm. In the United States, only one prospective study has been carried out for ASF and none for CSF, rendering it impossible to compare the outcomes. While numerous prospective economic studies have been published for the three FADs (primarily for European countries), we are unable to infer any meaningful conclusions for the United States, due to regional specificity and a myriad of disparate methodologies. Anecdotally, among the risk evaluation studies that analysed pathways of introduction related to a specific disease, ASFV was the most studied pathogen, which could indicate that this pathogen is the most concerning with respect to an incursion event. However, by a substantial margin, FMD has the largest number of economic impact studies. It is important to note that this relationship may be a relic of the temporality of disease outbreaks (e.g. the global spread of ASFV since 2018).

Our intention in undertaking this project is that we would use U.S. literature to guide our understanding of introduction risk and economic impact; however, the paucity of research on these topics compelled us to utilize all existing data globally. Conducting these reviews in tandem demonstrated substantial gaps in knowledge; however, it led to some additional broad generalizations regarding the potential impact of these diseases to the United States. First, there was not uniform consensus among the risk analyses for the potential disease introduction point or points within the United States. Second, while it is clear all of these diseases can cause significant economic harm, the variation in economic scope, definitions and data sources makes it difficult to aggregate economic study results for continent-wide or even global research. Third, our review pointed to a lack of correlation between the number of disease outbreaks and corresponding retrospective economic analyses, highlighting either a lack of data collection on previous outbreaks or a lack of motivation to publish such data. Fourth, despite the potentially large impact of an introduction of ASF, CSF or FMD on large sectors of the economy, few prospective (forecasting) economic studies have been peer-reviewed and published, leaving researchers and practitioners (including governments and institutions) without data or results to assess the cost effectiveness of different mitigation strategies in the case of an outbreak. Fifth, in addition to some oversight in including important details like relevant currency and reference years for economic values, there was a stark difference between what economic estimates like 'cost' and 'loss' were comprised of. Lastly, these reviews have not considered the potential role of feral swine in perpetuating and amplifying the spread of these diseases in the United States. Feral swine may be a significant variable relative to foreign animal diseases and could play a critical role in the potential economic impact associated with an outbreak event. Without at least a qualitative examination of the potential role of these invasive mammals, these reviews lack a crucial element in understanding the risk and certainly the economic impact. These six points leave governments and institutions without tools to assess the cost effectiveness of different mitigation strategies in the case of an outbreak resulting in potentially devastating consequences to the U.S.

4.1 | Disease risks in the United States

The introduction of any of these diseases has the capacity to quickly impact the United States livestock industry, and the potential economic costs for a multispecies pathogen (i.e. FMDV) would be expected to be even larger. According to the 2017 U.S. Census of Agriculture, the 2017 value of livestock production in the United States alone was $77.2 billion USD, $26.3 billion USD and $36.7 billion USD for cattle and calves, hogs and pigs, and milk, respectively (USDA, 2019a). In recent years, the United States has been either the world's largest or second largest exporter of pork and pork products and is the third-largest producer and consumer of pork and pork products globally (USDA, 2019b) with just under 200 million head sold (USDA, 2019a). In 2018, the United States was the fourth largest exporter of beef (USDA, 2019b, 2019c).

In addition to the economic impacts associated with an outbreak of ASF, CSF or FMD, the United States is home to at least six million invasive feral swine that roam in the majority of U.S. states (Lewis *et al.*, 2019; USDA, 2020). Feral swine pose a threat to domestic livestock due to their high densities, rapid reproductive rate, and omnivorous and opportunistic diet (Brown *et al.*, 2018) Additionally, anthropogenic activities (e.g. baiting, translocation and hunting pressures) and interaction with domestic livestock make feral swine an optimal vector for foreign and domestic animal disease spread. In some instances, feral swine live in urban and peri-urban environments and have been documented to feed in landfills. While there was not uniform consensus in the literature related to route of pathogen incursion, legal and illegal imports of animals and animal products were considered in some assessments to be the highest risk pathway of introduction, most commonly via air passengers or air passenger baggage (Brown & Bevins, 2018a, 2018b, 2019). Introduction via other fomites such as shoes, clothing and supplies was one of the least common risks. Feral swine foraging at a landfill containing contaminated products could serve as an additional potential route for viral introduction and spillover.

The paucity of information available on the highest risk and highest consequence routes for ASFV, CSFV and FMDV is problematic relative to developing targeted preventative methods, performing economic analyses for control methods and minimizing damage to related industries. Indeed, Buhnerkempe et al. (2014) showed that epidemic behaviour is strongly dependent on the introduction site of the pathogen. Insight for control and surveillance could be gained through an understanding of the most likely routes of introduction and the heterogeneity in disease spread processes that create the variation in outbreak sizes and corollary economic impacts, which is crucial for targeted preventative measures and resource allocation.

5 | DATA AVAILABILITY STATEMENTS

These reviews were based on the methodological guidance outlined by Peters et al. (2015) [29] and utilized the PRISMA methods (Preferred Reporting Items of Systematic Reviews and Meta-Analyses) [30, 31] for systematic scoping reviews. Specific text evaluated, search terms, and exclusion criteria, based on each PRISMA step are outlined for the risk assessment and economic literature reviews (respectively) in Table 1.

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ETHICAL APPROVAL

The authors confirm to adhere to the ethical policies of the journal. No ethical approval was required as this is a review article with no original research data.

CONFLICT OF INTEREST

The authors do not have any conflicts of interest.

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APPENDIX

TABLE A1 Description of included studies of risk evaluations

Authors & date	Pathogen	Type of study	Assessed pathways of introduction	Highest risk pathway of introduction
U.S. Assessments				
Blackwell et al. (1985)	ASFV	Qualitative	Feeding garbage to livestock, international trade of food products of animal origin	Not identified
USDA (1995)	ASFV	Quantitative	Feeding household waste contaminated by contraband or legal imports to domestic swine	Contraband contaminated household waste being fed to domestic swine
Corso (1997)	ASFV	Quantitative	Uncooked swill, (Due to legal/illegal importation of food items of animal origin by way of traveller or by mail, subsequently discarded in household waste)	Uncooked contaminated swill feeding
USDA (2014a)	ASFV	Qualitative	Dietary supplements/traditional medicines, veterinary vaccines and miscellaneous biological products, unprocessed animal feed ingredients derived from plants or plant products, commercial swine meat and meat (by) products for human consumption, non-rendered pet food treats and chews, bushmeat, non-regulated garbage, livestock and germplasm, humans, other live animals, airborne, inanimate articles that may serve as fomites, vehicular fomites, equipment, garbage (every possible pathway)	Diagnostic samples collected from swine or ruminants
Chen and Jiang (2017)	ASFV	Qualitative	Animal waste in manure	Not identified
Herrera-Ibatá et al. (2017)	ASFV	Quantitative	Legal importation of swine and swine products	Legal importations of live pigs
Brown and Bevins (2018b)	ASFV	Qualitative	Illegal/legal movement/importation of live animals or their products, by-products, or animal feed or bioterrorism	Illegal/legal movement of live animals or their products, by-products, or animal feed or bioterrorism
Dee et al. (2018)	ASFV	Quantitative	Importation of feed ingredients	Not identified
Golnar et al. (2019)	ASFV	Semi-quantitative	Soft ticks, domestic pigs, bushpigs, warthogs	*Ornithodoros coriaceus* (highest risk soft tick in those evaluated)
Jurado et al. (2019)	ASFV	Quantitative	Swine products carried by air passengers	Not identified
Wormington et al. (2019)	ASFV	Qualitative	Sylvatic establishment and spillover to domestic swine	Not identified
Blackwell et al. (1985)	CSFV	Qualitative	Feeding garbage to livestock, international trade of food products of animal origin	Not identified
Corso (1997)	CSFV	Quantitative	Uncooked swill (due to legal/illegal importation of food items of animal origin by way of traveller or by mail, which is then discarded in household waste)	Uncooked contaminated swill feeding
USDA (1998a)	CSFV	Qualitative	Imported infected pork and/or pork products either discarded as household waste and deposited in landfill or fed to backyard pig herd	Illegal importation of pork/pork products via airline passengers
USDA (1998b)	CSFV	Both	Legal importation of fresh, chilled and frozen pork; import of breeding animals (boars and gilts); and imports of fresh and frozen semen	Not explicitly stated; however data implies import of breeding boars (very high cost scenario), import of fresh, chilled and frozen pork (low cost scenario), import of fresh and frozen semen (low, moderate high and very high cost scenarios)

Assessed geographic source	Highest risk geographic source	Assessed geographic destination	Highest risk geographic destination	Highest risk consequence	Model
Not identified	Not identified	United States	Not identified	Not identified	N/A
Foreign countries	Not identified	United States	Puerto Rico	Not identified	Scenario event trees with nesting binomial probability formulas
Not identified	Not identified	United States	Not identified	Not identified	Nested binomial model and Monte Carlo modelling
Not identified	Not identified	United States	Not identified	Not identified	N/A
Not identified	Not identified	United States	Not identified	Not identified	N/A
Worldwide	Canada (for live swine pathway)	United States	Iowa, Minnesota and Wisconsin (for live swine pathway)	Not identified	Stochastic
North America, Africa, Asia, South America, Australia, Europe	Africa, Asia, Europe	United States	Not identified	Spread and persistence of disease	N/A
China (Trans-Pacific), and the Caucasus, Eastern Europe, the Baltic states (Trans-Atlantic)	Not identified	United States	Not identified	Not identified	N/A
Ornithodoros coriaceus (highest risk soft tick in those evaluated)	Not identified	United States	Not identified	Not identified	N/A
Foreign countries	Ghana, Cape Verde, Ethiopia, Russian Federation	United States	Main airports in Virginia, New York, Texas, Rhode Island, Puerto Rico	Not identified	Quantitative stochastic models for each disease
Not identified	Not identified	United States	Counties of California, Florida and 'much of the South-western United States'	Not identified	Spatial
Not identified	Not identified	United States	Not identified	Not identified	N/A
Not identified	Not identified	United States	Not identified	Not Identified	Nested binomial model and Monte Carlo modelling
Dominican Republic	Not identified	United States	Not identified	Not identified	N/A
European Union	Not identified	United States	Texas or Florida	Import of infected breeding boars (very high cost scenario)	Net Trade Model (Partial Equilibrium Welfare Model also mentioned as being used to model impacts of disease on US)

(Continues)

TABLE A1 (Continued)

Authors & date	Pathogen	Type of study	Assessed pathways of introduction	Highest risk pathway of introduction
USDA (1998c)	CSFV	Both	Legal importation of fresh, chilled and frozen pork; import of breeding animals (boars and gilts); and imports of fresh and frozen semen	Not identified
USDA (1998d)	CSFV	Both	Importation of pork	Not identified
USDA (1999)	CSFV	Both	Unmitigated importation of swine semen; fresh, chilled and frozen pork (and subsequent feeding of food waste to pigs); and breeding swine	Not explicitly identified, although swine semen model appeared to have the highest expected frequency under unmitigated conditions (within the 'most likely' output category)
USDA (1998e)	CSFV	Both	Unmitigated importation of swine semen; fresh, chilled and frozen pork (and subsequent feeding of food waste to pigs); and breeding swine	Not explicitly identified, although swine semen model appeared to have the highest expected frequency under unmitigated conditions (within the 'most likely' output category)
Dietrich and Adams (2000)	CSFV	Quantitative	Legal and illegal importation of food products via garbage or waste feeding operations; contact of domestic swine with feral hogs exposed through contaminated food dropped in areas frequented by feral hogs	Not identified
USDA (2000)	CSFV	Both	Movement of domestic animals, transmission from wild boars, distribution of contaminated swine semen, distribution of fresh/frozen pork, and movement of contaminated people, vehicles or equipment	Contaminated swine semen
USDA (2002)	CSFV	Qualitative	Not identified	Not identified
NABC (2004)	CSFV	Qualitative	Live swine, hog products industry related products (e.g. feed and farm equipment) and humans. Also discusses wild boar and domestic swine direct/indirect contact; feeding of unsanitized garbage to swine; javelina and pet pigs as pathways/maintenance factors	Importation of infected swine products (legal and illegal)
USDA (2014a)	CSFV	Qualitative	Dietary supplements/traditional medicines, veterinary vaccines and miscellaneous biological products, unprocessed animal feed ingredients derived from plants or plant products, commercial swine meat and meat (by) products for human consumption, non-render	Diagnostic samples collected from swine or ruminants
Chen and Jiang (2017)	CSFV	Qualitative	Animal waste in manure	Not identified
Herrera-Ibatá et al. (2017)	CSFV	Quantitative	Legal importation of swine and swine products	Legal importation of live pigs
Dee et al. (2018)	CSFV	Quantitative	Importation of feed ingredients	Not identified

Assessed geographic source	Highest risk geographic source	Assessed geographic destination	Highest risk geographic destination	Highest risk consequence	Model
Netherlands, Italy, Spain, Belgium-Luxembourg, Portugal, Germany, Denmark, Austria, France	Not identified	United States	Not identified	Not identified	Net Trade Model
European Union (with specific attention to Germany, the Netherlands, Italy and Spain)	Not identified	United States	Not identified	Not identified	N/A
European Union	Not identified	United States	Not identified	Not identified	Stochastic (nested probability approach)
European Union	Not identified	United States	Not identified	Not explicitly identified, although unmitigated swine semen model generated the lowest NPV value (indicating the costs associated with this pathway are higher than any benefits of trade)	Stochastic (nested probability approach) for Biological Risk Analysis; economic values determined through estimation, not modelling
Not identified	Not identified	Southern United States (Alabama, Arkansas, Florida, Georgia, Louisiana, Mississippi, North Carolina, South Carolina, Tennessee, Texas)	Not identified	Scenario 2; introduction of CSFV into 3 geographically separated regions	Agricultural Sector Model (linear programming model)
European Union	Not identified	United States	Not identified	Not identified	Multi-level binomial
Not identified	Dominican Republic	United States	Puerto Rico	Not identified	N/A
Worldwide	United Kingdom (for live swine); United Kingdom, Germany, Italy (for pig meat); Dominican Republic and the Caribbean (for illegal pigs/pig products)	United States	Puerto Rico, South-eastern United States (for illegal movement of pigs and pig products)	Texas	Trading grid (to describe movement of live swine and swine products and relate to the occurrence of CSFV worldwide); also survey of experts and swine producers
Not identified	Not identified	United States	Not identified	Not identified	N/A
Not identified	Not identified	United States	Not identified	Not identified	N/A
Worldwide	Canada (for live swine pathway)	United States	Iowa, Minnesota and Wisconsin (for live swine pathway)	Not identified	Stochastic
China (Trans-Pacific), and the Caucasus, Eastern Europe, the Baltic states (Trans-Atlantic)	Not identified	United States	Not identified	Not identified	N/A

(Continues)

TABLE A1 (Continued)

Authors & date	Pathogen	Type of study	Assessed pathways of introduction	Highest risk pathway of introduction
Jurado et al. (2019)	CSFV	Quantitative	Swine products carried by air passengers	Not identified
Blackwell et al. (1985)	FMDV	Qualitative	Feeding garbage to livestock, international trade of food products of animal origin	Not identified
USDA (1994)	FMDV	Qualitative	Import of infected live animals, contaminated animal products and fomites	Not identified
USDA (1995)	FMDV	Quantitative	Feeding household waste contaminated by contraband or legal imports to domestic swine	Contraband contaminated household waste being fed to domestic swine
Corso (1997)	FMDV	Quantitative	Uncooked swill (due to legal/illegal importation of food items of animal origin by way of traveller or by mail, which is then discarded in household waste)	Uncooked contaminated swill feeding
CEAH (2001)	FMDV	Qualitative	Contraband, illegal trans-shipments, garbage, animal products, human movements from foreign countries, live animals, animal germplasm, military movements	Contraband (meat products carried by passengers/in cargo containers/sent by mail/FedEx, black market)
Federal Inter-agency Working Group (2003)	FMDV	Qualitative	Importation of infected animals or contaminated animal products	Contraband from international passengers, cargo, mail and vehicles
Breeze (2004)	FMDV	Qualitative	Agroterrorism	Not identified
USDA (2007)	FMDV	Qualitative	Meat, meat products or garbage feeding pathways; livestock importations	Not identified; results of this analysis reported the hazard ranking (low, moderate or high) of potential sources including animals, animal products and fomites. Of 99 animals identified as possible FMDV sources, 31 categorized as high hazards (Antelope, African buffalo, domestic cattle, mountain gazelle, impala, goat, sheep, alpaca, Bactrian camel, llama, fallow deer, mule deer, muntjac deer, red deer, roe deer, sika deer, white-tailed deer, domestic pig, fox human, capybara, coypu, rat, grey kangaroo, red kangaroo, tree kangaroo, hedgehog, starling, house fly, biting fly, tick). Of 97 animal products/other fomites identified, 53 categorized as high hazards (hides/skins, bovine manure, bovine pituitary extract, bovine semen, sheep wool, bacon, whole beef, bovine blood, bovine bone marrow, porcine bone marrow, cultured butter, buttermilk, bovine dried casein, ham, sheep intestinal casings, swine intestinal casings, bovine lymph node, porcine lymph node, bovine milk, pork muscle, bovine rumen, dry sausage, bovine tongue. *See tables for details on product processing). Of 15 non-food products identified, 12 were categorized as high hazard (straw/wood shaving bedding, clothing, feed and fodder, garbage, packing/wrapping materials, shoes/boots, autumn/winter soil, vegetables, water)
USDA (2012)	FMDV	Qualitative	Legal and illegal import of contaminated products, fomites, infected animals or animal products	Legal and illegal imports
USDA (2013)	FMDV	Qualitative	Importation of beef products	Feeding contaminated food waste to swine
Slingluff et al. (2014)	FMDV	Both	Movement of infected carcasses (swine and cattle) during an outbreak	Not identified
USDA (2014a)	FMDV	Qualitative	Import of infected live animals, infected embryos and semen, and contaminated sheep meat	Not identified

Assessed geographic source	Highest risk geographic source	Assessed geographic destination	Highest risk geographic destination	Highest risk consequence	Model
Foreign countries	Dominican Republic, followed by Cuba	United States	Main airports in Puerto Rico, Florida, North Carolina, New Jersey, Ohio	Not identified	Quantitative stochastic models for each disease
Not identified	Not identified	United States	Not identified	Not identified	N/A
Countries with past outbreaks	Not identified	North America	Not identified	Not identified	N/A
Foreign countries	Not identified	United States	Puerto Rico	Not identified	Scenario event trees with nesting binomial probability formulas
Not identified	Not identified	United States	Not identified	Not identified	Nested binomial model and Monte Carlo modelling
Worldwide	Not identified	United States	United States swine waste feeding operations (Puerto Rico and the Virgin Islands have the most)	Not identified	N/A
Not identified	Not identified	United States	Areas most densely populated with livestock in the United States (see map 2 page 10)	Not identified	N/A
Worldwide	Not identified	United States	Midwest (for swine); Midwest and Southwest states (for feedlot cattle)	Not identified	N/A
Countries with past outbreaks	Not identified	North America	Not identified	Not identified	N/A
Infected countries, Canada and Mexico	Not identified	United States	Texas	Not identified	N/A
Brazil	Not identified	United States	Not identified	Not identified	N/A
United States	Not identified	United States	Not identified	Not identified	Within herd stochastic disease spread model
Argentina	Not identified	United States	Not identified	Not identified	N/A

(Continues)

TABLE A1 (Continued)

Authors & date	Pathogen	Type of study	Assessed pathways of introduction	Highest risk pathway of introduction
USDA (2014b)	FMDV	Qualitative	Dietary supplements/traditional medicines, veterinary vaccines and miscellaneous biological products, unprocessed animal feed ingredients derived from plants or plant products, commercial swine meat and meat (by) products for human consumption, non-render	Diagnostic samples collected from swine or ruminants
USDA (2018)	FMDV	Both	Feeding livestock contaminated ready-to-eat pork products	Not identified
Chen and Jiang (2017)	FMDV	Qualitative	Animal waste in manure	Not identified
Dee et al. (2018)	FMDV	Quantitative	Importation of feed ingredients	Not identified
Bair-Brake et al. (2014)	Not identified	Both	Bushmeat importation	Not identified
Foreign assessments				
MacDiarmid (1991)	ASFV	Qualitative	Importation of meat and meat products	Not identified
CFIA (1999)	ASFV	Both	Salted intestinal casings fed to domestic pigs (legally or illegally imported)	Salted intestinal casings fed to wild pigs
Adkin et al. (2004)	ASFV	Quantitative	Illegally imported meat and meat products and imported catering waste (e.g. ship and aircraft waste)	Imports of de-boned meat via air-passenger baggage most likely to cause subsequent livestock infection after being introduced
Gale (2004)	ASFV	Quantitative	Composted catering waste containing uncooked meat discarded on farm land or fed to animals	Composted uncooked animal waste being fed to farm animals or distributed near them
Wooldridge et al. (2006)	ASFV	Quantitative	De-boned meat, and meat that follows human carriage (litter, 'fly-tipping', direct feeding)	Illegal importation of meat by way of passenger baggage
Sánchez-Vizcaíno et al. (2009)	ASFV	Qualitative	Tick bites and movement of infected pigs	Free-ranging pigs
DEFRA (2008)	ASFV	Qualitative	Import of animal products	Not identified
Beltrán-Alcrudo et al. (2008)	ASFV	Qualitative	Wild boar, vectors (e.g. ticks), pork and pork products imported and swill feed to domestic swine or accessed by wild boar	Not identified
Costard et al. (2009)	ASFV	Quantitative	Animal-contact, person- and vehicle-contact, feeding	Not identified
Hartley (2010)	ASFV	Qualitative	Legal/illegal importation of pig products, direct and indirect contact between feral swine and livestock (airborne, faeco-oral, food borne, vector borne), import or translocation of feral swine	Oral consumption of illegally imported pig products by domestic pigs

Assessed geographic source	Highest risk geographic source	Assessed geographic destination	Highest risk geographic destination	Highest risk consequence	Model
Not identified	Not identified	United States	Not identified	Not identified	N/A
United States	Not identified	United States	Not identified	Not identified	Within herd stochastic disease spread model
Not identified	Not identified	United States	Not identified	Not identified	N/A
China (Trans-Pacific), and the Caucasus, Eastern Europe, the Baltic states (Trans-Atlantic)	Not identified	United States	Not identified	Not identified	N/A
Not identified	West Africa	United States	Not identified	Not Identified	N/A
Not identified	Not identified	New Zealand	Not identified	Not identified	N/A
Not identified	Not identified	Canada	Not identified	Not identified	N/A
Non-EU countries	Eastern Africa	Great Britain	Not identified	Not identified	Stochastic
United Kingdom	Not identified	United Kingdom	Not identified	Multiple farm animals eating bits of the same contaminated waste, rather than one single pig eating all of the contaminated portion of waste	Source-pathway-receptor approach
Worldwide	Eastern Africa	Great Britain	Not identified	Not identified	Common structure model
Europe and Africa	Not identified	Europe and Africa	Not identified	Not identified	This document is more of a scientific and pathobiology review rather than a risk assessment. It states that the exponential intensification of animal movements and product exchanges enhances the risk of ASFV introduction in a free country
Non-EU countries	Not identified	Great Britain	Not identified	Not identified	N/A
Caucasus region	Not identified	Turkey, Iran, Russian Federation, Ukraine	Russian Federation and Ukraine	Not identified	N/A
Not identified	Not identified	Madagascar	Not identified	Not identified	Multiple factor analysis and hierarchical cluster analysis
Not identified	Not identified	England	Not identified	Introduction into wild boar population/spread and duration of the disease	N/A

(Continues)

TABLE A1 (Continued)

Authors & date	Pathogen	Type of study	Assessed pathways of introduction	Highest risk pathway of introduction
Wieland et al. (2011)	ASFV	Qualitative	Domestic pigs: direct contact between pigs, indirect contact between pork products and pigs, contaminated feed, fomites, mechanical vectors (pets and pests), ticks, contamination of environment which spills over in wild boar and tick population. Wild Boar: direct contact, indirect contact through hunting or contaminated environment	Not identified
Mur, Martínez-López, Martínez-Avilés, et al. (2012)	ASFV	Quantitative	Importation of an ASF-infected (but non-detected) pig during the high risk period, subsequent contact with susceptible pig	Importation of infected live pigs
Mur et al. (2012)	ASFV	Semi-quantitative	Returning livestock trucks from affected areas, waste from international ships and waste from international planes	Returning livestock vehicles (trucks)
Nigsch et al. (2013)	ASFV	Both	Pig to pig contact; pig transport lorries; professional contacts	Not identified
Costard et al. (2013)	ASFV	Semi-quantitative	Illegal importation of pork and pork products via personal consumption purposes and commercial/re-sale purposes	Illegal importation by EU residents originally from ASFV affected areas
Cardoso de Carvalho Ferreira (2013)	ASFV	Qualitative	Transmission between individuals within the same group, between different groups/individuals on different farms, and via tick vectors	Not identified
Mur et al. (2014)	ASFV	Both	Legal importations of pigs, legal/illegal imports of products, transportation fomites (including contaminated trucks or waste from international planes and ships) and wild boar movements	Highest risk route depended on pathway and EU member-state. Bulgaria highest risk for legally imported products during the high risk period; Finland highest risk for wild boar movement route; Slovenia and Sweden for legally imported pigs during the high risk period
EFSA Panel on Animal Health and Welfare (2014)	ASFV	Qualitative	Movement of contaminated pork, movement of infected pigs, movement of contaminated vehicles	Chilled meat; transported wild boar; transported domestic swine; skin fat; vehicles for animal transport-contaminated inside
Roelandt et al. (2017)	ASFV	Semi-quantitative	Not identified	Not identified
Martínez-López et al. (2015)	ASFV	Quantitative	Not identified	Not identified
Torre et al. (2015)	ASFV	Semi-quantitative	Infected wild boars; contact with uninfected swine (wild and domestic)	Not identified
Bellini et al. (2016)	ASFV	Qualitative	Direct pig-to-pig contact, contaminated feed (swill feeding), workers visitors, contaminated fomites, slurry, genetic materials and tick bites	Not identified
Dejyong (2016)	ASFV	Qualitative	Legal and illegal import of live pigs, pig products, pig semen and embryos, wild boars, wild boar meat, biological products, potbellied pigs and personal items	Shipment of pig products (frozen meat considered very high risk)
CFSPH (2016)	ASFV	Quantitative	Feeding of food waste from international airplanes or ships from countries where disease is found, feral swine movements, movement of trucks between infected and disease-free areas, illegal movement of infected pigs or pork products	Not identified
Halasa, Boklund, et al. (2016)), Halasa, Bøtner, et al. (2016))	ASFV	Quantitative	Dead animal (pig) residues: (blood, liquids and faeces), and contact between pigs	Not identified

Assessed geographic source	Highest risk geographic source	Assessed geographic destination	Highest risk geographic destination	Highest risk consequence	Model
Not identified	Not identified	European Union	Germany, Northern France, Central Italy (places with high feral swine populations)	Not identified	Generic model
Albania, Canada, Switzerland, Norway, Russian Federation, United States, Australia, Belarus	Russian Federation	European Union	Poland	Not identified	Stochastic. Parameters individually defined using various distributions (beta, pert, normal and binomial)
Russian Federation, Africa	Not identified	European Union	Poland, Lithuania	Not identified	Linear-weighted
European Union	Denmark, Netherlands, Lithuania, Latvia	European Union	Germany and Poland	Not identified	Stochastic spatio-temporal state-transition model
Not identified	Not identified	European Union	France, Germany, Italy, United Kingdom (high risk for release)	Spread of the disease: France, Italy, Poland, Romania and Spain at highest risk for exposure after virus release	Linear-weighted combination
Not identified	Not identified	Not identified	Not identified	Not identified	Descriptive
Not identified	Not identified	European Union	Bulgaria- for legally imported products, Finland- for wild boar, Slovenia & Sweden- legally imported pigs	Not identified	Modular risk assessment framework
Countries neighbouring the European Union	Georgia, Armenia and the Russian Federation	European Union	Not identified	Not identified	Expert elicitation/matrix model
Not identified	Not identified	Belgium	Not identified	Introduction and spread in domestic animals	Pandora risk assessment tool
Not identified	Not identified	Sardinia	Not identified	Not identified	Bayesian
Russia, Belarus, Ukraine, Moldova and Turkey	Ukraine, Russia, Turkey	European Union	Finland, Romania, Latvia, Poland	Not identified	Stochastic
Not identified	Not identified	Europe	Not identified	Not identified	N/A
Italy	Italy	Thailand	Thailand	Not identified	N/A
Not identified	Not identified	Not identified	Not identified	Not identified	N/A
Not identified	Not identified	Not identified	Not identified	Sustained infectiousness and disease spread	Dynamic Monte Carlo simulation model

(Continues)

TABLE A1 (Continued)

Authors & date	Pathogen	Type of study	Assessed pathways of introduction	Highest risk pathway of introduction
Guinat et al. (2016)	ASFV	Qualitative	Direct contact between infected and uninfected domestic pigs, feeding domestic pigs contaminated feed, direct contact between wild boar and domestic pigs, contaminated fomites, ticks	Not identified
Dione et al. (2016)	ASFV	Qualitative	Collection/bulking (live pig traders and brokers); Transportation (live pig traders and transporters of pig meat/materials); Slaughter (Backyard slaughters, authorized slaughter slabs and the Wambizzi abattoir)	Live pig traders and transport of pig meat/materials
Huang et al. (2017)	ASFV	Quantitative	Transmission by direct contact between humans, domestic pigs, wild suids and ticks	West Africa- direct contact between domestic pigs or pork products and pigs; East Africa- not identified
Hwang et al. (2018)	ASFV	Semi-quantitative	Migration or natural movement of wildlife, International human movement, Illegal importation of wildlife and wildlife parts, Accidental introduction of disease vector, Smuggling of livestock products, legal importation of wildlife and wildlife parts, Legal importation of livestock and products, Importation of biological materials and pathogens, Importation of vegetables and plant material, Bioterrorism or the deliberate release of pathogens	Migration or natural movement of wildlife, illegal importation of wildlife and wildlife parts, accidental introduction of a disease vector, smuggling of livestock products
Kyyrö et al. (2017)	ASFV	Semi-quantitative	Sperm and embryos; contaminated feed and bedding materials; contaminated animal transport vehicles operating internationally; infected wild animals crossing the border; movements of other contaminated goods and transport; infected live animals; air stream and/or vectors; infected meat and meat products; and people travelling from diseased areas	Products of animal origin (e.g. meat and meat products)
Bosch et al. (2017)	ASFV	Semi-quantitative	Wild boar	Not identified
Bosch, Rodríguez, et al. (2017)	ASFV	Semi-quantitative	Infected wild boars coming into contact with uninfected wild or domestic swine	Natural movements of wild boar; domestic pig to wild boar introduction; freshly harvested grass from infected areas to low biosecurity farms
Anonymous (2017)	ASFV	Qualitative	Movement of infected live animals, infected products or contaminated equipment, vehicles, clothing and footwear, subsequent contact with domestic or feral swine (including wild boar)	Contaminated clothing, footwear, equipment and vehicles; illegal movement of contaminated meat
DEFRA (2018)	ASFV	Qualitative	Legal/illegal trade of live animals, products of animal origin, clothing/footwear, boats, vehicles, crops seeds and feeds, resulting in subsequent exposure to domestic or feral pigs	Illegal trade of products of animal origin, vehicles
Sugiura and Haga (2018)	ASFV	Qualitative	Legal/illegal importation/transportation of domestic pigs, wild boar, feed, pork products, foreign workers	Illegal importation of food (pork products)

Assessed geographic source	Highest risk geographic source	Assessed geographic destination	Highest risk geographic destination	Highest risk consequence	Model
Not identified	Not identified	Europe	Not identified	Not identified	Literature review
Uganda	Not identified	Uganda	Not identified	Not identified	Ranked interview/group discussion responses
Not identified	East and West Africa	East and West Africa	East and West Africa	Not identified	Generalized linear mixed models with a binary response (logic link)
Not identified	Not identified	Republic of Korea	Not identified	Not identified	N/A
Not identified	Not identified	Finland	Not identified	Not identified	NORA (developed for Finland)
Not identified	Not identified	Eurasia	Not identified	Not identified	Cartographic
Belarus, Estonia, Latvia, Lithuania, Moldova, Poland, Russia, Turkey, Ukraine	Russian Federation and Ukraine, Lithuania, Poland, Latvia, Estonia	Disease-free European Union countries (Bulgaria, Czech Republic, Finland, Germany, Greece Hungary, Romania and Slovakia)	Slovakia, Romania, Finland, Czech Republic, Germany	Not identified	Stochastic
Not identified	Not identified	European Union	Not identified	Not identified	N/A
Not identified	Not identified	Europe	Not identified	Economic impact, as well as effect on community cohesion and animal welfare; loss of public confidence in pig industry	OIE framework of release (or entry), exposure and consequence assessment
Africa (Burundi, Cape Verde, Kenya, Mali, South Africa, Uganda Zimbabwe), Caucasus (Moldova), East Europe (Estonia, Latvia, Lithuania, Poland Ukraine), Russian Federation, West Europe (Italy-Sardinia), East Asia (China)	China	Japan	Kanto and Kyushu	Spread and persistence of disease	Survey of experts' opinions

(Continues)

TABLE A1 (Continued)

Authors & date	Pathogen	Type of study	Assessed pathways of introduction	Highest risk pathway of introduction
Jarvis (2018)	ASFV	Qualitative	Swill feeding and long-distance transport of pigs, along with the use of spray-dried porcine plasma in feed	Importation of swine, pork products and feed
Middlemiss (2018)	ASFV	Qualitative	Movement of infected meat, meat products resulting in consumption by domestic swine or movement of contaminated equipment/materials	Personal import of meat products
Fekede et al. (2019)	ASFV	Semi-quantitative	Infected wild boar contacting uninfected domestic swine	Infected wild boar
DEFRA (2017)	ASFV	Qualitative	Legal and Illegal trade of live animals or animal products, contaminated fomites	Trade of pig meat (fresh or frozen meat or untreated pig products)
Scientific Committee of the FASFC (2018)	ASFV	Qualitative	Geographic spreading via wild boars, introduction and spread in Belgian pig farms, dissemination between infected and non-infected pig farms	Wild boars (to other wild boars outside of introduction region of Luxemburg)
Jurado et al. (2018)	ASFV	Qualitative	Wild boar; biosecurity breaches on domestic pig farms (including movement of animals and semen/ova); swill feeding; vectors; use of fresh fodder	Swill feeding; pig-pig and/or pig-wild boar contact
Beltran-Alcrudo et al. (2019)	ASFV	Qualitative	International trade animals and animals products, and fomites	Not identified
MacDiarmid (1991)	CSFV	Qualitative	Importation of meat and meat products	Not identified
CFIA (1999)	CSFV	Not identified	Salted intestinal casings fed to domestic pigs (legally or illegally imported)	Salted intestinal casings fed to wild pigs
Mintiens et al. (2003)	CSFV	Quantitative	Neighbourhood infections	Not identified
DeVos et al. (2003)	CSFV	Qualitative	Imports of genetic material (legal and illegal), returning livestock trucks, imports of wild animals, imports of batches of domestic animals, illegal imports of live animals, imports of animal products for human consumption, illegal imports of animal products (including tourists), professional staff, imports of manure, birds, pets, arthropods, and rodents, air currents, laboratories, harbours and airports, and wildlife	Animal movements, swill feeding and wild boar
Gale (2004)	CSFV	Quantitative	Composted catering waste containing uncooked meat discarded on farm land or fed to animals	Composted uncooked animal waste being fed to farm animals or distributed near them
Adkin et al. (2004)	CSFV	Quantitative	Illegally imported meat and meat products and imported catering waste (e.g. ship and aircraft waste)	Imports of de-boned meat via air-passenger baggage most likely to cause subsequent livestock infection after being introduced
Vos et al. (2004)	CSFV	Quantitative	Importation of pigs and pork products, returning livestock trucks, direct and indirect contact with wild boar, feeding of improperly heated swill	Returning livestock trucks
DEFRA (2006)	CSFV	Qualitative	Importation of animal products	Not identified
Wooldridge et al. (2006)	CSFV	Quantitative	Dried de-deboned meat, and meat that follows human carriage (litter, 'fly-tipping', direct feeding)	Illegal importation of meat by way of passenger baggage
DEFRA (2008)	CSFV	Qualitative	Importation of animal products	Not identified
Bronsvoort et al. (2008)	CSFV	Quantitative	Importation of live swine, importation of swine semen, returning livestock vehicles, legal importation of meat and illegal importation of meats	Returning livestock trucks and legal meat imports

Assessed geographic source	Highest risk geographic source	Assessed geographic destination	Highest risk geographic destination	Highest risk consequence	Model
Not identified	Not identified	United Kingdom	Not identified	Not identified	N/A
Not identified	Not identified	United Kingdom	Not identified	Not identified	N/A
Sino-Russia border; Sino-Korean border	Sino-Russian border section	Northern China	Northern China	Infection of the Sino-Russian border section	Spatial
European Union	Romania	United Kingdom	United Kingdom	Not identified	N/A
Luxembourg province of Belgium	Not identified	Belgium (e.g. further spread within country from introduction site of Luxembourg)	Not identified	Not identified	N/A
Infected European Union countries	Not identified	Domestic farms within Uninfected European Union countries	Not identified	Not identified	Literature review
Not identified	Not identified	Not identified	Not identified	Not identified	N/A
Not identified	Not identified	New Zealand	Not identified	Not identified	N/A
Not identified	Not identified	Canada	Not identified	Not identified	N/A
Not identified	Not identified	Belgium	Regions of Belgium (see map in paper)	Areas within Belgium	Logistic regression and spatial
Not identified	Not identified	European Union	Southern Netherlands, Sudoldenburg Germany, Hannover Germany, West-Flanders Belgium, Cotes-d'Amor France	Not identified	Pathway diagram and conceptual framework
United Kingdom	Not identified	United Kingdom	Not identified	Multiple farm animals eating bits of the same contaminated waste, rather than one single pig eating all of the contaminated portion of waste	Source-pathway-receptor approach
Non-EU countries	Western Africa	Great Britain	Not identified	Not identified	Stochastic
European Union	Germany, Belgium, United Kingdom	Netherlands	Netherlands	Not identified	Probability scenario tree
Non-EU countries	Not identified	Great Britain	Not identified	Not identified	N/A
Worldwide	Western Africa	Great Britain	Not identified	Not identified	Common structure model
Non-EU countries	Not identified	Great Britain	Not identified	Not identified	N/A
European Union	Germany, Netherlands	Denmark	Not identified	Not identified	Multi-level binomial

(Continues)

TABLE A1 (Continued)

Authors & date	Pathogen	Type of study	Assessed pathways of introduction	Highest risk pathway of introduction
Costard et al. (2009)	CSFV	Quantitative	Animal-contact, person- and vehicle-contact, feeding	Not identified
Martínez-López et al. (2009)	CSFV	Quantitative	Importation of infected domestic and wild swine	Importation of domestic swine
Hartley (2010)	CSFV	Qualitative	Legal/illegal importation of pig products, direct and indirect contact between feral swine and livestock (airborne, faeco-oral, food borne, vector borne), import or translocation of feral swine	Oral consumption of illegally imported pig products by domestic pigs
Cardoso de Carvalho Ferreira (2013)	CSFV	Qualitative	Transmission between individuals within the same group, between different groups/individuals on different farms, and via tick vectors	Not identified
Delgado et al. (2017)	CSFV	Both	Not identified	Movement of goods outside the EU; movements of wild boar, human contacts with wildlife and humans
Gamado et al. (2017)	CSFV	Quantitative	Not identified	Not identified
Hwang et al. (2018)	CSFV	Semi-quantitative	Migration or natural movement of wildlife, international human movement, illegal importation of wildlife and wildlife parts, accidental introduction of disease vector, smuggling of livestock products, legal importation of wildlife and wildlife parts	Migration or natural movement of wildlife, illegal importation of wildlife and wildlife parts, accidental introduction of a disease vector, smuggling of livestock products
Beltran-Alcrudo et al. (2019)	CSFV	Qualitative	International trade animals and animals products, and fomites	Not identified
MacDiarmid (1991)	FMDV	Qualitative	Importation of meat and meat products	Not identified
Forbes et al. (1994)	FMDV	Both	legal and illegal importation of live animals and animal products, terrorism, commercial passengers, vehicles and equipment, waste disposal for sea and air transport	Illegally imported meat products (5 year timeframe) or terrorist/criminal intent (20 year timeframe)
CFIA (1999)	FMDV	Not identified	Salted intestinal casings fed to domestic pigs (legally or illegally imported)	Salted intestinal casings fed to wild pigs
Moutou et al. (2001)	FMDV	Qualitative	Importation or trade of animal and animal products, cross-border mingling of livestock herds, movement of infected wildlife	Not identified
Pharo and Biosecurity Authority (2002)	FMDV	Qualitative	Illegally imported meat fed to pigs	Illegally imported meat fed to pigs
Pharo (2002)	FMDV	Qualitative	Legally and illegally imported animals and animal products, fomites	Illegally imported meat fed to pigs
DEFRA (2003)	FMDV	Both	Illegal importation of meat and meat products	Personal baggage

Assessed geographic source	Highest risk geographic source	Assessed geographic destination	Highest risk geographic destination	Highest risk consequence	Model
Not identified	Not identified	Madagascar	Not identified	Not identified	Multiple factor analysis and hierarchical cluster analysis
Countries that export products to Spain	Netherlands, Germany, Slovakia, Belgium	Spain	Lerida, Gerona, Huesca, Barcelona and Zaragoza provinces of Spain	Not identified	Stochastic
Not identified	Not identified	England	Not identified	Introduction into wild boar population/spread and duration of the disease	N/A
Not identified	Not identified	Not identified	Not identified	Within and between group transmission	Descriptive
Not identified	Not identified	England, United Kingdom	Not identified	Not identified	Network model
Not identified	Not identified	East Anglia, United Kingdom	Not identified	Not identified	Stochastic spatio-temporal Susceptible-Infectious-Removed (SIR) epidemic model
Not identified	Not identified	Republic of Korea	Not identified	Not identified	N/A
Not identified	Not identified	Not identified	Not identified	Not identified	N/A
Not identified	Not identified	New Zealand	Not identified	Not identified	N/A
Argentina, Brazil, China, Columbia, East Germany, India, Iran, Italy, Kenya, Nigeria, Saudi Arabia, Soviet Union, Thailand, Turkey, West Germany (currently or recently infected countries listed prior here) and (non-infected countries listed after here) Australia, Chile, Egypt, Fiji, France, Indonesia, Japan, Malaysia, Mexico, Morocco, South Africa, Spain, United Kingdom, USA	Thailand (for currently/recently infected) or Australia (for non-infected)	New Zealand	New Zealand	Not identified	Probability and stochastic simulation
Not identified	Not identified	Canada	Not identified	Not identified	N/A
Georgia, Armenia and Azerbaijan	Not identified	Russia and Europe	Not identified	Not identified	N/A
Not identified	Not identified	New Zealand	Not identified	Not identified	N/A
Not identified	Not identified	New Zealand	Not identified	Not identified	Literature Review
Worldwide	Not identified	Great Britain	Not identified	Not identified	Probability with stochastic nature

(Continues)

TABLE A1 (Continued)

Authors & date	Pathogen	Type of study	Assessed pathways of introduction	Highest risk pathway of introduction
Sutmoller and Olascoaga (2003)	FMDV	Qualitative	Importation of FMDV vaccinated live animals and animal products from vaccinated animals (meat, meat products, milk and dairy products, bovine embryos, semen	Not identified
Adkin et al. (2004)	FMDV	Quantitative	Illegally imported meat and meat products and imported catering waste (e.g. ship and aircraft waste)	Imports of cattle and pig meat via passenger baggage pose highest risk to livestock infection
Gale (2004)	FMDV	Quantitative	Composted catering waste containing uncooked meat discarded on farm land or fed to animals	Composted uncooked animal waste being fed to farm animals or distributed near them
Schijven et al. (2005)	FMDV	Quantitative	Illegal discharge of contaminated milk in sewerage resulting in livestock contact with contaminated surface water from treatment plants	Not identified
Hong et al. (2005)	FMDV	Quantitative	Contaminated smuggled animal products fed to swine	Feeding contaminated waste to susceptible swine
DEFRA (2006)	FMDV	Qualitative	Importation of animal products	Not identified
Wooldridge et al. (2006)	FMDV	Quantitative	Cattle and pig meat, and meat that follows human carriage (litter, 'fly-tipping', direct feeding)	Illegal importation of meat by way of passenger baggage
EFSA (2006)	FMDV	Qualitative	Legal and illegal importation of infected animals and contaminated animal products, contaminated fomites (i.e. trucks)	Illegally imported animal products
Hartnett et al. (2007)	FMDV	Quantitative	Illegally imported contaminated meat	Illegal import of bone-in and dried de-boned products from cattle and pigs in passenger baggage
DEFRA (2008)	FMDV	Quantitative	Importation of animal products	Not identified
Rodeia (2008)	FMDV	Qualitative	Not identified	Not identified
Bender et al. (2006)	FMDV	Qualitative	Direct contact between animals, aerosol from infected animals or milk trucks, fomites, artificial insemination	Not identified
Martínez-López et al. (2008)	FMDV	Quantitative	Legal importation of live animals	Import of pigs
Hartley (2010)	FMDV	Qualitative	Legal/illegal importation of pig products, direct and indirect contact between feral swine and livestock (airborne, faeco-oral, food borne, vector borne), import or translocation of feral swine	Oral consumption of illegally imported pig products by domestic pigs
Wieland et al. (2015)	FMDV	Qualitative	Livestock, animal-derived products, feed, vehicles/fomites, people, wildlife, aerosol and water	Cross-border movement of livestock
Dewey et al. (2014)	FMDV	Qualitative	Fomites (people, boots, vehicles, feed bags)	Not identified
Şenturk et al. (2016)	FMDV	Quantitative	Animal production chain aspects including input, processing, production, movement and marketing infrastructure	Importation of animals
Hernández-Jover et al. (2016)	FMDV	Both	Illegal importation of infected meat	Direct feeding of infected meat to pigs at small-scale piggeries

Assessed geographic source	Highest risk geographic source	Assessed geographic destination	Highest risk geographic destination	Highest risk consequence	Model
Not identified	Not identified	Not identified	Not identified	Not identified	N/A
Countries outside the European Union	Near and Middle East	Great Britain	Not identified	Not identified	Stochastic
United Kingdom	Not identified	United Kingdom	Not identified	Multiple farm animals eating bits of the same contaminated waste, rather than one single pig eating all of the contaminated portion of waste	Source-pathway-receptor approach
Not identified	Not identified	Not identified	Not identified	Not identified	Dose-response model
Not identified	Not identified	South Korea	Not identified	Not identified	Monte Carlo Simulation
Non-EU countries	Not identified	Great Britain	Not identified	Not identified	N/A
Worldwide	Near and Middle East	Great Britain	Not identified	Not identified	Common structure model
Infected non-EU countries	Southeast Asia, China, South Asia	European Union	Europe	Introduction of infected live animal	N/A
Eastern Asia, Near and Middle East, Eastern Europe, Southern Africa, Western Africa, North America, Caribbean, Southern Asia, Eastern Africa, Oceania, Central and South America, South-eastern Asia, Northern Africa, Central Africa	Near and Middle East region	Great Britain	Great Britain	Not identified	Object-oriented simulation of flow, probability, Monte Carlo simulation
Non-EU countries	Not identified	Great Britain	Not identified	Not identified	N/A
Not identified	Southeast Asia, China, South Asia	European Union	Europe	Not identified	N/A
Not identified	Not identified	Not identified	Not identified	Not identified	N/A
European Union	Not identified	Spain	North-eastern Spain	Not identified	Binomial probability, Monte Carlo approach
Not identified	Not identified	England	Not identified	Introduction into wild boar population/spread and duration of the disease	N/A
Mongolia	Mongolia (eastern region)	Mongolia	Mongolia (western region)	Not identified	N/A
Canada (Ontario)	Not identified	Canada (Ontario)	Not identified	Not identified	Focus groups and interviews of feed-company personnel and swine producers
Not identified	Not identified	Turkey (Samsun Province)	Not identified	Not identified	Linear regression
Not identified	Not identified	Australia	Not identified	Not identified	Scenario trees and Monte Carlo stochastic simulation

(Continues)

TABLE A1 (Continued)

Authors & date	Pathogen	Type of study	Assessed pathways of introduction	Highest risk pathway of introduction
DEFRA (2017)	FMDV	Both	Commercial and personal importations of products of animal origin; live animals commercial and personal imports and the EU Pet Travel Scheme; commercial and personal imports of plant and plant products (including wood, wood products and bark); veterinary medicines (commercial and personal import of illegal veterinary medicines)	Meat and dairy products
Delgado et al. (2017)	FMDV	Semi-quantitative	Legal and illegal movements of animals and animal products, and airborne transmission	Legal, non-commercial movement of people and goods across and within borders of live animals and animal products
Goldsmith et al. (2017)	FMDV	Qualitative	Not identified	Not identified
Beltran-Alcrudo et al. (2019)	FMDV	Qualitative	International trade animals and animals products, and fomites	Not identified
Davidson (1992)	Not identified	Quantitative	Importations of animal materials by mail or air passengers	Animal products imported by air passengers
Shih et al. (2005)	Not identified	Quantitative	Illegal importation of animal products by air passenger baggage	Not identified
Whyte (2006)	Not identified	Qualitative	Legal and illegal imports (including infected materials brought in passenger baggage and sent in the mail)	Not identified
Chaber et al. (2010)	Not identified	Qualitative	Illegally imported bushmeat by air passenger	Not identified
Noordhuizen et al. (2013)	Not identified	Qualitative	Illegal importation of animals and animal products by travellers	Not identified
Falk et al. (2013)	Not identified	Qualitative	Illegal importation of bushmeat and meat products by air passenger baggage	Not identified
Porphyre et al. (2014)	Not identified	Both	Fomites and human mediated movement	Not identified
Melo et al. (2014)	Not identified	Quantitative	Illegal importation of animal products via air travel	Not identified
Beutlich et al. (2015)	Not identified	Qualitative	Illegally imported food by air passenger	Air passenger baggage
Jansen et al. (2016)	Not identified	Both	Illegal importation of products of animal origin by air passenger	Not identified
Melo et al. (2018)	Not identified	Qualitative	Illegally imported food by air passenger	Illegally imported food by air passenger

Assessed geographic source	Highest risk geographic source	Assessed geographic destination	Highest risk geographic destination	Highest risk consequence	Model
Worldwide	Passengers returning from Southern and Eastern Asia, Near and Middle East, and West Africa	United Kingdom	Not identified	Not identified	N/A
Non-EU trading partners/countries, EU member countries with confirmed FMDV outbreaks and laboratories	European Union and trading partners with FMDV outbreaks	United Kingdom	United Kingdom	Not identified	Systemic model
Not identified	Not identified	Not identified	Not identified	Not identified	N/A
Not identified	Not identified	Not identified	Not identified	Not identified	N/A
Not identified	Not identified	New Zealand	Not identified	Not identified	N/A
Worldwide	China and Hong Kong	Taiwan	CKS International Airport	Not identified	Monte Carlo Simulation
Not identified	Not identified	New Zealand	New Zealand	Not identified	N/A
Sub-Saharan Africa	Central African Republic, Cameroon, Republic of Congo	France	Not identified	Not identified	N/A
Worldwide	Not identified	European Union	Not identified	Not identified	N/A
Worldwide	Kosovo	Switzerland (Zurich and Geneva airports)	Not identified	Not identified	Stochastic model
Scotland	Not identified	Scotland	Not identified	Not identified	External-Internal Index
Worldwide	Eastern Europe, Portugal	Brazil	Not identified	Not identified	Chi square, logistic regression and odds ratios
Worldwide	Turkey and Russia	Germany	Not identified	Not identified	N/A
Worldwide	Meat- Russia and the Caucasus, Dairy- Turkey and Middle East	Germany	International airports	Not identified	N/A
Worldwide	China	Brazil - GRU/SBGR Airport	Not identified	Not identified	N/A

TABLE A2 Global economic impact estimates of African swine fever (ASF) outbreaks

ASF study	Retro./For. analysis? (economic approach[a])	Year[b]	Duration	Continent	Country	Cost estimate (2019 USD[c])	Economic Measure	Economic estimation description	Other economic estimates
Halasa, Boklund, et al. (2016)), Halasa, Bøtner, et al. (2016))	Forecast (BCA)	2016	1–29 days	Europe	Denmark	$435,531,250	Total median cost + loss	Direct costs (surveillance costs, depopulation costs, cleaning and disinfection, compensation, empty stables, welfare slaughter, 3 days national standstill) + export loss	N/A
Fasina et al. (2012)	Forecast (BCA)	2011	3 years	Africa	Nigeria	$649,000	Total average annual loss	Production loss *Sum of 3 annual totals given in paper*	Estimated annual value of pig production losses from an outbreak of ASFV in Nigeria
Babalobi et al. (2007)	Retrospective (BCA)	2001	1 year	Africa	Nigeria	$1,350,836	Total loss	Financial losses from pig mortality defined as 'total mortality cost'	Herd mortality distribution in 306 farms affected by outbreak, unit cost of testing pigs for the presence of ASF in Oyo State, Nigeria
Babalobi et al. (2007)	Retrospective (BCA)	2001	1 year	Africa	Nigeria	$142,477,345	Total cost	Direct costs for farm biosecurity against outbreak (carcass disposal, quarantine animal entering the herds, buying only from herds with trusted animal health program, testing for ASF)	Herd mortality distribution in 306 farms affected by outbreak, unit cost of testing pigs for the presence of ASF in Oyo State, Nigeria
Rendleman and Spinelli (1999)	Forecast (PEA)	1993	10 years (program duration)	North America	USA	$5,930,039,264	Total cost	Prevention and cleanup costs	Estimated program costs for outbreak of ASF in U.S. Costs include: an indemnity portion, present value measure of market prices paid for hogs slaughtered throughout the disease run, and a non-indemnity portion paid throughout the run
Bech-Nielsen et al. (1993)	Forecast (BCA)	1992	20 years (program duration)	Europe	Spain	$94,539,870,064	Total loss	Economic loss: value of swine depopulated	Direct costs: producers and government Indirect loss: export loss

(Continues)

TABLE A2 (Continued)

ASF study	Retro./For. analysis? (economic approach[a])	Year[b]	Duration	Continent	Country	Cost estimate (2019 USD[c])	Economic Measure	Economic estimation description	Other economic estimates
Terpstra (1987)	Retrospective (FC)	1983	2 years	Europe	Netherlands	$227,881,000	Total cost	Direct costs of control measures (transport destruction of infected herds, disinfection of premises, indemnities to farmers, vaccination, identification & registration of pigs)	N/A

[a](BCA) Benefit–cost analysis, (CGE) computable general equilibrium, (EIA) economic impact assessment, (I/O) input–output, (PE) partial equilibrium, (PBM), partial budget model, (FC) 'Financial costing'.

[b]Year of outbreak. Was not always clearly provided.

[c]To adjust values presented in paper to 2019 USD ($), year which the value presented in the paper represents must also be present. If this was not clearly given, the year of publication was assumed to be the year belonging to the value. References used for calculations include: DeNederlandscheBank (2002), Antweiler (2019), European Central Bank (2019), United States Bureau of Labor Statistics (2019), United States Department of the Treasury (2019).

TABLE A3 Global economic impact estimates of classical swine fever (CSF) outbreaks

CSF Study	Retro./For. analysis? (Economic approach[a])	Year[b]	Duration	Continent	Country	Cost Estimate (2019 USD[c])	Economic Measure	Economic Estimation Description	Other Economic Estimates
Hop et al. (2016)	Forecast (FC)	2010	129 days (max median)	Europe	Netherlands + Germany	$81,142,730	Total cost	Direct costs (disease control, program organization, clinical examination, depopulation of sows, vaccination, destruction of feed) + direct consequential costs (from disease control)	Costs for simulated outbreaks for various regions &control strategies. Also address cross-border spread among regions
Boklund et al. (2009)	Forecast (FC)	N/A	15 days (maximum median)	Europe	Denmark	$585,762,061	Maximum median cost	Epidemic cost (public costs: depopulated pigs, culling, rendering, cleaning, production loss, blood tests, vaccination; industry costs: empty housing units, welfare slaughter, 3-day national standstill; export losses: ban on pigs and pig product export. *Average of upper and lower median cost for production herd and nucleus herd presented here*	N/A
Mangen et al. (2004)	Retrospective (PEA & EpiCosts)	1997–1998	436 days (large epidemic)	Europe	Netherlands	$1,172,343,683	Average median cost	Control cost [medium outbreak] not explicitly defined	Welfare measures, regression analysis, comparison to actual epidemic costs
Mangen and Burrell (2003)	Forecast (PEA & Excel)	1997–1998	1 year	Europe	Netherlands	$1,096,000,000	Total cost	Government expenditures [medium outbreak] (depopulation, control of quarantine, preventative slaughter, welfare slaughter, detected farms)	Welfare measures, prices changes during epidemic

(Continues)

TABLE A3 (Continued)

CSF Study	Retro./For. analysis? (Economic approach[a])	Year[b]	Duration	Continent	Country	Cost Estimate (2019 USD[c])	Economic Measure	Economic Estimation Description	Other Economic Estimates
Garner et al. (2001)	Forecast (FC)	NA	3 weeks	Australia	Australia	$97,335,595	Total cost	Direct costs [nation wide] (stamped-out farms, farms in restricted areas, price effects [whole industry)])	Value of livestock affected (Darling Downs), expected on-farm costs (Darling Downs, Northern Victoria), costs associated with movement restrictions, expected gross income of regional pig industry
Garner et al. (2001)	Forecast (FC)	NA	3 weeks	Australia	Australia	$58,338	Total loss	Direct loss [annual] (production loss - number of herds affected, fall in output [tons])	Value of livestock affected (Darling Downs), expected on-farm costs (Darling Downs, Northern Victoria), costs associated with movement restrictions, expected gross income of regional pig industry
Saatkamp et al. (2000)	Forecast (Analysis of cost-effectiveness, disclaim BCA)	NA	16 weeks	Europe	Belgium, Netherlands	$248,934,198	Maximum total loss	Direct loss [current policy] (removal, welfare slaughter, operational costs, reduced net cash-flow trade and industry)	Summary of reported direct costs caused by CSF in Belgium and Netherlands (1990–1997)
Meuwissen et al. (1999)	Forecast (EpiLoss)	1997–1998	1 yr	Europe	Netherlands	$3,663,548,983	Total loss	Economic loss (direct costs, consequential losses farms, consequential losses related industries)	(see below)
Meuwissen et al. (1999)	Forecast (FC)	1997–1998	1 year	Europe	Netherlands	$2,068,182,994	Total cost	Direct costs (compensation paid for pigs and feed destroyed, compensation for sows under a breeding prohibition, organizational aspects-equipment and personnel for outbreak response)	(see below)

(Continues)

TABLE A3 (Continued)

CSF Study	Retro./For. analysis? (Economic approach[a])	Year[b]	Duration	Continent	Country	Cost Estimate (2019 USD[c])	Economic Measure	Economic Estimation Description	Other Economic Estimates
Meuwissen et al. (1999)	Forecast (FC)	1997–1998	1 year	Europe	Netherlands	$1,595,365,989	Total loss	Consequential loss (farm loss: idle production, supply and delivery problems, losses from repopulation; [related industries] slaughterhouses, animal traders, feed suppliers, breeding organizations) *Added farm and related industry loss*	(see above)
Garner and Lack (1995)	Forecast (I/O)	NA	12.5 (avg.)	Australia	Australia	$364,411	Average cost	Control cost [medium outbreak] (output effects, income effects, job losses, compensation) *Average of three regions presented here*	Economic effects for foot-and-mouth disease and sheep pox

[a](ASM) Agricultural sector model, (BCA) Benefit–cost analysis, (CGE) computable general equilibrium, (EIA) economic impact assessment, (I/O) input–output, (PE) partial equilibrium, (PBM), partial budget model, (FC) 'Financial costing'.

[b]Year of outbreak. Was not always clearly provided.

[c]To adjust values presented in paper to 2019 USD ($), year which the value presented in the paper represents must also be present. If this was not clearly given, the year of publication was assumed to be the year belonging to the value. References used for calculations include: DeNederlandscheBank (2002), Antweiler (2019), European Central Bank (2019), United States Bureau of Labor Statistics (2019), United States Department of the Treasury (2019).

TABLE A4 Global economic impact estimates of foot-and-mouth disease (FMD) outbreaks

FMD study	Retro./For. analysis? (Economic approach[a])	Year[b]	Duration	Continent	Country	Cost estimate (2019 USD[c])	Economic measure	Economic estimation description	Other economic estimates
Miller et al. (2019)	Forecast CGE (REMI Policy Insight +)	2014	2 years	North America	USA	$13,063,884,307	Maximum total loss	Vaccination strategies and impacts on GDP and employment over 10-year study period + job losses by industry sector	Total government cost (euthanasia, vaccination, disposal, cleaning & disinfecting, indemnity) [presented in paper Appendix]
Countryman and Hagerman (2017)	Retrospective (CGE, Global Trade Analysis Project (Hertel, 1997)	2001	1 year	South America	Argentina	$5,886,221	Total loss	Loss in beef cattle production value resulting from cattle deaths, depopulation, sick but not killed/dead	Export market loss, export enhancement shock regression results, global trade analysis, welfare changes (equivalent variation) in Latin America
Countryman and Hagerman (2017)	Retrospective (CGE, Global Trade Analysis Project (Hertel, 1997)	2001	1 year	South America	Brazil	$39,221,659	Total loss	Loss in beef cattle production value resulting from cattle deaths, depopulation, sick but not killed/dead	Export market loss, export enhancement shock regression results, global trade analysis, welfare changes (equivalent variation) in Latin America
Countryman and Hagerman (2017)	Retrospective (CGE, Global Trade Analysis Project (Hertel, 1997)	2001	1 year	South America	Uruguay	$20,985,638	Total loss	Loss in beef cattle production value resulting from cattle deaths, depopulation, sick but not killed/dead	Export market loss, export enhancement shock regression results, global trade analysis, welfare changes (equivalent variation) in Latin America
Countryman and Hagerman (2017)	Retrospective (CGE, Global Trade Analysis Project (Hertel, 1997)	2001	1 year	South America	Ecuador	$27,301	Total loss	Loss in beef cattle production value resulting from cattle deaths, depopulation, sick but not killed/dead	Export market loss, export enhancement shock regression results, global trade analysis, welfare changes (equivalent variation) in Latin America
Countryman and Hagerman (2017)	Retrospective (CGE, Global Trade Analysis Project (Hertel, 1997)	2001	1 year	South America	Venezuela	$14,236	Total loss	Loss in beef cattle production value resulting from cattle deaths, depopulation, sick but not killed/dead	Export market loss, export enhancement shock regression results, global trade analysis, welfare changes (equivalent variation) in Latin America

(Continues)

TABLE A4 (Continued)

FMD study	Retro./For. analysis? (Economic approach[a])	Year[b]	Duration	Continent	Country	Cost estimate (2019 USD[c])	Economic measure	Economic estimation description	Other economic estimates
Countryman and Hagerman (2017)	Retrospective (CGE, Global Trade Analysis Project (Hertel, 1997)	2001	1 year	South America	Colombia	$537,499	Total loss	Loss in beef cattle production value resulting from cattle deaths, depopulation, sick but not killed/dead	Export market loss, export enhancement shock regression results, global trade analysis, welfare changes (equivalent variation) in Latin America
Halasa, Bøtner, et al. (2016)	Forecast (BCA)	NA	67 days (median, cattle herds)	Europe	Denmark	$1,009,394,597	Total cost	Government loss: direct costs (surveillance, depopulation, cleaning & disinfection, empty housing, compensation, national standstill) + indirect costs (export loss)	Other total costs varying by control strategy, median direct costs and export losses
Schroeder et al. (2015)	Forecast (PEA)	NA	10 years	North America	USA	$13,063,884,307	Maximum median total cost	Government costs [with emergency vaccination strategy] (euthanasia, indemnity, vaccination, disposal, cleaning & disinfection)	Welfare measures, returns to capital and management
Jemberu et al. (2014)	Retrospective (EIA)	2012	2 years	Africa	Ethiopia	$83	Total average loss	Economic loss [per herd]: direct impacts (visible - milk loss, draft power loss, mortality loss + invisible losses)	Indirect impacts: additional costs and revenues foregone
Bergevoet and Asseldonk (2014)	Forecast (PBM)	NA	61 days	Europe	Netherlands	$171,229,404	Maximum total loss	Direct outbreak costs (culled animals, destruction of feed and milk, clearing and disinfection, empty farm buildings during outbreak, costs of vaccinating, costs of transportation prohibition, loss of vaccinated animals)	Export loss of different sectors due to logistic processing and value of loss given a vaccination strategy

(Continues)

TABLE A4 (Continued)

FMD study	Retro./For. analysis? (Economic approach[a])	Year[b]	Duration	Continent	Country	Cost estimate (2019 USD[c])	Economic measure	Economic estimation description	Other economic estimates
Boklund et al. (2013)	Forecast (BCA)	NA	80 days (median)	Europe	Denmark	$617,523,000	Total median cost + loss	Direct costs [basic control strategy] (surveillance, depopulation, cleaning & disinfection, empty stables, compensation, welfare slaughter, national standstill, vaccination) + indirect costs (export bans on livestock and livestock products to EU and non-EU countries)	Estimated costs from an airborne virus strain
Knight-Jones and Rushton (2013)	Retrospective (Aggregate national and regional studies, WHO)	NA	1 year	Global	Multi-country	$12,983,000,000	Total annual average cost + loss	Government & producer costs: diagnostic tests + loss (milk production loss, mortality, extra-replacement, condemnation, loss from compulsory health measures)	Global annual impact of FMD-caused loss
Carpenter et al. (2011)	Forecast (ASM)	NA	22 days (median)	North America	USA (California)	$84,584,000,000	Maximum median total loss	National loss in total agricultural surplus	Estimated total and incremental daily economic losses associated with a diagnostic delay in a California dairy
Elbakidze et al. (2009)	Forecast (Economic costing module)	N/A	Not given	North America	USA	$1,410,000,000	Average total cost	Loss [for high-intensive cattle industry, compared to other herd types presented]: losses incurred within the cattle industry because of the outbreak (gross lost value of animals and lost gross income due to temporary business inactivity of affected producers)	Median economic costs and loss by herd type associated with early detection/early & delayed vaccine availability/ enhanced & regular surveillance, cumulative distribution of losses

(Continues)

TABLE A4 (Continued)

FMD study	Retro./For. analysis? (Economic approach[a])	Year[b]	Duration	Continent	Country	Cost estimate (2019 USD[c])	Economic measure	Economic estimation description	Other economic estimates
Elbakidze et al. (2009)	Forecast (Economic costing module)	N/A	Not given	North America	USA	$312,176,320	Max median loss	Cost [for high-intensive cattle industry, compared to other herd types presented]: disease management strategy costs (slaughter, costs of appraisal, euthanasia, carcass disposal, cleaning, disinfection, quarantine implementation, vaccination, surveillance) + loss [cattle industry loss]: gross lost value of animals and lost gross income due to temporary business inactivity of affected producers	Median economic costs and loss by herd type associated with early detection/early & delayed vaccine availability/ enhanced & regular surveillance, cumulative distribution of losses
Barasa et al. (2008)	Retrospective (BCA + Participatory Epidemiology (PE) methods)	2004	1 year	Africa	South Sudan	$285,924	Maximum total cost	Costs of biannual foot-and-mouth disease vaccination of the entire cattle population	Mortality & milk production effects, livelihoods analysis
Senturk and Yalcin (2008)	Forecast (FC)	NA	Not given	Transcontinent	Turkey	$15,881,000	Total loss	Production related loss [national scale] (milk yield, fertility, delay in age of first calving, premature culling, live-weight loss, expected profit)	Production loss (infected animals) by production animal type (e.g. heifer, female calve) (milk yield, fertility, delay in age of first calving, premature culling, live-weight loss, expected profit), Weighted loss by cattle breed (per head)
Pendell et al. (2007)	Forecast (PEA & I/O)	NA	89 days	North America	USA (Kansas, region and state-wide)	$1,345,262,043	Total impact	'Direct and total impact' [SW Kansas and 'rest of Kansas'] associated with alternative hypothetical FMD outbreak scenarios (sum of respective totals, see paper tables for respective details of costs)	Changes in producer surplus at market level, economic value of livestock production and processing in SW Kansas, estimated direct and total impacts for SW Kansas and 'rest' of Kansas (all with hypothetical incidence scenarios), impact on 'value-added' markets

(Continues)

TABLE A4 (Continued)

FMD study	Retro./For. analysis? (Economic approach[a])	Year[b]	Duration	Continent	Country	Cost estimate (2019 USD[c])	Economic measure	Economic estimation description	Other economic estimates
Belton (2004)	Forecast (Reserve Bank's internal 'forecasting and policy system')	NA	2 yrs	New Zealand	New Zealand	$6,028,498,356	Total nominal GDP loss	Cumulative nominal GDP loss [two years]	Percent change in real GDP, changes in unemployment, aggregate demand, investment, inflation and exchange rate
Blake et al. (2003)	Forecast (CGE & Micro-Regional Tourism Simulation Model)	2001	4 years	Europe	Great Britain	$5,816,068,000	Total loss	Government revenue loss: total government revenue loss after tax revenue and direct effects of agriculture (62% of costs to gov.) are accounted for over two years	Tourism expenditure reductions for UK economy (2001), reductions in total tourism expenditure and GDP (2001–2004), change in real factor earnings by sector
Bates et al. (2003)	Forecast (BCA)	NA	71 days (median)	North America	USA (3-county region in California)	$131,564,000	Total cost	Direct costs [for baseline eradication strategy, typical dry lot dairy] (slaughter, indemnity, cleaning and disinfection)	Expected costs of indemnity for slaughtered animals and destroyed feedstuffs and milk (for dry lot diary, 3-county study region); expected costs for disposal, cleaning and disinfection; direct costs for supplemental strategies with varying assumptions; additional costs after baseline costs
Schoenbaum and Disney (2003)	Forecast (Welfare impacts)	NA	46 days (median)	North America	USA	$569,041,718	Maximum median cost	Government cost plus net welfare change [Slaughter (stamping out) strategy 3: contagious herds, and herds with direct or indirect contact]	Government cost of control and eradication & government cost of control and eradication plus net welfare change for 3 different herd populations, 2 rates of spread, 3 vaccination strategies and 4 slaughter strategies

(Continues)

TABLE A4 (Continued)

FMD study	Retro./For. analysis? (Economic approach[a])	Year[b]	Duration	Continent	Country	Cost estimate (2019 USD[c])	Economic measure	Economic estimation description	Other economic estimates
Schoenbaum and Disney (2003)	Forecast (Welfare impacts)	N/A	52 days (median)	North America	USA	$628,284,417	Maximum median cost	Government cost plus net welfare change [Vaccination strategy: all scenarios (no vaccine, early vaccine, late vaccine)]	Government cost of control and eradication & government cost of control and eradication plus net welfare change for 3 different herd populations, 2 rates of spread, 3 vaccination strategies and 4 slaughter strategies
Thompson et al. (2002)	Retrospective (Welfare impacts)	2001	1 year	Europe	Great Britain	$6,498,109,640	Total cost	Production (market prices, export loss, withholding costs, consequential loss, sheep annual premium, agri-monetary aid; food industry (auction markets, abattoirs, processors/haulers); public sector (compensation, welfare scheme payments, disposal costs, misc. costs, agri-monetary aid, sheep annual premium, business support measures, consumers of the U.K.)	Income effects (agricultural producers, food supply chain); indirect/direct effects on tourism; indirect impacts (multipliers for agriculture, tourism and retail)
Randolph et al. (2002)	Forecast (BCA)	1995–1999	~2 years	North America	USA	$22,166,000	Maximum total cost + loss	Cost [baseline scenario]: control cost to producers + loss: production loss	Benefit–cost indicators for eradication scenarios under varying export assumptions, total present value of costs & benefits over 25-year horizon by sector
Mahul and Durand (2000)	Forecast (I/O)	N/A	8 weeks (maximum)	Europe	France	$298,595,841	Maximum total cost	Direct cost: [maximum reported among 3 control strategies in two locations] disease-control costs and costs of vaccination, compensation payments, and costs due to movement restriction on livestock and livestock products	Size and direct costs of outbreak for various control strategies, net loss
Yang et al. (1999)	Retrospective (FC)	1997	5 months	Asia	Taiwan	$599,438,206	Total cost	Financial cost: control + market value loss	N/A

(Continues)

TABLE A4 (Continued)

FMD study	Retro./For. analysis? (Economic approach[a])	Year[b]	Duration	Continent	Country	Cost estimate (2019 USD[c])	Economic measure	Economic estimation description	Other economic estimates
Yang et al. (1999)	Retrospective (FC)	1997	5 months	Asia	Taiwan	$2,533,283,489	Total loss	Direct loss as a result of export ban of pork to Japan	N/A
Garner and Lack (1995)	Forecast (I/O)	N/A	12.5 (avg.)	Australia	Australia	$1,914,374	Total average cost	Control costs [medium outbreak]: production losses *(average across 3 regions is reported in this table)*	Output effects, income effects, job losses and compensation
Aulaqi & Sundquist (1978) (from McCauley et al. (1978)	Forecast (BCA)	NA	Not given	North America	USA	$18,815,564	Total loss	Direct monetary loss [initial year] (death & permanent disability in cattle, calf mortality abortions, death losses in swine, death loss in sheep, milk production loss, milk cows culled - FMD mastitis, other losses - inefficient weight gain, delayed conception)	Net benefits from prevention, export losses, labour and time requirements for eradication on infected premises, short-run effects on livestock sectors, cost of eradication for different farm operations/sizes
Aulaqi & Sundquist, 1978 (from McCauley et al. (1978)	Forecast (BCA)	NA	Not given	North America	USA	$33,628	Maximum total cost	Cost of FMD eradication for different farm operations [resulted presented - dairy farm, free stall, 150 head]	Net benefits from prevention, export losses, labour and time requirements for eradication on infected premises, short-run effects on livestock sectors, direct monetary loss (initial year)

[a](ASM) Agricultural sector model, (BCA) Benefit–cost analysis, (CGE) computable general equilibrium, (EIA) economic impact assessment, (I/O) input–output, (PE) partial equilibrium, (PBM), partial budget model, (FC) 'Financial costing'

[b]Year of outbreak. Was not always clearly provided.

[c]To adjust values presented in paper to 2019 USD ($), year which the value presented in the paper represents must also be present. If this was not clearly given, the year of publication was assumed to be the year belonging to the value. References used for calculations include: DeNederlandscheBank (2002), Antweiler (2019), European Central Bank (2019), United States Bureau of Labor Statistics (2019), United States Department of the Treasury (2019).

TABLE A5 (Global) Number of outbreaks by country and livestock population estimates (head)

Country Name	# FMD	# ASF	# CSF	Total # Outbreaks	2018 Livestock Pop. (head)	2018 Swine Pop. (head)	2018 Human Pop.
Afghanistan	4	0	0	4	24,790,567	–	37,171,921
Albania	3	0	4	7	4,880,269	231,680	2,882,740
Algeria	2	0	0	2	42,066,070	2,792	42,228,408
Angola	3	0	0	3	4,230,156	1,479,676	30,809,787
Antarctica	0	0	0	0	–	–	–
Argentina	5	0	3	8	26,123,915	6,778,976	44,361,150
Armenia	4	4	1	9	1,999,698	238,197	2,951,745
Australia	0	0	0	0	48,579,310	5,378,100	24,898,152
Austria	1	0	2	3	6,798,064	5,151,074	8,891,388
Azerbaijan	2	2	0	4	8,406,305	9,220	9,949,537
Bahamas	0	0	0	0	22,793	6,657	385,637
Bangladesh	9	0	1	10	70,277,526	–	161,376,708
Belarus	1	2	1	4	8,111,912	4,711,909	9,452,617
Belgium	1	3	3	7	12,827,789	11,230,544	11,482,178
Belize	0	0	1	1	54,759	39,003	383,071
Benin	9	9	0	18	2,321,858	207,606	11,485,044
Bhutan	10	0	7	17	229,165	19,185	754,388
Bolivia	9	0	7	16	6,753,435	2,145,000	11,353,142
Bosnia and Herz.	0	0	8	8	754,826	101,509	3,323,925
Botswana	14	2	0	16	974,861	13,006	2,254,068
Brazil	8	1	13	22	112,701,965	42,642,601	209,469,323
Brunei	0	0	0	0	9,437	1,424	428,963
Bulgaria	2	3	13	18	3,870,061	1,215,786	7,051,608
Burkina Faso	9	4	0	13	15,140,536	1,488,298	19,751,466
Burundi	4	5	0	9	1,362,765	83,664	11,175,374
Cambodia	8	1	3	12	2,388,054	1,729,610	16,249,792
Cameroon	9	9	0	18	7,486,838	1,103,239	25,216,267
Canada	0	0	0	0	26,942,592	21,561,500	37,074,562
Central African Rep.	5	4	0	9	3,052,998	616,519	4,666,368
Chad	8	6	0	14	28,238,491	79,898	15,477,729
Chile	1	0	1	2	7,746,152	5,011,692	18,729,160
China	25	4	16	45	1,090,792,328	694,540,656	1,427,647,786
Colombia	13	0	9	22	14,282,063	4,001,545	49,661,048
Congo	0	4	0	4	247,485	47,576	5,244,359
Costa Rica	0	0	2	2	1,768,731	862,448	4,999,441
Cote d'Ivoire	7	6	0	13	1,786,867	233,117	25,069,230
Croatia	1	0	6	7	2,606,234	1,567,200	4,156,405
Cuba	0	1	6	7	5,759,300	4,068,300	11,338,134
Cyprus	1	0	0	1	1,254,596	560,255	1,189,265
Czech Rep.	1	1	4	6	3,311,974	2,413,685	10,665,677
Dem. Rep. Congo	0	4	0	4	2,503,101	541,811	84,068,091
Dem. Rep. Korea	3	1	0	4	7,042,121	2,611,312	25,549,604
Denmark	1	0	0	1	19,231,680	18,085,605	5,752,126

(Continues)

TABLE A5 (Continued)

Country Name	# FMD	# ASF	# CSF	Total # Outbreaks	2018 Livestock Pop. (head)	2018 Swine Pop. (head)	2018 Human Pop.
Djibouti	0	0	1	1	516,423	—	958,923
Dominican Rep.	0	1	9	10	2,208,970	1,206,593	10,627,141
Ecuador	12	0	9	21	4,584,210	2,302,472	17,084,358
Egypt	7	0	0	7	13,425,639	15,811	98,423,598
El Salvador	0	0	7	7	477,669	147,279	6,420,746
Eq. Guinea	—	—	—	0	17,906	3,731	1,308,975
Eritrea	8	0	0	8	2,864,107	—	3,452,786
Estonia	1	5	1	7	686,578	537,888	1,322,920
Ethiopia	9	1	0	10	36,875,284	41,147	109,224,414
Falkland Is.	0	0	0	0	46,271	—	3,234
Fiji	0	0	0	0	142,931	94,558	883,483
Finland	0	0	0	0	2,450,979	1,827,840	5,522,576
Fr. S. Antarctic Lands	0	0	0	0	—	—	—
France	2	0	5	7	40,473,477	23,574,409	64,990,511
Gabon	0	0	0	0	236,059	119,368	2,119,275
Gambia	4	3	0	7	220,932	12,503	2,280,094
Georgia	7	2	1	10	1,638,640	464,538	4,002,942
Germany	1	0	10	11	65,726,989	56,895,229	83,124,418
Ghana	9	5	0	14	4,576,933	648,215	29,767,102
Greece	2	0	1	3	19,178,575	1,333,675	10,522,246
Greenland	—	—	—	0	16,906	—	56,564
Guatemala	0	0	11	11	3,211,402	1,320,445	17,247,849
Guinea	5	0	0	5	4,117,454	83,375	12,414,293
Guinea-Bissau	2	0	0	2	1,070,784	383,809	1,874,303
Guyana	1	0	0	1	119,726	5,709	779,006
Haiti	0	1	6	7	2,210,602	572,692	11,123,178
Honduras	0	0	9	9	1,058,566	184,007	9,587,522
Hungary	0	3	2	5	5,470,313	4,972,737	9,707,499
Iceland	0	0	0	0	730,780	81,442	336,713
India	9	0	9	18	241,820,866	8,461,298	1,352,642,280
Indonesia	1	1	9	11	44,853,983	16,476,007	267,670,543
Iran	10	0	0	10	42,801,621	—	81,800,188
Iraq	6	0	0	6	6,791,366	—	38,433,600
Ireland	1	0	0	1	10,047,900	3,446,700	4,818,690
Israel	15	0	1	16	1,719,944	170,809	8,381,516
Italy	1	35	7	43	24,451,688	11,251,367	60,627,291
Jamaica	0	0	0	0	749,828	124,176	2,934,847
Japan	2	0	2	4	18,370,787	16,430,235	127,202,192
Jordan	5	0	0	5	4,445,442	—	9,965,318
Kazakhstan	10	0	0	10	15,618,202	1,154,733	18,319,618
Kenya	9	0	11	20	25,386,794	388,200	51,392,565
Korea	8	1	9	18	15,230,382	11,332,812	51,171,706
Kosovo	1	0	9	10	8,836,806	—	1,932,774
Kuwait	11	0	0	11	2,558,216	—	4,137,312
Kyrgyzstan	7	0	1	8	5,147,138	229,748	6,304,030

(Continues)

TABLE A5 (Continued)

Country Name	# FMD	# ASF	# CSF	Total # Outbreaks	2018 Livestock Pop. (head)	2018 Swine Pop. (head)	2018 Human Pop.
Lao PDR	10	1	8	19	3,168,232	2,538,393	7,061,507
Latvia	1	10	2	13	794,214	486,130	1,928,459
Lebanon	11	0	0	11	1,237,385	10,855	6,859,408
Lesotho	0	0	0	0	1,069,171	71,429	2,108,328
Liberia	0	0	0	0	520,490	264,926	4,818,973
Libya	6	0	0	6	5,919,019	—	6,678,559
Lithuania	1	6	3	10	1,430,142	892,692	2,801,264
Luxembourg	0	0	6	6	245,148	159,924	604,245
Macedonia	1	0	7	8	1,156,435	145,000	2,082,957
Madagascar	0	7	9	16	5,141,526	932,251	26,262,313
Malawi	13	9	0	22	18,552,554	9,395,370	18,143,217
Malaysia	9	0	15	24	1,777,337	1,465,311	31,528,033
Mali	8	2	0	10	48,892,857	59,605	19,077,749
Mauritania	8	0	0	8	8,362,146	—	4,403,313
Mexico	0	0	10	10	36,743,298	18,526,707	126,190,788
Moldova	0	8	0	8	1,720,287	740,465	3,364,496
Mongolia	11	1	6	18	23,239,008	13,771	3,170,216
Montenegro	—	—	—	0	289,948	34,101	627,809
Morocco	5	0	0	5	18,794,043	12,868	36,029,093
Mozambique	9	9	0	18	5,250,678	2,279,523	29,496,004
Myanmar	14	1	7	22	25,369,278	12,506,464	53,708,320
N. Cyprus	0	0	0	0	—	—	1,266,676
Namibia	11	9	0	20	1,436,543	101,197	2,448,301
Nepal	11	0	9	20	13,294,059	731,435	28,095,714
Netherlands	2	1	3	6	19,713,748	15,246,163	17,059,560
New Caledonia	0	0	0	0	48,233	32,514	279,993
New Zealand	0	0	0	0	34,176,136	680,169	4,743,131
Nicaragua	0	0	8	8	1,834,069	235,600	6,465,501
Niger	9	0	0	9	14,487,751	33,480	22,442,822
Nigeria	8	12	0	20	55,522,573	6,306,518	195,874,683
Norway	0	0	0	0	3,658,387	1,703,823	5,337,962
Oman	8	0	0	8	3,840,898	—	4,829,473
Pakistan	8	0	0	8	81,482,184	—	212,228,286
Palestine	12	0	0	12	1,315,008	—	4,862,979
Panama	0	0	0	0	1,066,130	594,917	4,176,869
Papua New Guinea	0	0	0	0	2,042,330	2,014,729	8,606,323
Paraguay	5	0	1	6	4,722,134	2,315,343	6,956,066
Peru	5	0	9	14	8,688,064	3,090,907	31,989,260
Philippines	9	1	9	19	32,353,557	27,712,985	106,651,394
Poland	0	9	1	10	27,092,284	22,779,899	37,921,592
Portugal	1	9	1	11	7,468,718	5,550,127	10,256,193
Puerto Rico	0	0	0	0	203,382	62,137	3,039,596
Qatar	6	0	0	6	999,725	—	2,781,682
Romania	0	5	4	9	22,635,877	5,579,000	19,506,114
Russia	15	13	21	49	73,654,466	41,746,342	145,734,038

(Continues)

TABLE A5 (Continued)

Country Name	# FMD	# ASF	# CSF	Total # Outbreaks	2018 Livestock Pop. (head)	2018 Swine Pop. (head)	2018 Human Pop.
Rwanda	4	3	0	7	2,665,835	234,179	12,301,970
Saudi Arabia	10	0	0	10	11,380,905	–	33,702,756
Senegal	8	8	0	16	6,623,796	274,082	15,854,323
Serbia	0	2	1	3	8,546,858	5,744,543	8,802,754
Sierra Leone	1	0	0	1	694,055	34,131	7,650,150
Slovakia	0	1	10	11	1,141,768	638,317	5,453,014
Slovenia	0	0	2	2	683,313	325,354	2,077,837
Solomon Is.	–	–	–	0	66,555	60,011	652,857
Somalia	1	0	0	1	22,010,802	2,036	15,008,226
Somaliland	–	–	–	0	–	–	4,500,000
South Africa	18	14	0	32	13,676,415	2,802,484	57,792,518
Spain	1	9	5	15	70,682,711	52,289,200	46,692,858
Sri Lanka	9	0	6	15	817,561	19,077	21,228,763
Sudan	3	–	0	3	83,079,000	–	43,100,000
S. Sudan	3	–	0	3	41,875,603	–	10,975,927
Suriname	0	0	0	0	43,026	30,209	575,990
Swaziland	3	0	0	3	–	–	1,104,479
Sweden	0	0	0	0	3,664,910	2,646,040	9,971,638
Switzerland	1	0	3	4	4,085,305	2,568,789	8,525,611
Syria	3	0	0	3	18,745,765	–	16,945,057
Taiwan	1	–	–	1	–	8,073,454	23,603,049
Tajikistan	5	0	1	6	5,217,641	12,000	9,100,835
Tanzania	9	8	0	17	19,831,261	374,524	56,313,438
Thailand	9	0	7	16	14,239,826	13,362,014	69,428,453
Timor-Leste	0	1	1	2	392,111	289,726	1,267,974
Togo	6	7	0	13	1,547,062	325,220	7,889,093
Trinidad and Tobago	0	0	0	0	42,171	16,597	1,389,843
Tunisia	5	0	0	5	5,624,953	2,463	11,565,201
Turkey	12	0	0	12	61,302,557	–	82,340,088
Turkmenistan	3	0	1	4	11,100,463	4,625	5,850,901
Uganda	11	9	0	20	12,100,044	2,153,110	42,729,036
Ukraine	1	14	3	18	13,895,041	8,135,100	44,246,156
United Arab Emirates	8	0	0	8	5,891,091	–	9,630,959
United Kingdom	5	0	2	7	30,048,000	10,938,000	67,141,684
United States	0	0	1	1	170,883,118	124,512,300	327,096,265
Uzbekistan	1	0	1	2	19,875,506	236,828	32,476,244
Vanuatu	0	0	0	0	112,258	73,988	298,333
Uruguay	3	0	1	4	4,272,703	198,000	3,449,285
Venezuela	9	0	5	14	6,632,551	2,382,941	28,887,118
Vietnam	11	1	9	21	52,795,473	49,743,746	95,545,962
W. Sahara	–	–	–	0	148,828	–	567,402
Yemen	7	0	0	7	16,690,868	–	28,498,683
Zambia	13	16	0	29	3,194,712	741,874	17,351,708
Zimbabwe	13	4	0	17	3,942,135	323,713	14,438,802