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REVIEW

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Challenges and opportunities for using national animal datasets to support foot-and-mouth disease control

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Abstract

National level databases of animal numbers, locations and movements provide the essential foundations for disease preparedness, outbreak investigations and control activities. These activities are particularly important for managing and mitigating the risks of high-impact transboundary animal disease outbreaks such as foot-and-mouth disease (FMD), which can significantly affect international trade access and domestic food security. In countries where livestock production systems are heavily subsidized by the government, producers are often required to provide detailed animal movement and demographic data as a condition of business. In the remaining countries, it can be difficult to maintain these types of databases and impossible to estimate the extent of missing or inaccurate information due to the absence of gold standard datasets for comparison. Consequently, competent authorities are often required to make decisions about disease preparedness and control based on available data, which may result in suboptimal outcomes for their livestock industries. It is important to understand the limitations of poor data quality as well as the range of methods that have been developed to compensate in both disease-free and endemic situations. Using FMD as a case example, this review first discusses the different activities that competent authorities use farm-level animal population data for to support (1) preparedness activities in disease-free countries, (2) response activities during an acute outbreak in a disease-free country, and (3) eradication and control activities in an endemic country. We then discuss (4) data requirements needed to support epidemiological investigations, surveillance, and disease spread modelling both in disease-free and endemic countries.

KEYWORDS

data quality, disease preparedness, disease response, epidemiology, transboundary disease

1 | INTRODUCTION

A transboundary animal disease (TAD) is defined by the Food and Agriculture Organization of the United Nations (FAO) as an infectious disease of significant economic, trade and/or food security importance for a considerable number of countries that can easily reach epidemic proportions when it spreads into disease-free countries and for which disease control or management requires cooperation between several countries (Otte et al., 2004). An outbreak of such a disease can prove devastating to countries whose economies rely on the export of live animals and/or animal products due to the trade restrictions that are applied until proof of freedom can be established (Anonymous, 2013). As such, it is the responsibility of the competent animal health authority to prevent and prepare for outbreaks in disease-free countries and to eradicate, manage and report outbreaks in affected countries.

A relevant example of a TAD is foot-and-mouth disease (FMD), which is a rapidly spreading viral disease caused by a picornavirus that causes significant production losses due to high morbidity, but has very limited mortality (Alexandersen, Zhang, et al., 2003). The presence of FMD in a country limits the options for primary sector exports and so countries that are regarded as FMD-free have strong economic incentives to mount national eradication campaigns in the event of an FMD incursion. As highlighted by the 2001 FMD outbreak in the United Kingdom, the impact of the disease and the associated eradication efforts are profound at every level including effects on gross domestic profit, international trade, the primary sectors, human and animal welfare, tourism and the environment (Blake et al., 2003; Hayama et al., 2016, 2017; Hibi et al., 2015; Leslie & Black, 2006; O'Toole et al., 2002; Tildesley et al., 2012; Williams & Ferguson, 2005; Wilson & Kinsella, 2004).

In countries that are currently free of FMD, preparedness and response efforts are generally focused on preventing the introduction of FMD and minimizing the time from introduction to declaration of freedom should an outbreak occur. Countries where FMD has become endemic also generally wish to gain disease freedom since the impacts of subclinical production losses on food security and clinical production losses associated with the circulation of new strains are deemed to be substantial (Knight-jones & Rushton, 2013). In 2010, for example, it was estimated that the benefit to cost ratio of eradication of FMD from South East Asia was 3:1 (Mcleod, 2010). The losses attributed to FMD in South East Asia include lost work from draft animals and lost production at the household level, which both negatively affect food security and household income (Nampanya et al., 2015, 2016; Perry et al., 1999; Young et al., 2013). The control of FMD in endemic countries can also have positive externalities for disease-free countries by reducing the risk of FMD entry since border control and import regulations cannot completely eliminate the movements of high-risk products and fomites (Rweyemamu et al., 2008).

Irrespective of the current disease status of a country, it is important to have accurate baseline data on the numbers and locations of animal populations that are potentially susceptible to the TAD to adequately plan, resource and prioritize operations in the field as well as to quantify the amount of disease in a population (Buhnerkempe et al., 2014; Porphyre et al., 2013; Thrusfield, 2013; Woolhouse, 2003). In the unfortunate event of an incursion of a fast-moving disease like FMD in a disease-free country, it is essential to have these data available and in place prior to the introduction of this disease to maximize the possibility that the eradication programme does not transition to a control programme should the disease become widespread. In countries where FMD is already endemic, the availability of these population data will provide the basis for planning and progressing a control programme. Although these data are acknowledged to be important for disease control, maintenance of national databases is problematic. Even in countries where national databases exist, the quality and timeliness of the data are questionable (Honhold & Taylor, 2006; Jewell et al., 2015). In many developed countries, for example animal demographic and health data are collected for purposes other than biosecurity and protected by privacy legislation and so are not fit for purpose or not available for use. For controlling any infectious disease within a country, the ideal data situation would include linking of movement and demographic datasets in a region to enable a coordinated approach to disease control. There are significant legal and political challenges to such data linking activities, but without them, epidemiologists must rely on the results of population models or extrapolated surveys to furnish the essential population information. The challenges become even greater with TADs where it is also essential for countries to have knowledge about the animal population and disease status of trading partners as well as neighbours to make more informed decisions to manage the risks of disease introductions.

The result of having poor quality data on populations is that competent authorities are often required to make decisions about disease preparedness and control that may result in suboptimal outcomes for their livestock industries. It is important to understand the limitations of poor quality data as well as the range of methods that have been developed to compensate in both disease-free and endemic situations. Using FMD as a case example, we first review the different activities that competent authorities use farm-level animal population data for to support (1) preparedness activities in disease-free countries, (2) response activities during an acute outbreak in a disease-free country, and (3) eradication and control activities in an endemic country. We then discuss (4) data requirements needed to support epidemiological investigations, surveillance and disease spread modelling both in disease-free and endemic countries.

2 | PREPAREDNESS ACTIVITIES IN DISEASE-FREE COUNTRIES

2.1 | Surveillance to maintain disease freedom status

Similar to most other infectious diseases, FMD can broadly be diagnosed in three ways: (i) tests such as PCR or Antigen ELISA that detect the presence of the virus, (ii) tests such as Antibody ELISA that detect a susceptible host's immune response at some time in the past to the virus and (iii) the direct observation of compatible clinical signs (Alexandersen, Zhang, et al., 2003; Longjam et al., 2011). Diagnosis by PCR and Antibody ELISA requires samples either submitted to laboratories or analysed using pen-side tests (Longjam et al., 2011; Reid et al., 2001). In most disease-free countries, diagnosis based on clinical signs alone is not sufficiently accurate since there may other endemic diseases with similar clinical presentations that must be ruled out (Bates et al., 2003; Holliman, 2005; Watson, 2004). These tests alone or in combination are usually part of a larger active or passive surveillance system which provides the necessary level of assurance required for the country to fulfil its obligations to the OIE and trading partners (Tana, 2014).

2.2 | Identifying risk pathways for disease entry

Given the severe impacts of an outbreak of FMD and the fast spread of the disease, it is essential that the competent authority of a disease-free country have a policy framework in place in preparation for an FMD outbreak. The length of time between introduction and detection of a disease outbreak has a profound impact on the extent of the spread of any infectious disease outbreak. Especially in the case of a highly infectious disease like FMD, any delay between introduction and detection may result in a large number of additional disease cases (Bouma et al., 2003; Davies, 2002; Dubé et al., 2008; Ferguson et al., 2001; Muroga et al., 2012; Park et al., 2013; Yang et al., 1999) and substantial economic impacts (Hayama et al., 2013; Ward et al., 2009). The objective of surveillance for an exotic disease is then to direct the available surveillance resources towards the sector or geographic region where disease is most likely to be introduced and to perform surveillance in the manner which optimizes detection sensitivity (Garner, East, Stevenson, et al., 2016; Kompas et al., 2017). For example, in New Zealand, the risk of introduction of FMD is deemed highest by the pathway of illegal feeding of imported waste food to backyard pigs (Pharo, 2002) and being able to develop accurate risk models therefore requires data on importation of animal products as well as knowledge of the location and management practices of backyard pig operations.

2.3 | Predicting spread post-introduction

It is difficult to completely eliminate all risk of disease introductions and so the competent authorities are also interested in understanding how disease may spread after introduction to predict the potential size and scale of outbreaks. Spatially explicit stochastic disease simulators are widely used by FMD-free countries to assess the impact of hypothetical FMD outbreaks and different control options in naïve animal populations (Garner et al., 2016; Kitching et al., 2006; Roche et al., 2015). Spatially stochastic spread modelling of FMD has historically been centred in FMD-free countries and used to compare the costs and impacts of different control options in the event of an outbreak of FMD (Kompas et al., 2017; Roche et al., 2015; Sanson et al., 2017). The investigation of the early characteristics of large outbreaks is also of great interest (Sarandopoulos, 2015; Webb et al., 2017). These models are typically visual representations of the primary production sector with the location of farms, movement patterns and counts of susceptible animal populations used as starting parameters. This allows disease investigators to create different disease introduction, spread and control scenarios which can then be compared when making policy decisions.

These simulation models rely on accurately replicating disease transmission pathways, which can be difficult to predict without having information from past outbreaks in the country. FMD is able to be spread both by susceptible live animal movements and via mechanical contact with contaminated personnel, vehicles, fomites and wildlife (e.g., rats, mice and birds) (Alexandersen, Zhang, et al., 2003; Sutmoller et al., 2003). It may be possible to inform some parameters from previous outbreaks in other historically free countries and some from endemically affected countries. However, such an approach should be adopted with caution—much remains unknown about the between and within herd transmission rates due to varying animal population structures, movement patterns and country-specific farming practices. Disease spread is affected by the number of animals present on farms, as well as animal and vector movements that link farms to each other spatially. Modelled predictions of spread are affected by the scale of the model. For example, the use of polygon or farm-level area information as opposed to point features that represent the weighted centroids of farms may affect model predictions of spread (Flood et al., 2013). In the event of prioritization of farms to receive surveillance visits, those with a boundary that is shared with an infected premises (IP) can be expected to have higher priority than those in close proximity, but not sharing a fence line.

Although some of these models have been refined over many years, most still require specialized expertise as well as many input parameter values to run (Owen et al., 2011). Animal population estimates will have variable effects on the model outputs depending on how susceptible populations are used in the spread simulation and the economic component of the model (Keeling et al., 2001; Porphyre et al., 2013; Shea et al., 2014). For example, in the Australian Animal Disease spread model (AADIS) (Bradhurst et al., 2015) the population of animals on each farm is used to generate infectivity for each farm according to latent periods, within herd contact rates and incubation periods specific to the species and numbers of each species present; this creates a unique probability of transmission curve for each farm based on its population. In the disease spread simulator InterSpread Plus (ISP) (Stevenson et al., 2013), a probability of transmission curve is applied to each farm type based on the average size (in chosen number of geographic strata) of a herd of a particular type.

Advances in modelling techniques and increased computational ability have resulted in the current trend in veterinary epidemiology of using individual animals to generate infectivity at the farm-level by the inclusion of intraherd spread within disease spread simulators. Due to this high level of detail at the farm level, these models are being used to evaluate the impacts of management decisions at a microeconomic level on individual farms and to address the effects of vaccine strategies, false-positive results and test and removal control strategies for some diseases. Livestock density strongly influences the farm-level reproductive number used in these models (Porphyre et al., 2013) and can only be estimated for a particular farm by knowing the count of animals present on the property. Porphyre et al. (2013) further show that it is the spatial variation of these farm-level reproductive numbers that best inform a decision to deploy vaccination for FMD in the United Kingdom, along with knowledge of the circulating strain of virus.

In situations where it is not possible to survey every farm in a population, risk-based surveillance is an option. The rationale is that failure to detect disease in a high-risk subgroup at a specified design prevalence provides greater confidence of freedom from disease than a random sample of the whole population at the same design prevalence (Astudillo et al., 2016; Caporale et al., 2016). However, to use this technique, the population demography is a prerequisite and the integration of animal movement patterns is common (Frössling et al., 2014; Frössling et al., 2012, Gates, Volkova, et al., 2013; Gates, Woolhouse, et al., 2013; Gates & Woolhouse, 2015).

In countries where disease is endemic, the competent authority must have existing knowledge of where disease is located before any model can be parameterized. In the absence of such a model (or whilst such a model is being developed), decisions must be made about deployment of control efforts. In endemic disease situations where some historical data are available, maximum likelihood models and machine learning models can be used to predict outbreaks based on the presence or absence of risk factors. Logistic regression is considered to be a standard approach to predicting a binary outcome (e.g., outbreak in the period of interest or no outbreak in the period of interest) especially when modelling is undertaken not only for prediction but also to describe and increase understanding of risk factors that could cause the outcome of interest (Langford et al., 2009). By contrast, the random forest (RF) prediction algorithm (a machine learning technique) is focused on prediction rather than explanation of risk factors. Furthermore, RF models have been found to out-perform logistic regression models in cases where prediction is the primary goal of the modelling activity (Breiman, 2001; Brownstein et al., 2005; Cutler, 2007; Nicolas et al., 2016; Prasad et al., 2006).

3 | IMPACTS OF INCOMPLETE DATA ON POLICY DECISIONS BASED ON SPREAD MODELLING

There is an increasing body of literature related to the impacts of missing and/or inaccurate data on simulation modelling of disease spread. This work focusses for the most part on comparing methods such as multiple imputation to predict missing data that ensures maximal model performance. Both animal movement networks and farm locations have been studied in this way. It has been found that a realistic entire animal movement network can be predicted using targeted node surveillance or snowball sampling techniques. The authors point out that the method has some limitations in application to entirely unknown networks as it is not possible to know when sufficient nodes have been sampled to accurately predict the entire extent (Dawson et al., 2015). When exact animal locations are not available, land cover maps can be used to infer the location of the susceptible population (Burdett et al., 2015; Louz et al., 2013; Tildesley & Ryan, 2012). The performance of this method varies based on the scale of aggregation with larger aggregations performing less well than small scale ones (Tildesley & Ryan, 2012). When these modelled populations are included in disease spread simulators and policy options compared, it is possible to make policy recommendations that would be the same as those made with disaggregated data in some cases (Tildesley et al., 2010); however, this ability is specific to the question at hand and the parameterization of the model being used (which includes country-specific factors that influence disease spread). Other studies focus on the value that perfect information adds to a response to an infectious disease by identifying where more information should be collected as a part of preparing for an outbreak (Bradbury et al., 2017; Shea et al., 2014), which helps us to identify optimal control strategies in the event of uncertainty during the early stages of emerging outbreaks.

All of these studies provide essential insight into the functioning of our model frameworks, our available data sets and the biases that could be introduced into preparedness planning as a result of incomplete and flawed data. What these studies cannot do is provide data that are sufficiently nuanced for operational purposes in the field when a disease outbreak occurs.

4 | RESPONSE ACTIVITIES DURING AN ACUTE RESPONSE IN A DISEASE-FREE COUNTRY

4.1 | Contact tracing

Disease control policies must be developed prior to the identification of an outbreak as field activities will have to be implemented urgently upon disease emergence. In particular, the immediate establishment of movement controls and controlled areas can greatly limit the spread of an FMD disease outbreak (Carpenter et al., 2011). Although all possible efforts should be made to develop a robust policy framework prior to the discovery of an outbreak, some strategic changes in direction will be required as the outbreak progresses and data from field operations become available. The ability to process and analyse the outbreak data in real time allows decision makers to strategically evaluate control policies and make appropriate changes (Mansley, 2004). Epidemiologists employed by the competent authority for biosecurity provide information and reports to decision makers on progress of disease control activities and advise on strategic and operational changes that could be implemented in the field to improve outcomes. These reports will include advice of whether an outbreak is under control (Ferguson et al., 2001; Paine et al., 2010) and inform policy adjustments in the face of an outbreak. Ongoing real-time analysis of testing data is also required.

It is clear that not all farms will present the same risk of onward spread of disease. In particular, the number and different species of animals present on the farm as well as the characteristics of the animal populations in the immediate surrounding area are important with risk usually estimated as function of Euclidean distance from an infected farm. Similarly with live animal contact tracing and fomite tracing, those farms with the presence of large numbers of virus excretors or those with many contacts should be prioritized for immediate visits (Eames & Keeling, 2003). Farms in close proximity to infected premises are known to be at higher risk of infection and authorities will often use an arbitrary 3 km radius cut-off value to prioritize which farms are visited by surveillance teams during a response. However, evidence suggests that those farms which share contiguous borders are at even greater risk than those which are nearest neighbours but one or those separated by a road or other geographic feature and should be visited first (Flood et al., 2013; Gibbens et al., 2001; Thrusfield et al., 2005). In addition to geographic proximity, those farms with large numbers of links to and from other farms act as hubs in the network of movements formed by farming practices. These farms with high in and out degree are important sentinel sites and provide information about unrecognized disease circulating in the population. These farms can act as a proxy for large numbers of farms which supply animals and are of particular value following eradication of all known infectious premises when scanning of the population is being undertaken to gather evidence of disease freedom in the population (Caporale et al., 2016; Gates, Woolhouse, et al., 2013; Gates & Woolhouse, 2015; Schärrer et al., 2015).

4.2 | Epidemiological investigations

The situation and best course of action can change very rapidly during a fast-moving disease response particularly as new data about the disease and the population at risk become available. It is therefore essential that field priorities are continuously reviewed and the updated priorities communicated to the field control centres for implementation (Bessell et al., 2010a; Mansley, 2004). As an example, those properties with intensively housed pig populations within a 3km surveillance zone around a property that has been infected with FMD may be visited first due to the high risk of aerosolized virus attributed to pigs. These results should be examined in combination with climatological modelling of viral plume spread to gain further information on properties at highest risk. Populations of animals present on the source farm, populations of animals present on farms under the modelled plume and the prevailing weather conditions are required to complete this analysis (Alexandersen et al., 2002; Alexandersen and Donaldson, 2002; Bessell et al., 2010; Donaldson et al., 2001; Hess et al., 2008; Sanson, 1994; Sorensen et al., 2000).

A further source of surveillance data during an outbreak response to FMD is the investigation of disease reports by the public. Each of these trace events must be documented, assessed for the risk they present, and then followed up with field visits when appropriate. The disease investigator on the farm must collect the movement and demographic information, and clinically examine and sample an appropriate subset of animals on the farm to adequately determine the true disease status of the farming operation (Alexandersen, Kitching, et al., 2003; Cleland et al., 1995; Thrusfield, 2013). Until these investigations are completed, the suspect farms as well as other holdings which present the same level of epidemiological risk because of spatial or movement contacts are often treated as infected premises to reduce the chances of onward disease spread (Brangenberg & van Andel, 2011).

4.3 | Evaluating control strategies

4.3.1 | Test and cull

Once FMD is identified in a historically free country, depopulation with accompanying cleaning and disinfection of all fomites in contact with the farm are required immediately to limit the potential for onward disease spread. This urgency relates to the infection pressure that a single farm infected with FMD presents and the fact that the spread of FMD may occur aside from recorded animal or vector movements to nearby farms. This unclassified spread over short distances has at times been labelled under the heading “local spread” due to a lack of resources to investigate every infectious event. Failure to have sufficient sites available to bury infected animals resulted in disease spread in Japan which delayed eradication efforts (Flory et al., 2017; Hayama et al., 2012; Muroga et al., 2013). Aside from immediate impact on disease spread, insufficient planning for associated disposal activities has numerous impacts that may extend many years after the end of an outbreak and can include economic losses, groundwater contamination and air pollution from burial sites (Gwyther et al., 2011; Hseu & Chen, 2017; Joung et al., 2013; Kim and Kim, 2012). Alternative strategies to burial include composting, high-temperature gasification or the negotiation with government bodies regarding the transportation of carcasses across multiple regions to reach suitable landfill sites. These negotiations must be informed by geospatial analyses to compare livestock densities with local capacities to bury or burn carcasses to identify areas that require special measures.

4.3.2 | Vaccination strategies

Various FMD vaccination policies have been explored by disease-free countries using spread modelling including single species vaccination, zonal vaccination, vaccinate-to-live (VTL) and vaccinate-to-die (VTD) policies. Models of hypothetical FMD outbreaks have returned conflicting results regarding the benefit of vaccinating cattle only (Roche et al., 2015; Sanson et al., 2017; Tildesley et al., 2006). Laboratory transmission studies have shown that cattle and sheep are equally susceptible to FMD virus infection, but cattle are more infectious than sheep (de Rueda et al., 2014). From an epidemiological perspective, there might be merit in vaccinating cattle in preference to sheep in order to reduce transmission rates in the population when vaccination resources are limited. In New Zealand, livestock industries are primarily focused on sheep and cattle farming. As cattle and pigs are better indicator species for FMD than sheep and goats, cattle-only vaccination may mask infection in an area where diagnosis of disease was dependent on clinical signs. This could delay eradication or interfere with proof of freedom surveillance testing after an outbreak. If vaccinating cattle only were to be shown to be equally effective as vaccinating all species, this could result in substantial savings in the number of vaccine doses required to confer benefits and decrease the number of animals to be destroyed in “vaccinate-to-die” policies.

The options for vaccination under the OIE code for historically FMD-free countries with animal and animal product export markets are limited to either a VTL or VTD policy (Anonymous, 2017). Under the former policy, vaccinated animals continue to be farmed normally for the duration of their productive lives, and the country seeks to prove to the Office International des Épizooties (OIE) that is it "free from FMD with vaccination". The latter means that the vaccinated animals are slaughtered as soon as there is culling capacity available, and the country seeks to then prove that it is "free from FMD without vaccination". Under a VTD policy, vaccinating animals places a near-immediate death sentence on them. The associated costs, including loss of genetic material, compensation to farmers, time to depopulate and dispose the animals following the epidemic is expected to be very high. In these cases, vaccination would likely be deployed around infected farms to stop local spread of the disease and would be deployed from the outside of an agreed size circular zone inwards. The OIE allows countries to regain disease freedom 3 months after culling all vaccinated animals (although importing countries may still take longer to restore trade) if a country adopts a VTD policy (Anonymous, 2017). Under a VTL policy, a country can only regain FMD freedom 6 months after the last case is identified and surveillance on all vaccinated animals is completed. The objective of this surveillance is confirmation that no infection is present in the national herd. A blanket vaccination strategy that supplied complete coverage with a trusted vaccine was successful at ending the 2001 outbreak in Argentina (Knight-Jones et al., 2016; Perez et al., 2004) and similar approaches have been successful at ending outbreaks in large parts of Brazil, Chile and Uruguay (Barteling & Sutmoller, 2002). Under the current OIE regulations, the fast and aggressive use of vaccination, which maximizes the usefulness of its deployment, is unattractive to decision makers who must minimize the length of the outbreak to rapidly return to trade (Roche et al., 2015). This must be weighed against the impacts of a VTD policy.

Under specific circumstances, it is possible to practise zonal vaccination for FMD and for the remainder of the country to be declared free of disease without vaccination by the OIE, thus allowing international trade in animal products. This is the case in South Africa where the South African Territory (SAT) strains of FMD are endemic in the Kruger National Park and surrounding reserves. These strains are maintained in Africa Buffalo *(Syncerus caffer)* and the disease is successfully contained by the maintenance of game proof fences, vaccination of susceptible cattle in the directly proximal area (known as the buffer zone) and maintenance of a surveillance zone between the buffer and the rest of the country (Bruckner et al., 2002, Bruckner et al., 2004).

5 | ERADICATION ACTIVITIES IN FMD ENDEMIC COUNTRIES

5.1 | Progressive control pathway framework

To address the situation of FMD endemic countries, the OIE has created the progressive control pathway (PCP), which allows the countries to step towards freedom (Rweyemamu et al., 2008; Sumption et al., 2012) by participating in a 7 stage programme which can run over 30 years (Rweyemamu et al., 2008). The first stage requires the disease distribution and epidemiology in the country be described and assessed at the country level. Once this is adequately understood, movement control and vaccination can be sensibly instituted (stage 2). The purpose of stage 2 is to establish disease-free zones and to develop strategies in both the free and infected areas. Stage 3 has the objective of suppressing virus transmission by preventing clinical disease. During stage 4, the country applies to the OIE to be recognized as free from FMD with vaccination in designated zones. In stage 5 the objective is to transition the designated zone from free with vaccination to free without vaccination. This is followed by expansion of the free zones (stage 6) and prevention of reintroduction of FMD (stage 7). The South-East Asia and China FMD (SEACFMD) Campaign implements the Food and Agriculture Organization of the United Nations (FAO) and World Organization for Animal Health (OIE) Global FMD Control Strategy based on the Progressive Control Pathway (PCP) for Foot and Mouth Disease (Jamal & Belsham, 2013; OIE and FAO, 2012; OIE World Organization for Animal Health, 2016).

For those countries where FMD is endemic the PCP offers a framework to move towards disease freedom. Stage 3 of the PCP suggests the use of vaccination to limit clinical disease expression and production losses in particular sectors or regions. Recent examples are the pig industry in the Philippines and Thailand (Gleeson, 2002) with the Philippines having recently obtained FMD-free status. The objective of the PCP is for small regions to be expanded over time so that the countries are eventually able to become FMD-free (Abila & Foreman, 2006). Some countries vaccinate in endemic zones to control spread to free areas. This is the case in South Africa where SAT strains are endemic in wildlife (Bruckner et al., 2004). In these cases, the prioritization of resources is essential if zones are to be established and successfully maintained. In those countries with endemic disease, the value of vaccination should be examined by collection of information on household level economic factors especially where vaccination is being done outside of commercial enterprises. The value of vaccination in dairy cattle has been documented in Vietnam at the householder level at a benefit to cost ratio of 3 (CI 0.76–7.19) and even less for beef cattle in the same country (Truong et al., 2018). The clinical signs of FMD in endemic regions where large numbers of carriers are present and endemic strains are circulating are not particularly well described in the literature (Bertram et al., 2018) but are expected to be less dramatic than those seen in naïve populations (Kitching, 2002). In addition, there is widespread recognition that disease reports made by human observers are by no means perfect indicators of disease presence or absence—they vary based on the disease under investigation, the individual surveyed (e.g., knowledge and experience) and the production system (Bellet et al., 2012; Morgan et al., 2014; Vergne et al., 2012). In addition to this, even in disease-free countries, the presentation of FMD may be indistinguishable from endemic differentials (Bates et al., 2003).

For developing countries (many of which have endemic FMD), resources to perform disease testing on large scale and the logistical difficulty of obtaining reagents and getting samples to laboratories can prove to be prohibitive. In these limited conditions, verbal disease reports may be used as a source of surveillance information and may provide additional insights about the extent of clinical disease that cannot be gained from serology alone (Goutard et al., 2015; Muellner et al., 2016; Robertson et al., 2010; Sawford, 2011). When the disease distribution in a country is uncertain, the direction of resource to the sector which will benefit most becomes challenging and the external validity of surveys is difficult to establish.

The testing strategy deployed during the delimiting, eradication and proof of freedom phases of an FMD outbreak will in part be informed by the sample numbers required and the capacity of the national laboratory to process large volumes of samples. A strategic decision must be made (preferably prior to any outbreak) relating to diagnoses based on clinical signs versus the presence of DNA or serological disease markers. Return to trade relies on the testing of large numbers of serum samples as specified by the OIE. In the case of FMD, whilst "vaccinate-to-live" policies are attractive from a compensation and disposal point of view the delay in return to trade and the extensive DIVA (differentiating infected from vaccinated animals) testing has to be considered when considering the viability of such a policy (Caporale et al., 2016; Longjam et al., 2011; Paton et al., 2014, Paton et al., 2009).

5.2 | Data requirements for FMD preparedness

In the context of livestock diseases, the basic building blocks of field operations and preparedness for disease response include knowing the locations, counts and movement patterns of all individual animals in the national herd (Forman et al., 2012; Riley, 2010). The availability of these data at the country level varies greatly, from countries that have mandatory centrally held agricultural property and animal movement databases to countries where no information on animal movements or farm locations exist. Every permutation and combination of voluntary, mandatory, regional and national system exists between these two extremes (Cheneau et al., 2004). Even amongst those countries with central property databases there are those that have property boundaries recorded (as spatial polygons) and those that record the property centroids.

Countries with a single mandatory national farm and livestock population database available for TAD preparedness and response are limited to a relatively small number of developed countries. Most competent authorities must amalgamate data from various sources to populate disease spread models or augment their existing preparedness data with data collected during response operations for the purposes of disease control activities in the field. In some countries industry sectors would share information related to farm populations and locations at the time of an outbreak.

In multi-jurisdiction countries, field operations are generally managed at the regional/state/provincial/territory level, whilst disease spread modelling for preparedness purposes typically happens at the federal level. This difference means that there may be disparities at different levels in access to datasets and that preparedness and operational activities may be done using different data. When national datasets are available, the data contained within the databases may not be up to date or the data may have been collected for purposes other than disease control, limiting its use in supporting epidemiological investigations (Honhold & Taylor, 2006; Jewell et al., 2015). As an alternative to these national data sets, cross-sectional surveys can be performed, but these are constrained by resources to perform them at a sufficiently large geographic scale and it may be difficult to extrapolate the findings from one or more regions or time periods to other situations. Expert opinion has frequently been used when data are not available and strategies for making the best use of expert opinion and eliciting unbiased estimates have been well described (Burgman, 2015). Techniques for combining survey data, national level information and local knowledge exist so that all sources may be included (Sumption et al., 2008).

In a country where primary sector exports make up a significant part of GDP, preparing for a catastrophic situation that an outbreak of FMD would present is essential. However, reaffirmation of the value of investment in these activities is needed in a resource scarce economy. The United Kingdom Rapid Analysis and Detection of Animal-related Risks (RADAR) was established in the wake of the 2001 FMD outbreak when it became clear that population information available to the competent authority was not fit for purpose(Paiba et al., 2007). RADAR created a way to rationalize animal location, population, movement and disease data in a central data warehouse. Although funding for RADAR has been scaled back, they continue to work closely with researchers to provide support where possible.[1] A way to quantify the value of accurate and timely animal population and movement data is urgently required. Whilst economic modelling that includes both farm and country level detail provides an indication of the cost of an incursion of disease, information on the additional cost that would be incurred if data are missing or inaccurate and the magnitude of the harm caused by these data is difficult to quantify (Forbes & van Halderen, 2014; Garner et al., 2016; Kompas et al., 2017; Mitchell, 2003; Van Andel et al., 2018).

Animal movement databases enable the rapid tracing of animals to and from infected premises and are essential to identify population level movement patterns. These patterns include regional differences in movement volumes and high-risk locations which could be targeted for surveillance activities. The alternate to having an national animal movement recording system is for interviewers to collect movement information at each infected premises for the purposes of disease outbreak response and for national level surveys to be completed to identify movement patterns (Sanson, 2005). The time consuming and manual nature of these activities had led to uptake of centralized animal movement databases. However, the benefits of national level movement databases can only be realized if the data are complete and well understood. Incomplete data can be used appropriately only if the limitations are known. In this case, additional time and resource will be required to amalgamate additional sources of information with the existing national records to effectively trace and contain disease spread. The success of animal movement databases requires the full cooperation of the farming sector along with intelligent integration of the technological solutions at critical control points in the production system to streamline collection of information. Establishing such a system is resource intensive and demands that both the drivers for reporting of animal movements and the requirements of the farming sector and the data users are fully understood. Restrictive legislation, lack of consultation with system users and ignorance of farming practices will result in the failure of such a system or at the very least in complicated and expensive retro-fitting of solutions after implementation has already occurred. It is important to note that all ungulates are affected by FMD virus and are able to infect individuals of other species. This means that maintaining an integrated single system for cattle, deer, sheep, pigs and goats will be mandatory for a successful FMD response.

6 | DISCUSSION

This review has highlighted many of the challenges associated with conducting disease preparedness and response activities in countries with missing or incomplete data on animal populations using FMD as a case example. The daunting extent and complexity of preparedness and eradication activities for FMD are widely documented and the high costs and far-reaching consequences of these activities can be described in detail (Forbes & van Halderen, 2014; Honhold et al., 2004; Mansley et al., 2016; Wada et al., 2016). Yet despite this awareness of the importance of FMD control, the suitability and accuracy of the national data sources used during such activities have seldom been assessed or discussed as highlighted by our review (Honhold & Taylor, 2006; Jewell et al., 2015). There is also currently even less information in the literature on the impacts of data quality on other transboundary animal diseases such as bovine tuberculosis that spread over much longer time scales and have very specific animal-level and herd-level risk factors that drive the epidemiology unlike FMD which spreads rapidly and indiscriminatingly between livestock. Consequently, we anticipate that the preparedness and response efforts for these diseases will be disproportionately more affected by the lack of good quality data, but further research that considers the nuances of each disease is needed.

Given that the data are time-consuming and resource intensive to collect and maintain, the question arises of how much resource should be allocated to the activities surrounding their upkeep. When deciding how much to invest in their upkeep, it is important to understand how large the impact of inaccuracies on decision-making could be (van Andel et al., 2018; Wada, Carpenter, et al., 2016). Inaccurate data causes delays to field operations which can extend the duration of an outbreak, cause confusion and distress to farmers and embarrassment to the competent authority. Undesirable as these are, the effect is acknowledged and potentially quantifiable (Carpenter et al., 2011). The effect of inaccurate data on preparedness activities is more difficult to quantify (Bradbury et al., 2017; Jewell et al., 2015; Probert et al., 2015, 2018; van Andel et al., 2018). If the impacts on both operations and preparedness could be adequately quantified, an estimate of the value of national farm movement, population and location databases could be obtained. This estimate could then be compared with the cost of the maintenance of such databases in a traditional cost-benefit analysis.

Such an analysis would need to take into account that ongoing upkeep of the national data resource is essential as it is required for preparedness activities. Although disease control field activities will be performed on an ongoing basis; however, it is essential (in the case of an FMD-free country) that those who perform these activities are familiar with them so that they can be performed quickly under stressful conditions. The best way to ensure this is for the participants to regularly practise these activities and for preparation to focus on the availability of the necessary data and development of appropriate systems, processes and capacity before an incursion. All of these tasks depend on a knowledge of the size and location of the animal populations so that adequate human resources can be deployed to efficiently perform the tasks at hand. Accurate information on how many livestock and what species are present is essential information at disease control centres and the information must be updated in real time to ensure that the right people and supplies are deployed on visits and so that targeting and prioritizing of surveillance, vaccination, culling and cleaning and disinfection activities is optimized especially since any control activities fit within limited resources.

One way to improve data quality in a fragmented data landscape is to attempt the linking of different levels of nationally held data (Jewell et al., 2015; Paiba et al., 2007). Whilst technically attractive as a solution, the costs and complexities of government levels and legal restrictions on the use of different data sources make the maintenance and linking of these data sets in real time from multiple sources unfeasible for most countries. The technical difficulties inherent in linking datasets which are collected for varying purposes and have inherent biases are complex and may in some cases not be possible to resolve (Paiba et al., 2007). An alternate to data linking is the use of statistical and geospatial techniques to simulate farm sites and animal counts from census and survey information for national preparedness (Burdett et al., 2015; Hollings et al., 2017, 2018; van Andel et al., 2017). This is a logical and responsible choice for the competent authority in the case of animal population information when it is not available elsewhere. In the case of animal movement information (where databases are not available to analyse), surveys and expert opinion must be used to fill the information gaps that exist.

Even with perfectly up to date and accurate national data available, any strategic policy choice in a country that does not have FMD can only rely on models which provide an estimate of variability and indicate the comparative outcomes of different control options (Kitching et al., 2006). The extent of the mismatches and inaccuracies in national level databases are most often only realized during a disease outbreak of national concern. The 2001 FMD epidemic in the UK came under intense scrutiny by the public and academics with some authors suggesting that decisions based on the models may have changed if researchers had made different assumptions about the population demographics and changing infectiousness within individual farms over time (Savill et al., 2007; Tildesley et al., 2010; Tildesley & Ryan, 2012). However, this only speculation in hindsight and aside from these policy decisions, the impacts data quality and model assumptions on field operations are well documented even if the size of the impact is not quantified (Honhold & Taylor, 2006).

7 | CONCLUSIONS

This review has collected a cross section of epidemiological uses for nationally held animal demographic and animal movement information in the context of FMD eradication programmes. Sufficient evidence exists to accept that animal demography and up to date animal movements are essential for the veterinary government authority to adequately perform its function both in an endemic and disease-free situation. Urgent improvements to data systems are required to create an environment that encourages the contribution of essential data by producers and this must be supported by adequate investment by regulators to curate, store and streamline this resource. Only when there is a single coherent source of unbiased animal demographic and animal movement data can the biosecurity authority hope to fulfil its responsibilities.

ETHICAL STATEMENT

An Ethical Statement is not applicable as no sample collection was required for this study, and no questionnaires were administered for this study.

DATA AVAILABILITY STATEMENT

The peer-reviewed literature that supports this review article are available in the Web of Science. No data sets were required for this review article.

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ENDNOTE

[1] Email communication with Helen Gartner, Helen.Gartner@apha.gsi.gov.uk on 14 July 2015.

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