U.K. Foot and Mouth Disease: A Systemic Risk Assessment of Existing Controls

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This article details a systemic analysis of the controls in place and possible interventions available to further reduce the risk of a foot and mouth disease (FMD) outbreak in the United Kingdom. Using a research-based network analysis tool, we identify vulnerabilities within the multibarrier control system and their corresponding critical control points (CCPs). CCPs represent opportunities for active intervention that produce the greatest improvement to United Kingdom's resilience to future FMD outbreaks. Using an adapted 'features, events, and processes' (FEPs) methodology and network analysis, our results suggest that movements of animals and goods associated with legal activities significantly influence the system's behavior due to their higher frequency and ability to combine and create scenarios of exposure similar in origin to the U.K. FMD outbreaks of 1967/8 and 2001. The systemic risk assessment highlights areas outside of disease control that are relevant to disease spread. Further, it proves to be a powerful tool for demonstrating the need for implementing disease controls that have not previously been part of the system.

KEY WORDS: Disease; FMD; foot; mouth; network; risk; systemic

1. INTRODUCTION

Foot and mouth disease (FMD) is an exotic animal disease (EAD) classified as notifiable by the World Organisation for Animal Health.[1] The disease is caused by the FMD virus (FMDv), of the *Aphthovirus* genus and *Picornaviridae* family[2–4] with manifestations ranging from acute to mild and subacute forms, in cloven-hoofed animals, e.g., cattle,

pigs, sheep, and deer. Under certain conditions, damp soil and cold temperatures, FMDv can persist for over a month outside its host, and plumes of virus within droplets can travel over long distances,[5] all of which can contribute to the spread of infection across large distances. Cattle, sheep, and pigs can be infected through inhalation of virus particles, ingestion of FMDv particles from contaminated food, contact with fomites, e.g., vehicles and people, and direct contact with infected animals.[4,6] As a result, infection tends to spread quickly through multiple mechanisms making the control of widespread infections challenging.[6] Morbidity and mortality rates vary according to the species infected and the virulence of the strain.[3,4]

Outbreaks of FMD can result in severe economic losses, from the cost of essential eradication measures, lost market share and impacts to tourism.[7–9] The United Kingdom maintains a multibarrier system that seeks to prevent the introduction

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of EADs such as FMD into the country. The system of controls comprises the collaborative actions of a partnership of government organizations and independent agents; for example, the Department for Environment, Food and Rural Affairs (Defra), local authorities, Border Force, wildlife conservation groups, farmers, and veterinarians.[10] Working independently, these agents operate a complex network of protection barriers to prevent the transmission of EAD, including FMD, that operates as a whole system.[11] The system purposefully incorporates an element of redundancy, to ensure that multiple opportunities for detection and elimination of an FMD outbreak are available from source to receptor. This increases protection against a multitude of possible transmission routes.[12] However, occasional outbreaks do occur, such as those of 2001 and 2007 (for the United Kingdom), which exposed vulnerabilities in the multibarrier system.[7,13–15] Since then, significant effort has been made to increase awareness of U.K. vulnerabilities to FMD in order to reduce the chances of a future outbreak.[10] However, reports suggest that developed countries may still be vulnerable to the threat of FMD and other EADs.[8,16,17]

Government is responsible for developing and enforcing regulations that reduce the United Kingdom's vulnerability to FMD alongside other EADs.[10] Analysis of the existing system of controls for policy development needs to consider the extent to which current practices are either effective; could be enhanced, or where priorities should change focus of attention to new areas for active intervention. Improvements require the prioritization of possible failures that might drive exposure to FMD of susceptible livestock. Critically, these priorities must be risk-informed and reflect the entire system. Securing this insight involves developing a comprehensive analysis of the systemic interactions between FMD and the points of potential failure within the multiple-barrier system, using a systemic risk assessment.[11]

Here, we present a systemic risk assessment for the introduction of FMD into the United Kingdom. The objectives of this research were the identification of vulnerabilities within the multibarrier control system and corresponding critical control points (CCPs). CCPs represent opportunities for active intervention that produce the greatest improvement to United Kingdom's resilience to future FMD outbreaks.[18] The expectation is that this approach to developing priorities can inform decisions about resource allocation for risk management.[18]

2. METHOD

We applied the systemic model of Delgado *et al.* (2013) and increased the level of detail with which the outputs are produced.[11] In its current format, this is a research model that provides an analysis of all pathways of exposure available within the conceptual representation of the U.K. livestock system using a network to represent the system (Fig. 1). The network considers the frequency of movements and the effectiveness of barriers to transmission between nodes. This includes legal, illegal movements, and airborne transmission, as the base for characterizing system behavior. A series of sensitivity analyses was applied to the network, allowing the identification of those nodes and arcs with the greatest influence on the system's performance. These represent the CCPs, indicating where intervention might be most effective.[11,18]

2.1. Description of the System

The network is a representation of the system describing (i) the collection of entities influencing transmission, which by interacting with the FMDv establish a connection linking the FMD source to a susceptible receptor. The network then (ii) describes the controls and regulations in place that these entities and stakeholders must uphold to interrupt connections between the source and receptors, and so prevent exposure. Entities include several components of the livestock and meat industries, facilities for trade, human population, and pet-shops, as well as a range of control processes.[10] The system considers three disease sources, where pathways must begin and for the purpose of this assessment, where FMDv is present, confirmed and contingency measures put in place. These are represented by the nodes: (1) 1.1 World (all remaining countries)/non-EU trading partners/bilateral; (2) 1.2 European Union and trading partners (Positive) (i.e., EU member country with a confirmed outbreak, and where measures are in place to prevent spread); and (3) 1.3 Laboratories. European countries where an outbreak is present but not yet detected are defined as 2.1 European Union & trading partners (negative—disease free status) and are not a considered source but part of the pathway. The system also allows the analyst to consider nine possible final receptors, which are broadly representative of different husbandry practices, where pathways must end and thus represented by the nodes. (1) 3.1 Pig Indoor production
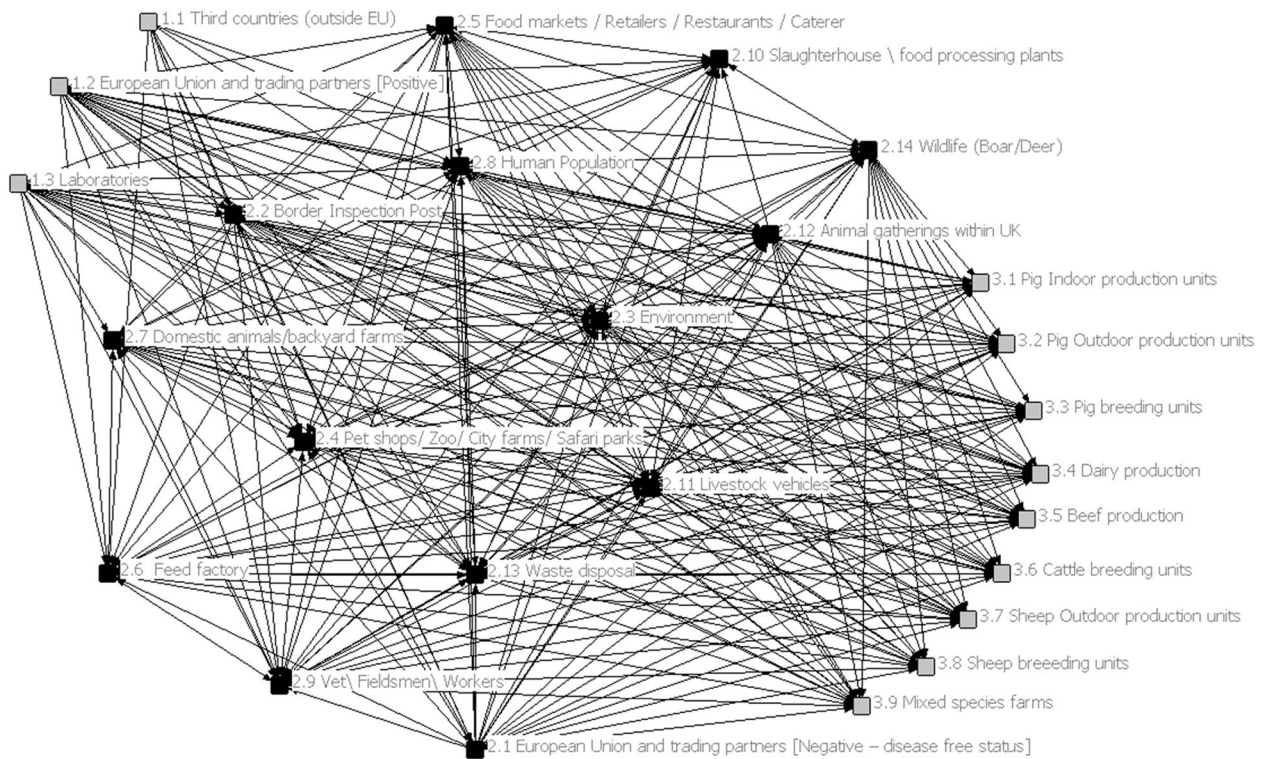
Fig. 1. The network system developed for foot and mouth disease (FMD). Nodes starting with 1 represent disease sources (gray), nodes starting with 2 represent full functioning nodes (black), and nodes names starting with 3 represent terminal nodes (gray)

units; (2) 3.2 Pig Outdoor production units; (3) 3.3 Pig breeding units; (4) 3.4 Dairy production; (5) 3.5 Beef production; (6) 3.6 Cattle breeding units; (7) 3.7 Sheep outdoor production units; (8) 3.8 Sheep breeding units; and (9) 3.9 Mixed species farms (Fig. 1). The different receptor categories were informed by experts and represent production systems with different biosecurity challenges and expectations. The system is constructed using a "features, events, and processes" (FEPs) list.[19,20] The FEP list records the network nodes as features, network arcs representing activities enabling transmission recorded as processes, and the incidents driving failure to detect and eliminate the disease agent are recorded as events. Disease transmission between two nodes requires the combination of a process and an event, referred to here as process/events.[11] For example, a border inspection post is the node, the process is the release of meat goods to food markets/retailers, and the event is failure to detect contaminated meat. This systemic approach allows discrimination between transmission movements associated with legal and illegal activities, and airborne transmission of the disease agent. Up to three separate process/events can be

associated with a connection between two adjacent nodes.

2.2. The Interaction Matrix

The analytic foundation of the model is the network (Fig. 1) represented by an interaction matrix (Fig. 2). In the matrix, diagonal cells (black) correspond to nodes and the off-diagonal cells (white and color) correspond to arcs. Features from the FEP list populate the node cells and the associated process/events populate the off-diagonal cells. Rows list all movements outgoing from the respective node. For example, row "j" represents all outgoing connections enabling transmission from the node, i.e., "2.7 Domestic animals/backyard farms." Columns list all incoming movements to the respective node. Each node is associated with three columns: "Legal" represents legal movements; "Airbrn" represents airborne transmission of FMD; "Illegal" represents illegal movements (top of Fig. 2). For example, columns 19, 20, and 21 contain all legal, airborne, and illegal incoming movements enabling transmission to node "2.7 Domestic animals/backyard farms." Filled cells
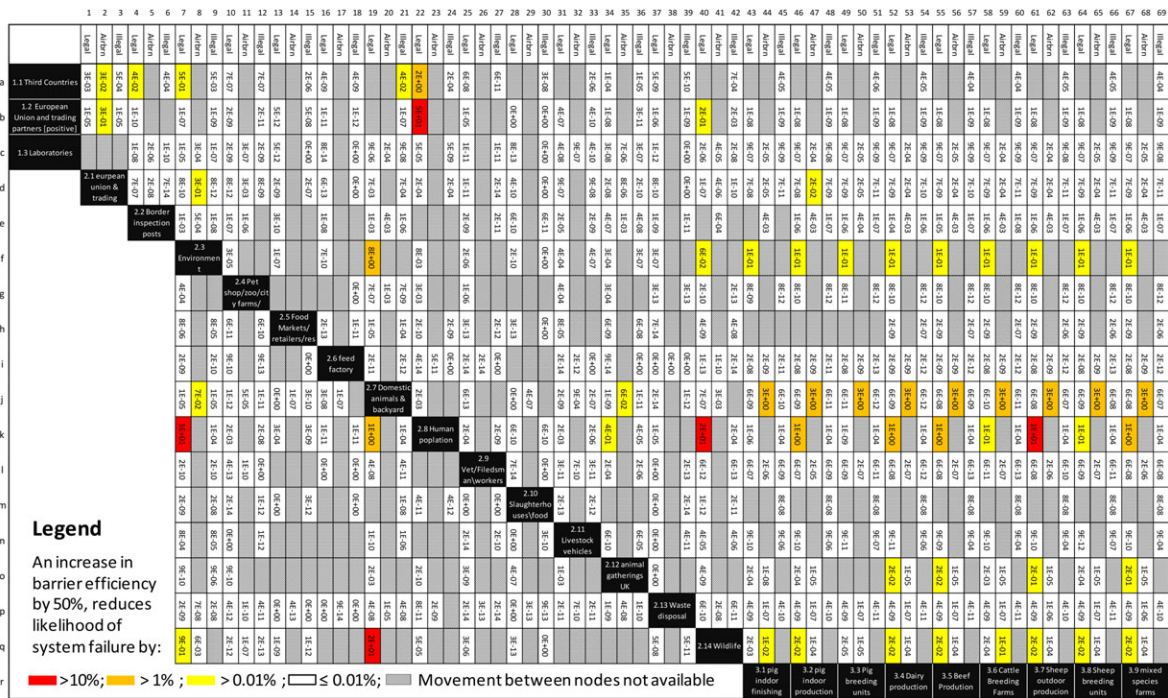
Fig. 2. FMD interaction matrix. The diagonal cells (black) represent the nodes (features) and the off-diagonal cells represent the arcs (process events, where L—legal movement; A—airborne transmission; and I—illegal movements). Empty cells represent impossible movements between two adjacent nodes. (b) represents a close-up of a section of the matrix.

represent the movements considered possible by the experts. These contain the value for the reduction in the likelihood of system failure associated with intervention in the respective process/event. The definition of illegal movement was the subject of substantial debate during the preparatory stages of the model. Following expert consultation, illegal movements were broadly defined as *"noncompliant movements, sabotage, negligence, and recklessness."* Using this definition, experts were given discretion to apply professional judgment when interpreting the concept of legal and illegal activities in the context of each process. The completed matrix in Fig. 2 represents all possible adjacent connections in the system and the building blocks to create all possible pathways of exposure.

2.3. Data Collection

The matrix was populated using expert elicitation, with a two-stage process[21,22] used to accomplish this. The first stage involved five interviews that took place between second and fourth week of Jan 2011, and the second stage involved one workshop on the March 9th, 2011.

2.3.1. Stage 1: Defining the Network

The first stage of elicitation aimed at developing the collection of nodes that form the basic structure of the network. After preparatory work, where a collection of nodes were defined, a series of unstructured interviews were used to revise the node collection.[11] Information was elicited from Defra in-house experts, performing roles requiring a wide understanding of the system. Experts were allowed to add, eliminate, and redefine nodes. The final version of the network was presented and accepted by a technical advisory group, composed of experts in notifiable diseases, in risk and disease modeling and policy development, four weeks prior to the second stage of the elicitation process in March 2011.

2.3.2. Stage 2: Assessing Internodes Connections

The second stage of elicitation employed a structured workshop. The aim of this workshop was to characterize the connections between nodes, based on the frequency of movements between nodes and efficacy of barriers to transmission. As such, expert selection focused on identifying those individuals with specific knowledge of key areas of the

network. The process was mediated by Defra with individuals targeted from different organizations having responsibility over a different section of the system, e.g., policy makers and Trading Standards (Defra, LACORS), local authorities (London, Cornwall, and Suffolk), the National Pig Association (industry), epidemiology (VLA), and environment and wildlife (ADAS, Defra). Invitations included a questionnaire inviting experts to confirm their expertise, and the process concluded when all nodes were allocated. Experts were allocated to two nodes and a total of 24 experts took part in the workshop.

The workshop was structured in two sessions; a first session composed of presentations and calibration exercises to ensure experts started from a common understanding of the rules and use of elicitation scales (Fig. 3). We selected a logarithmic scale to characterize barrier efficacy in light of the extreme range of probabilities across the system.[23,24] This representation of probability has limitations examined in the discussion.

The second session that followed comprised exercises to elicit information on the connections between the 26 network nodes (Fig. 1). Experts were divided into groups based on the allocated nodes. The nine terminal nodes were excluded from the expert elicitation, thus only 17 nodes were part of the assessment. Exercises focused on assessing all outgoing connections from the allocated node to all other nodes comprised in the network. A node specific questionnaire, containing all predefined potential connections with adjacent nodes (25 legal, 25 illegal, and a variable number for airborne transmission) and respective elicitation scales (Fig. 3), was distributed to each group. When completing the questionnaire, for each connection between two nodes, experts were asked to ignore its placement within the network and consider the following questions: (1) Is a connection between node A to node X possible and, if YES, how frequent are movements between nodes A and X, using the quantitative scale on the left side?; (2) If there are barriers preventing the movement of contaminated goods and infected animals between the two nodes, could you define how likely they are to fail, using the right-side scale? All information was obtained following group discussion and questionnaires were completed as a group. The same sequence of questions was used independently for legal and illegal movements. Process/events associated with legal and illegal movement were characterized by expert knowledge of their incidence and barrier failure rates (BFRs). Airborne transmission

was considered possible between two nodes where live animals are present, and experts were asked to use the likelihood scale only, similar to that used to characterize legal and illegal movements, so to assess the likelihood of transmission between them. Facilitators listened to group discussions and intervened only when necessary to provide clarification on the process, in order to minimize the influence of bias and to ensure that the information gathered complied with data needs.[21,22,25] Connections identified as not available by experts had to be identified as not available in writing in the questionnaire. Two facilitators (JD and PL) monitored group discussions and intervened whenever necessary to ensure expert discussion remain consistent across groups. At the end of the exercise, over 1,000 possible connections were analyzed and a quantitative characterization of the network produced. Verification of the elicited data was performed through follow-up interviews. Here, after review of the data by the assessors, specific experts used in the workshop were contacted to confirm or comment on specific data points regarding issues of data quality, missing values, and unclear notes in the comment sections.[26]

2.4. Generating and Calculation of Scenarios for Disease Introduction

To generate all pathways available between source and receptors nodes, we applied the model described by Delgado *et al.* (2013).[11] An exposure scenario consists of a single pathway, composed of a sequence of movements between nodes allowing for the introduction of FMD and its onward exposure until livestock is exposed to it. Thus, it is defined as a sequence of nodes and arcs creating a pathway between source and receptor, where the end point is the introduction of FMDv into a commercial livestock farm, which is assumed to result in exposure of livestock animals. For example, in Fig. 2, the representation of one from the array of possible pathways representing a contaminated product being introduced legally from an EU country without an FMD-free status and culminating with the exposure to sheep in an outdoor production unit, is achieved by this sequence of nodes and arcs: node 1.2 European Union and trading partners [Positive] $=>$ arc b22 $=>$ node 2.8 Human population $=>$ arc k63 $=>$ node 3.7 Sheep Outdoor production units. These can be direct pathways, composed of two nodes and one arc ($k = 1$, where k is the number of arcs) or indirect pathways that encompass more than two nodes and more
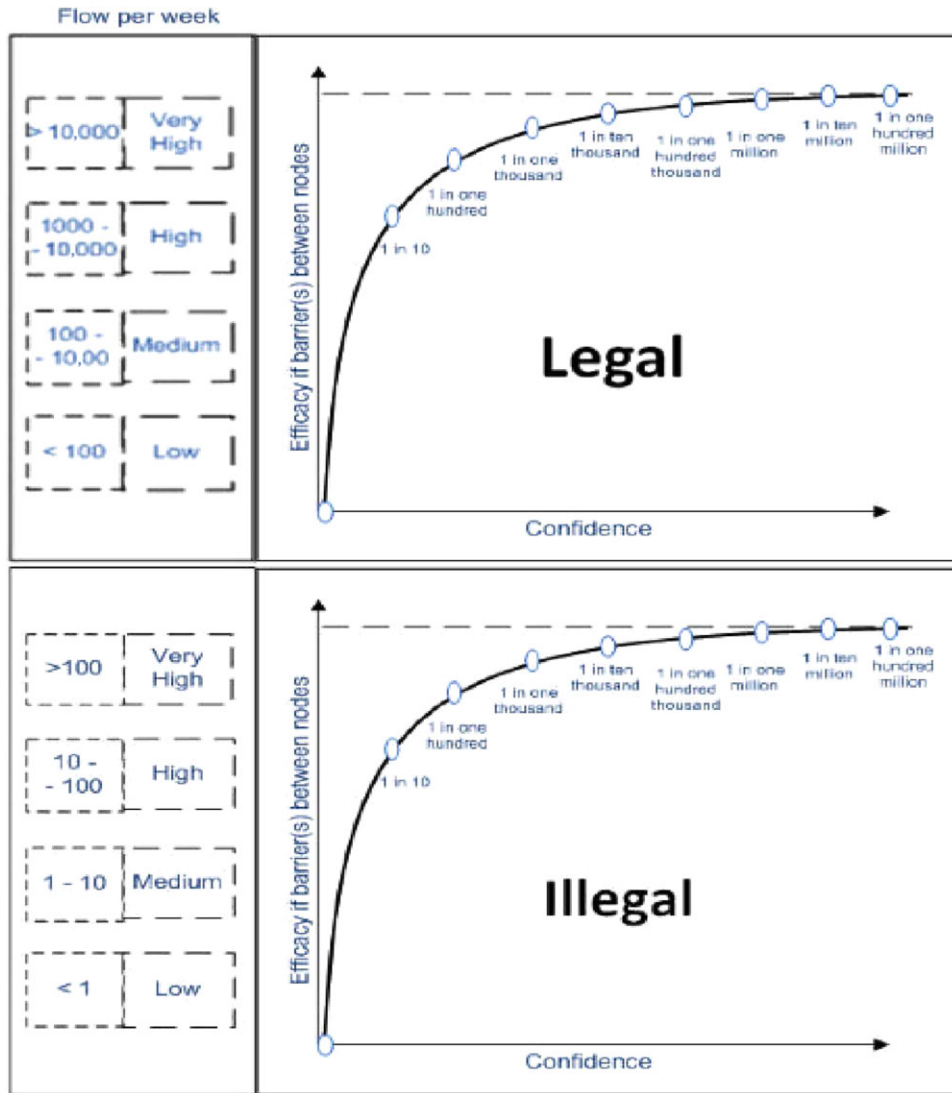
Fig. 3. Elicitation form used in the workshop to retrieve the seed variables associated with the process/events legal and illegal from experts. The same likelihood scale was used to characterize the likelihood of airborne transmission.

than one arc ($k \geq 2$).[27] In this assessment, a maximum scenario length of $k = 4$ was defined to manage the volume of outputs produced. This limit was based on the computing power available. A $k = 5$ simulation generates over 8 million pathways, and thus makes it impossible to complete the sensitivity analyses. The model was constructed on a preprogrammed Excel™ spreadsheet that, when applied to the interaction matrix, generated all possible combinations of scenarios introducing FMD into the United Kingdom for $k \leq 4$. Estimation of the likelihood for a pathway follows Equation (1)[11]:

$$P^*_{(s,r)} = X_{(s,i_1)}.X_{(i_1,i_2)}.X_{(i_2,i_3)}... .X_{(i_{m-1},i_m)}.X_{(i_m,r)}, \quad (1)$$

where $P^*_{(s,r)}$ represents the scenario likelihood from source node (s) and a receptor node (r) and i represents the random adjacent nodes in a network with n nodes. In Equation (2), $X_{(i,j)}$ represents the likelihood of a movement between two adjacent selected nodes in the network, defined as i and j due to the barrier within the system failing. This is calculated by Equation (2)[11]:

$$X_{(i,j)} = \frac{Ic_{(i,j)}}{\Sigma^{i-1}_{c=1} Ic_{(i,c)} + \Sigma^n_{c=i+1} Ic_{(i,c)}} \cdot$$
$$BFR_{(i,j)} \; ; \; \text{for } j \neq i \quad (2)$$

where $i = 1, \ldots, n.$

The value calculated by Equations (1) and (2) represents the likelihood of all barriers in the system failing when considering the levels of incidence between two adjacent nodes—$Ic_{(i,j)}$—and respective BFRs in the scenario.[11] It provides a "score" allowing for the comparative discrimination of scenarios according to the likelihood of a concerted failure of the complete set of controls in place. The sum of all scenario likelihoods provides an indication of the system vulnerability; an assessment of the likelihood of FMD introduction through any one of the available pathways and thus a baseline by which to compare the impact of changes to the system.

2.5. Sensitivity Analysis

System sensitivity analysis was achieved using a local "one at a time" sensitivity approach,[28,29] whereby the system was made more resilient by augmenting one process/event at a time. This targeted each arc (process/event) individually, reducing the likelihood of barrier failure by 50%[11,28,29] and examining the impact on the system performance as a whole. This allows for a better understanding of the relationships between improvement of the barriers in a specific arc, and the corresponding impact on the overall system resilience, considering all available pathways simultaneously. Additional sensitivity analyses were performed targeting multiple arcs simultaneously. These represent interventions that affect multiple barriers across the system and include:

(i) a sensitivity analysis targeting the nodes, that is, all outgoing arcs associated with a particular node—e.g., all outgoing movements from EU member countries where an outbreak has been confirmed (Fig. 4 describes the result of the 26 simulations); and

(ii) a sensitivity analysis targeting movement types, that is, those classified as legal, illegal, and airborne transmission. This involved running one simulation targeting all connections defined as legal, one targeting all illegal connections and one targeting all connections involving airborne transmission. In a scenario composed of three legal connections and two illegal ones considering, the likelihood of system failure for the two illegal connections was decreased by a likelihood of 50%, while the remainder remained unchanged. Fig. 7 later describes the results of the three simulations.

For all sensitivity analyses, the outputs describe, in percentage terms, the expected improvement in reducing the overall residual risk of exposure, i.e., resilience of the system to FMD.

3. RESULTS

3.1. Systemic Perspective of the Multibarrier System

The data provided by experts identified and quantified 694 adjacent connections between two nodes (Fig. 1). This study generated over half a million (i.e., 544,066) theoretical exposure pathways, allowing for successful exposure of FMD from any one of the three defined sources to any one of the nine defined receptors, and calculated a comparative likelihood value for each. This, in itself, improves our understanding of the behavior of system components and their influence on its vulnerability during an incursion of FMD into the United Kingdom (Fig. 2). The interaction matrix describes the arcs of the system characterized according to their impacts on system vulnerability—within the context of the full network. The color coding distinguishes those arcs with greater influence, based on the results produced by the arc sensitivity analysis. From the analysis, human actions play an important role in introducing the disease agent from foreign countries within and outside the European Union. From the collection of experts' comments included in the questionnaire, activities associated with human population mostly comprised of the ability to transport animal products, e.g., meat, or acting as a fomite. For example, importation of live animals to backyard farms does not involve the node "2.8 Human population." A connection is established directly between source country and the node backyard farms. The node, human population also plays a significant role in exposing livestock animals to FMDv, as does the environment, wildlife, and backyard farmers.

3.2. Varying the System Priorities

System size complicates the analysis. Therefore, the network and interaction matrix provides a valuable systemic understanding. However, as these compress the representation of knowledge into a single image, it may prove too simplistic for a comprehensive analysis of the system. This is caused by the large volume of information included, as each of the
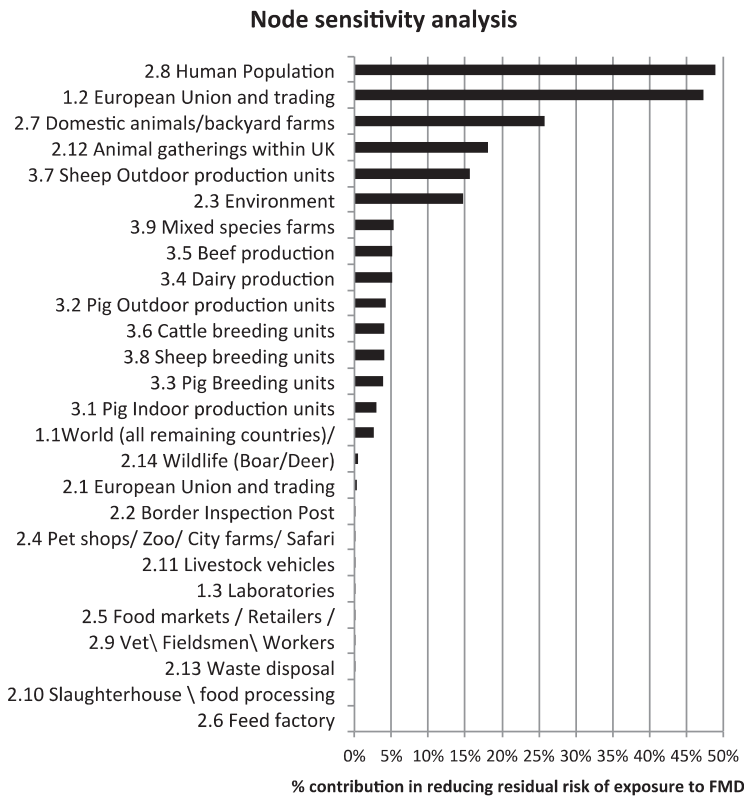
Node sensitivity analysis

Fig. 4. FMD node sensitivity analysis, describing the nodes of the network in order of importance regarding their influence in the likelihood of system failure. The figure describes the impact of decreasing by 50% all outgoing arcs from each node.
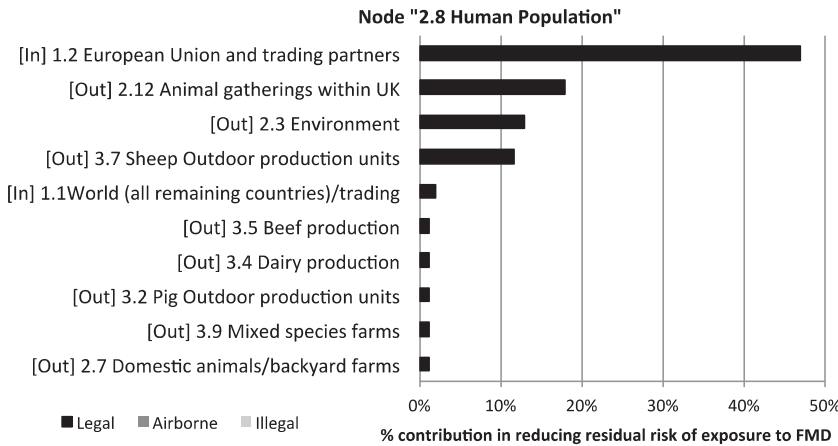
% contribution in reducing residual risk of exposure to FMD

Node "2.8 Human Population"

Fig. 5. "2.8 human population" arc sensitivity analysis. Representing the 10 most influential process/events associated with the "2.8 human population" node in order of importance regarding their influence in the likelihood of system failure.

% contribution in reducing residual risk of exposure to FMD

17 nodes—excluding receptor nodes—reflect an average of 65 connections to adjacent nodes, including incoming and outgoing movements, both of which include legal and illegal activities and airborne transmission. Compared to the detail provided by numerical outputs, the power to visualize the complexity of the interaction matrix is reduced by the broad categorical intervals used in the color scheme and in the difficulty of representing the comparative influence of nodes and associated arcs. To address this, a comprehensive output was developed using a sequence of analyses progressing with increasing detail (Figs. 4 and 5). The format results from the sensitivity analyses, which focused on nodes and the process/events separately, thus assessing the network at different levels of detail. This progressive analysis narrowed the perspective from top to bottom, permitting an increase in detail with which the system is described and analyzed when compared to conventional risk assessment methods.[11]

First, we present a high-level analysis of the system. This is associated with a node sensitivity analysis that focuses on the identification of the network nodes possessing the greatest influence on the likelihood of system failure. Fig. 4 displays the results of 26 analyses, with the influence of each node on system behavior represented by the reduction in percentage to system vulnerability compared to our baseline residual risk of exposing livestock to FMD. Human population (49%) and European countries (positive)—with confirmed FMD outbreak—(47%) had the greatest influence with over 40% reduction to the baseline residual risk. This means an intervention in all outgoing process/events (arcs) associated with these nodes may potentially result in a reduction in likelihood of an FMD outbreak of greater than 40%. In contrast, other nodes such as waste disposal, slaughterhouses, and feed factories apparently have negligible influence on network behavior.

Understanding the causes of node influence requires us to examine the process/events that most influence system behavior, and then to distinguish between those process/events delivered through legal and illegal routes, i.e., noncompliant activities and airborne transmission. Fig. 5 focuses on the most influential node, "2.8 Human population," describing the 10 highest influential process/events associated with this node. Forty-four additional process/events representing possible transmission to and from "2.8 Human population" were identified (Fig. 2) but not included here, for brevity. The process/events are characterized as legal, illegal, and airborne transmission movements (color scheme), and separated into outgoing and incoming movements through the prefix [Out] and [In], respectively. In this case, all 10 of the most influential process/events represent legal movements, as noted in the key to the graph. The most influential process/event, "[In] 1.2 European Union and trading partners [Positive]" (47%) represents the movement of FMDv from a country within the EU where FMD has been confirmed to the U.K. general population through, for example "*personal imports of meat-based food products*" (a comment collected in the workshop). The introduction of FMD from "[In] 1.1 World (all remaining countries)/trading partners/Bilateral" (2%) also presents a concern. The remaining eight process/events represent outgoing movements. The highest ranked is "[Out] 2.12 Animal gatherings within UK" (18%), which represents the potential transmission of FMDv by the human population, perchance acting as fomites and

carrying food products of animal origin to local markets trading live animals and animal shows. Other significant outgoing process/events involve connections to the "[Out] 2.3 environment" (13%), "Sheep outdoor production units" (12%), "[Out] 2.7 Domestic animals/backyard farms" (1%), "[Out] 3.5 Beef production" (1%), "[Out] 3.4 Dairy production" (1%), "[Out] 3.2 Pig Outdoor production units" (1%), and "[Out] 3.9 Mixed species farms" (1%).

3.3. Disease Sources

Outbreak pathways are significantly impacted by the disease source. The application of the systemic model to study FMD considers three independent disease sources. Fig. 6 displays the relationship between the disease sources relative to their contribution to the likelihood of an outbreak. Pathways initiating in "1.2 European Union and trading partners [positive]," representing EU member countries with a confirmed FMD outbreak, present the greatest threat, accounting for 95% of all residual risk of exposure of FMDv to susceptible receptors. Pathways initiating in "1.1 Third countries outside EU" representing third countries contribute to 5% of the residual risk of exposure. Lastly, pathways associated with "1.3 Laboratory" representing releases of FMDv from U.K.-based laboratories account for the remaining 0.003% of the overall residual risk of exposure.

3.4. Transmission of FMD through Legal, Illegal Movements, and Airborne Spread

Model development and its application sought to provide a distinction between the contributions to residual risk of exposure associated with legal and illegal activities and airborne transmission. The network considers 694 process/events from which 302 represent movements associated with legal activities, 264 represent movements associated with illegal activities, and 128 represent movements associated with airborne transmission of FMDv (Fig. 2). The sensitivity analysis applied to legal movements involved targeting all legal movements simultaneously. This analysis showed that improving the capacity to prevent transmission of the FMD through all legal movements would reduce the residual risk of exposure by 83%. In contrast, a similar analysis that targeted illegal movements disclosed a reduction in the risk of exposure to livestock by 0.06%. A third analysis applied to the transmission of FMDv through
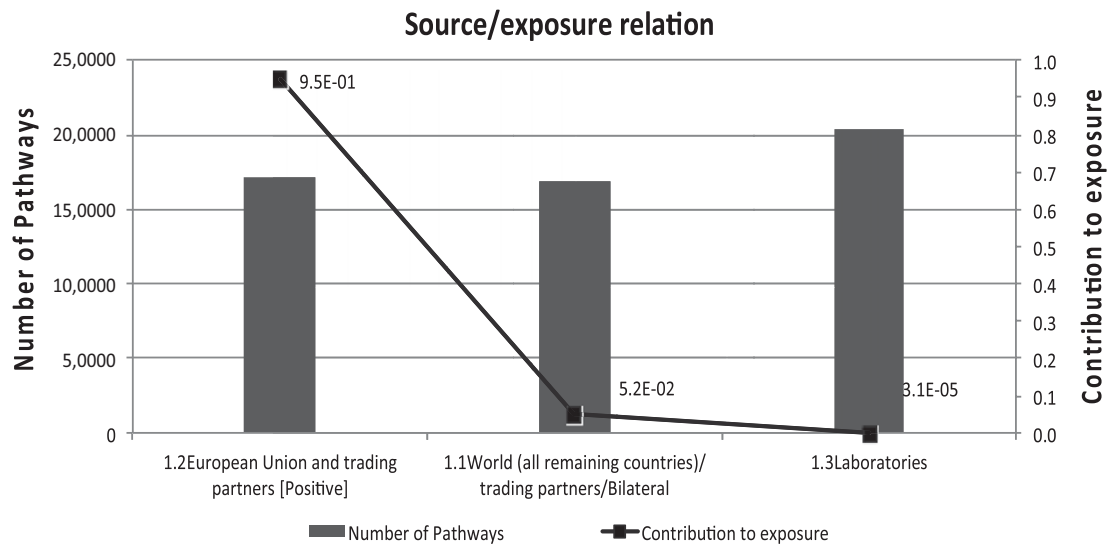
Fig. 6. Comparison between disease sources. Relation between the number of pathways and contribution to likelihood of system failure: Left *Y*-axis representing number of pathways; Right *Y*-axis the contribution to likelihood of exposure (0 to 1).

airborne movements describes an improvement in reduction of residual risk by 26%. Fig. 2 presents the results from the "one at a time" sensitivity analysis, where illegal movements between third countries and backyard farms are identified as the sole illegal movement where intervention is likely to improve resilience over the 0.01% threshold value.

4. DISCUSSION

4.1. Current Risk of an FMD Outbreak

Food safety authorities have expressed concern over the continued need to reduce the residual risk of EAD outbreaks, including FMDv.[8,16,17] This research offers insight into why further risk reductions are challenging to achieve, despite continuing improvements in monitoring and detection. We offer insight into where resources might be best targeted to reducing the United Kingdom's overall vulnerability to FMD. The strength of this analysis is in comparing the relative risk changes due to interventions within the system rather than the absolute risk of an FMD outbreak. Thus, it does not define an estimate of the current level of residual risk. Rather, it offers an analysis of the relative contributions from various interventions in specific nodes and arcs to reducing the residual risk of livestock being exposed to FMDv.

Understanding how system behavior changes, and identifying emerging threats driving the risk of

introducing an EAD, can inform intervention decisions. Historical records of animal disease outbreaks worldwide contain examples of where controls already in place were inadequate to deal with existing threats. Focusing on the suspected pathways of past FMD outbreaks in the United Kingdom alone provides examples of the systemic nature of exposure. For the 1967/1968 outbreak, FMD was likely to have been introduced through the legal importation of contaminated frozen lamb (on-the-bone) from Argentina, which was then used to feed pet dogs in contact with a piggery. Reactivation of the infection, following control of the outbreak, was attributed to straw and hay that remained on farm following stamp-out, cleansing, and disinfection.[30,31] Subsequent investigations into the outbreak led to policy changes, namely, for meat imports, in order to minimize the risk of a future outbreak with similar causes. Similarly, investigations of the FMD outbreak in 2001, linked it to swill fed to pigs at a finishing unit licensed to feed catering waste, albeit the swill was not properly treated, and led to the total ban of swill feeding in 2002 to improve U.K. protection to FMD.[7,32] These examples demonstrate outbreak incidents where disease transmission occurred despite the existence of regulation and codes of good practice. The regulations and controls did not consider the full range of practices undertaken by the industry and farmers, and in some cases did not provide adequate protection against exposure. In both

cases, regulation was amended postincident to avoid a future outbreak by the same routes.

National and international regulatory bodies responsible for preventing FMD outbreaks have increased focus on the changes to international trade and the political dynamics represented by European agreements for free trade and the movement of people.[9,33,34] These have eased the movement of goods and people, reducing the opportunities for control, especially in the case of personal imports of meat and other animal products, raising questions on the role that noncommercial pathways may play in the introduction of FMD into the United Kingdom and its exposure to commercial livestock.[8,17] Veterinary control measures are put in place when an outbreak is confirmed in an EU country with the aim of minimizing the risk of introducing FMD through the movement of contaminated animal products. However, the high frequency of these movements compared to those originating from outside the EU means their potential contribution to the United Kingdom's vulnerability to FMD remains worthy of further analysis and scrutiny.

4.2. Opportunities for Reducing the Residual Risk of Exposure to FMD

This considers (i) all entities influencing transmission, which, by interacting with a specific EAD agent establish a connection that links the source to the receptor; and (ii) the controls and regulations that stakeholders have to uphold in order to prevent connections and exposure. In doing so, it analyses all pathways of exposure simultaneously, irrespective of their likelihood, and allows for identification of the key nodes and process/events driving the risk of exposing livestock to an EAD.[11]

The results presented are consistent with the current shift in concerns regarding the causes of United Kingdom's and other developed countries, vulnerability to FMD. The focus on importation of live animals and other movements associated with the livestock industry, germplasm, feed, and livestock lorries,[35–41] has, to some extent, changed emphasizing the role that noncommercial routes have in the introduction of FMD.[42–44] The systemic model indicates that direct movements from source to farms and through border inspection posts, including trade associated with the livestock industry, pose little influence on system behavior. Thus, the controls in place are effective, further improvements may provide little reduction in residual risk (Fig. 4). Simi-

larly, our research results highlight noncommercial imports of food goods, and most importantly, those associated with freedom of movement for people and goods across borders, as of concern.[8,17] The results suggest a further reduction to the residual risk of introducing FMD into the United Kingdom could best be managed by focusing on improving controls over noncommercial movements across and within borders of live animals and animal products associated with the nodes "2.8 Human population" and "2.7 Domestic animals/backyard farms" (Fig. 4). Here, controlling movements between the source "1.2 European Union and Trading partners [positive]" and "2.8 Human population" would provide the greatest benefits in preventing future exposure of commercial livestock to FMD.

The findings of the systemic model highlight that "illegal" activities are not driving exposure. The outputs in Fig. 7 indicate that increasing control over activities currently defined as illegal and noncompliant is unlikely to significantly reduce resilience against EADs. Instead, the results suggest that intervention in movements, i.e., process/events, available between nodes that are currently legal, due to a lack of awareness and/or regulation, presents the greater opportunity to reduce the residual risk of exposure to FMD. We argue that legal movements pose a significant influence on system behavior. This is due to:[1] a much higher frequency of legal movements, compared to illegal ones, that amplifies the impact of barrier failure on system behavior due to the increased challenge that is a feature of the number of these legal movements. In addition,[2] legal movement can combine to create unforeseen scenarios of exposure, not dissimilar to those responsible for the FMD outbreaks of 1967/1968, for which regulations and controls do not provide adequate protection.[30,31]

Based on the findings of the systemic model, we argue that it is necessary to understand better the range of compliant practices associated with noncommercial activities and free movement of individuals that allow FMD to overcome and circumvent the barriers to transfer virus. Here, intervention provides a significant opportunity to improve system resilience.

4.3. Challenges and Limitations to Developing a Systemic Model

The application of systemic models is in its infancy and as such it presents a number of methodological issues, which need overcoming to improve
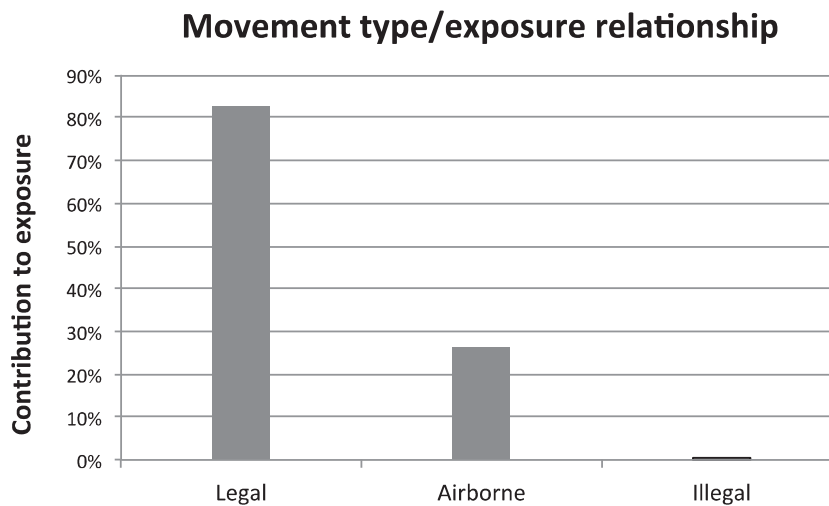
Movement type/exposure relationship

Fig. 7. Sensitivity analysis of the considered movement types: legal, illegal, and airborne transmission.

reliability. While the model does increase the number of pathways analyzed, to include pathways previously unaccounted for, the scope of the assessment involves managing a balance between level of detail and practicality. As such, calculated sacrifices were made on the details within the model in favor of a model that considers many different exposure routes. Here, we highlight some of the key issues, which need addressing in future applications.

The generic nature of the assessment meant that it was too complex to generate estimates of prevalence of FMD loads at the sources. As a result, the model does not consider the prevalence of disease at source or the quantity of virus present through the pathways. While the subject was discussed among members of the technical advisory group, its incorporation within the assessment was not straightforward and could not be pursued within this study. Prevalence of virus at source and load of virus are central in the development of probability-based risk assessment,[23,45,46] and its absence likely reduces the accuracy of the model and means that it does not account for the likelihood of an outbreak in the United Kingdom.

The number of variables to elicit and the limited time and experts present in the work meant selecting a time-efficient, pragmatic approach for the elicitation protocol in detriment of more time-consuming, albeit possibly more robust elicitation process.[26] Despite this compromise, the process was designed to minimize bias that we believe was reduced to acceptable levels.[26,47] Systemic modeling is

underpinned by limiting the use of experts to provide judgment on a narrow domain for which they are a recognized expert. Experts are encouraged to explore all possible connections within that domain, thus reducing the potential biasing effects of motivation and availability. However, selection of a simplistic elicitation process based on group discussions opens the process to other biasing effects, such as dominance by personality,[23] whereas alternative methods may control this better.[48,49] We also highlight the introduction of logarithmic scale of relative frequencies, necessary to capture the wide range of likelihoods of barrier failures where linear scales underperform.[24] Such scales tend not to conform with the experts' mental models of probability.[24] However, due to the experts' technical/scientific background, the elicitation protocol assumes a high degree of numeracy alongside their ability to interpret numeric scales correctly.[50]

Risk assessments vary in complexity and scope depending on what is proposed. Here, we present a relatively simple possible model to provide a fair representation of the system, i.e., controls preventing the introduction of FMD into the United Kingdom. We take a critical view of the model, suggest key areas where changes could improve reliability of the results, and we caveat the use of the output to ensure that the conclusions drawn are in line with the model capabilities. However, when considering the data currently available on the threat to United Kingdom's biosecurity, the systemic model provides an additional source of information with which to inform policy decisions.

4.4. Benefits of Systemic Risk Assessments to Improve System Resilience

The systemic approach offered in this research tool moves us on from an analysis of pathways of introduction in isolation,[36,37] and focuses on analyzing the overall performance of the multibarrier system. It allows for the identification of critical areas of the system, where intervention can reduce exposure through multiple pathways, and thus have the greatest impacts in reducing the overall residual risk of introduction and exposure of commercial livestock to FMDv.[11] This research does not comment on the methods and instruments available for intervention. It prioritizes the nodes and arcs of the system where intervention is of greatest value to reduce the residual risk of an FMD outbreak further, while additional work may be required on the method of implementation and its benefits and impacts.

Intervention on the system of controls is a complex task. Benefits from increasing control and restricting movements must be weighed against the potential direct and indirect costs to stakeholders, the wider economy and trade. Gaining a greater understanding of the causes of system vulnerability allows measures to be proposed that offer the greatest overall benefit for U.K. livestock health. In many cases, the introduction of sanitary barriers to goods traded has to be vetted. Political and regulatory authorities, such as the World Trade Organisation under the Sanitary and Phytosanitary agreements, require a strong case for implementation to ensure that additional barriers provide essential disease control and are not driven by trade protectionism.[51] Risk assessments are mandatory for supporting such cases. In this capacity, systemic risk assessment may highlight areas outside of disease control that are directly relevant to disease spread. Therefore, they may prove a powerful additional tool for demonstrating the need for implementing disease controls where they have not previously been part of the system.

5. CONCLUSIONS

We have demonstrated the value of applying a network analysis to the introduction of a specific disease, in this case FMD to the United Kingdom. The analysis of network nodes demonstrates the significant role of existing disease controls alongside the frequent challenge to control barriers that form part of the same system. Furthermore, it enables an examination of the opportunities for improvements in control points and the extent to which further investment in control may provide enhanced protection or be largely irrelevant compared to the overall likelihood of risks. Finally, the research model developed provides a structure with which to examine the significance of national disease control measures when reviewing potential changes that may impact on trade.

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