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Modelling the time at which overcrowding and feed interruption emerge on the swine premises under movement restrictions during a classical swine fever outbreak

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A stochastic risk model was developed to estimate the time elapsed before overcrowding (TOC) or feed interruption (TFI) emerged on the swine premises under movement restrictions during a classical swine fever (CSF) outbreak in Indiana, USA. Nursery (19 to 65 days of age) and grow-to-finish (40 to 165 days of age) pork production operations were modelled separately. Overcrowding was defined as the total weight of pigs on premises exceeding 100% to 115% of the maximum capacity of the premises, which was computed as the total weight of the pigs at harvest/transition age. Algorithms were developed to estimate age-specific weight of the pigs on premises and to compare the daily total weight of the pigs with the threshold weight defining overcrowding to flag the time when the total weight exceeded the threshold (i.e. when overcrowding occurred). To estimate TFI, an algorithm was constructed to model a swine producer's decision to discontinue feed supply by incorporating the assumptions that a longer estimated epidemic duration, a longer time interval between the age of pigs at the onset of the outbreak and the harvest/transition age, or a longer progression of an ongoing outbreak would increase the probability of a producer's decision to discontinue the feed supply. Adverse animal welfare conditions were modelled to emerge shortly after an interruption of feed supply. Simulations were run with 100 000 iterations each for a 365-day period. Overcrowding occurred in all simulated iterations, and feed interruption occurred in 30% of the iterations. The median (5th and 95th percentiles) TOC was 24 days (10, 43) in nursery operations and 78 days (26, 134) in grow-to-finish operations. Most feed interruptions, if they emerged, occurred within 15 days of an outbreak. The median (5th and 95th percentiles) time at which either overcrowding or feed interruption emerged was 19 days (4, 42) in nursery and 57 days (4, 130) in grow-to-finish operations. The study findings suggest that overcrowding and feed interruption could emerge early during a CSF outbreak among swine premises under movement restrictions. The outputs derived from the risk model could be used to estimate and evaluate associated mitigation strategies for alleviating adverse animal welfare conditions resulting from movement restrictions.

Keywords: classical swine fever, movement restriction, pigs, outbreak control, animal welfare

Implications

The estimated time when animal welfare problems would emerge can help decision makers plan for effective management of a classical swine fever (CSF) outbreak, allowing swine producers to minimize economic losses and make informed decisions on continuity of business. The finding that animal welfare problems could occur quickly during outbreak control indicates the importance of developing associated strategies to alleviate the concerns and estimating the required resources for their execution.

Introduction

CSF is a highly contagious viral disease among pigs and is endemic in many regions of the world. Because of its potentially significant impact on the US swine industry, CSF is listed as one of the most important foreign animal diseases in the United States (US Department of Agriculture (USDA), 2012a). Immediately after the detection of a CSF outbreak, movement restrictions are imposed in areas

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surrounding the infected swine premises until 28 days after depopulation and disinfection of the last confirmed infected premises (USDA, 2013). Under movement restrictions, all movements of finisher pigs to slaughter plants and weaning or nursery pigs to their destination premises are halted. Various implications for animal welfare might emerge when these routine movements are interrupted (Laurence, 2002; Galli, 2011). Overcrowding due to retention of pigs on premises that would otherwise be transported, feed interruption due to limited vehicular traffic to and from farms under movement restriction, or the producer's decision to discontinue feed supply and euthanize the pigs were recognized as the most important animal welfare outcomes that could result from movement restrictions by experts in swine veterinary medicine, animal welfare science, pork production and epidemiology, who attended a roundtable discussion held at Purdue University in 2014.

Despite the potential adverse impact on pork production and animal welfare, movement restriction is considered an essential control strategy during a CSF outbreak (Martinez-Lopez *et al.*, 2011; Thulke *et al.*, 2011). However, potential animal welfare implications arising from movement restrictions must also be evaluated, and mitigation strategies must be planned. Historically, CSF outbreaks have shown that the number of healthy pigs euthanized due to animal welfare concerns often exceeds the number of pigs euthanized due to infections. For example, during the 1997/98 CSF outbreaks in Germany, Spain and the Netherlands, the pigs euthanized due to adverse animal welfare conditions comprised 62% to 87% of the total pigs euthanized (Edwards *et al.*, 2000; Terpstra and de Smit, 2000). The costs associated with the activities for managing animal welfare concerns were estimated to be >50% of the total direct costs for the outbreak control (Saatkamp *et al.*, 2000). In addition, the timing of the emergence of adverse animal welfare outcomes is critical because the resources required for alleviating animal welfare conditions often overlap with the resources for other disease control activities such as depopulation of infected premises, preemptive culling and carcass disposal (East *et al.*, 2014; Roche *et al.*, 2014). Hence, an early onset of adverse animal welfare outcomes is expected to have a greater impact on outbreak management than a later onset during an outbreak. Inadequate preparedness to account for adverse animal welfare outcomes could greatly hinder disease outbreak controls as seen in historical foreign animal disease outbreaks (Terpstra and de Smit, 2000; Scudamore and Harris, 2002).

Despite their importance, only limited studies have attempted to quantitatively assess these animal welfare-related consequences of movement restriction during animal disease outbreak control. A study conducted in Canada quantified the time at which overcrowding on swine premises emerged under movement restrictions (Bargen and Whiting, 2002). Although the study provided empirical evidence on the importance and timing of overcrowding, the use of a small number of subjectively selected swine premises might limit the generalizability of the estimates derived from the data. Therefore, we developed a robust risk assessment model to estimate the time elapsed before overcrowding (TOC) or feed interruption (TFI) emerged on the swine premises under movement restrictions during a hypothetical CSF outbreak in Indiana, USA.

The US swine industry is the third largest in the world. The industry produced ~200 million pigs and generated >22 billion US dollars in revenue in 2012 (USDA, 2012b). Indiana is in the top fifth pork producing states in the United States. It has a mandatory livestock premises identification system called USAHERDS. The data housed in this system include spatial distribution of livestock premises and farm production types and sizes. Those routinely collected data are essential for disease spread modelling, biosecurity risk assessments, case of origin, traceback information, disease control zone designation, and animal and animal product movement tracking. There were 8631 swine premises listed in USAHERDS in 2012. Among them, 5% were nursery operations and 59% were grow-to-finish operations.

Material and methods

A stochastic risk assessment model was developed to estimate the time elapsed before animal welfare problems (i.e. overcrowding and feed interruption) emerged on swine premises under movement restrictions during a CSF outbreak in Indiana, USA. Nursery (19 to 65 days of age) and grow-to-finish (40 to 165 days of age) pork production operations were modelled separately. The data used to elicit the probability distributions for the model input parameters were collected from different sources including USAHERDS, the USDA foreign animal disease response plans and published studies (Table 1). The model outputs of interest were TOC, TFI and time when either overcrowding or feed interruption emerged on swine premises. Details on the model algorithms used to estimate these output parameters are described as follows.

Time to overcrowding

Overcrowding was defined as the total weight of pigs on premises exceeding 100% to 115% of the maximum capacity of the premises (measured in kg). To compute the total weight of pigs on a particular day, regression equations of age-specific weight for barrows (equation (1)) and gilts (equation (2)) were derived from published standards (Carr, 1998). Specifically, the data were fit with a regression model, in which the predictor was age (days) of pigs and the response variable was weight (kg) of pigs. Linear, quadratic, cubic and growth models were examined. The R^2 and residual plots were evaluated to select the best fit models. Regression intercepts were forced out of the equations because the weight of pigs cannot go below 0. Because the data used to derive the equations included only pigs that were 19 days and older, which was the study population of

Table 1 *Selected model input parameters, probability distributions and data sources for estimating time to overcrowding and feed interruption*

Input parameter	Probability distribution	Data source
Number of pigs on a premises when an outbreak starts (*Intl_numb*)	Lognormal (934, 2282)	Indiana premises identification database (USAHERDS)
Harvest/transition season (*Season*)	DUniform (1, 2, 3)	1: High proportion of reaching harvest/transition 2: Moderate proportion of reaching harvest/transition 3: Low proportion of reaching harvest/transition
Age (days) of pigs when an outbreak starts (*Intl_age*)	Nursery: If *Season* = 1, Triangle (19, 50, 65) If Season = 2, Triangle (19, 40, 65) If Season = 3, Triangle (19, 30, 65) Grow-to-finish: If *Season* = 1, Triangle (40, 150, 165) If *Season* = 2, Triangle (40, 100, 165) If *Season* = 3, Triangle (40, 50, 165)	USAHERDS, USDA (2002, 2014)
Mortality rate per day (*Death_rate*)	If *Intl_age* ⩽ 40, Triangle (0.001242, 0.00138, 0.001518) If *Intl_age* > 40, Triangle (0.0001, 0.0005, 0.001)	Maes *et al.* (2001), de Grau *et al.* (2005)
Final age (days) of production phase (*Fnl_age*)	Nursery: Triangle (42, 65, 70) Grow-to-finish: Triangle (150, 165, 180)	USDA (2002)
A factor applied to the maximum capacity to allow leeway for occurrence of 'overcrowding' after reaching the final age of production phase (*Capacity_adj_factor*)	Pert (0.85, 0.95, 1)	
Epidemic duration (*ED*)	Triangle (29, 192, 514)	Yadav *et al.* (2016)
Length of time that a swine premises owner could tolerate to not increase the chance of discontinuing feed supply (*Tolerance_fc*)	Nursery: IntUniform (14, 46) Grow-to-finish: IntUniform (30, 125)	
Probability to discontinue feed supply (*Pr_Fdc*)	Low: Bernoulli (0.05); 1 for discontinue High: Bernoulli (0.30); 1 for discontinue	
Feed storage capacity (*Feed_storage*)	IntUniform (2, 14)	

interest, these equations may not accurately estimate the weight for pigs younger than 19 days:

$$\text{Age-specific weight (kg) for barrows}: \quad 0.326 \times \text{age} + 0.003 \times \text{age}^2 - 06.6 \times 10^{-6} \times \text{age}^3 \qquad (1)$$

$$\text{Age-specific weight (kg) for gilts}: \quad 0.308 \times \text{age} + 0.003 \times \text{age}^2 - 5.7 \times 10^{-6} \times \text{age}^3 \qquad (2)$$

The two regression equations were used to compute the initial total weight of pigs on premises when an outbreak emerged using the initial age of pigs (*Intl_age*; Table 1) and the initial herd size (*Intl_numb*; Table 1). The probability distribution (Lognormal (μ, σ)) for *Intl_numb* was derived from the Indiana swine industry data in USAHERDS. Because a CSF outbreak could occur at any time, three different harvest/transition seasons (*Season*; Table 1) were created to represent different distributions for *Intl_age* among premises at the onset of an outbreak. A high harvest/transition season represented an age distribution shifting towards the harvest or transition age, whereas a low harvest/transition season represented an age distribution shifting away from the harvest/transition age. A discrete uniform distribution (i.e. the three groups had the same probability to occur) was used to model *Season* to represent the fact that a CSF outbreak could emerge at any time of the year.

After computing the initial total weight of pigs at the onset of a CSF outbreak, the model proceeded to calculate the daily total weight of pigs on premises in a time step of 1 day. The age-specific weight equations (equations (1) and (2)) and the number of pigs on a particular day were used in the computation. The age of pigs was progressed daily from the initial age at the onset of the outbreak (*Intl_age*), and the

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daily number of pigs was adjusted for the age-specific mortality rate (*Death_rate*; Table 1). The model assumed that no pigs would enter or exit (except for mortalities) the premises under movement restrictions during the outbreak.

Maximum facility capacity was computed as the total weight of pigs on premises at the final age of the production phase (*Fnl_age*; Table 1). The initial number of pigs (*Intl_numb*) at the onset of the outbreak was used in the computation of maximum facility capacity. The computed maximum capacity was further adjusted for a factor (*Capacity_adj_factor*; Table 1) of Pert (0.85, 0.95, 1) to reflect our definition of overcrowding as when the total weight of pigs on the premises exceeded 100% to 115% of the maximum capacity of the premises. The model algorithm then compared the daily total weight of pigs on the premises as described previously with the adjusted maximum facility capacity to determine whether overcrowding emerged on a particular day during the simulation period. TOC was estimated as the 1^{st} day when daily total weight of pigs on the premises exceeded the adjusted maximum facility capacity.

Time to feed interruption

Together, the capacity of feed storage and discontinuation of feed supply determined when feed interruption would emerge. In this study, a swine producer's decision to discontinue feed supply (followed by the euthanasia of pigs) was modelled to be dependent on (1) the epidemic duration (*ED*; Table 1) estimated at the onset of the outbreak: the assumption was that the longer the estimated *ED* was, the more likely a farmer would decide to discontinue feed supply; (2) the duration between the initial age (*Intl_age*) of pigs at the onset of the outbreak and the final age (*Fnl_age*) of production phase (i.e. harvest or transition to the next phase): the assumption was that the longer the duration was, the more likely a farmer would decide to discontinue feed supply; and (3) the progress (number of days) of the outbreak: the assumption was that the longer the outbreak has lasted, the more likely a farmer would decide to discontinue feed supply.

The probability distribution for *ED* was derived from the study that simulated various most likely CSF outbreak scenarios in Indiana (Yadav *et al*., 2016). To summarize, a risk metric was developed using the swine premises data retrieved from USAHERDS, the feral hog distribution data and the US Census data to select the most likely CSF outbreak scenarios in Indiana. Two types of outbreak scenarios: single site (with one index premises at the onset of the primary outbreak) and multiple site (with more than one index premises at the onset of the primary outbreak), were selected and simulated to estimate *ED* and other CSF outbreak-related outcomes using the North American Animal Disease Spread Model (NAADSM Development Team, 2013). Because our preliminary investigation found that the *ED* derived from both types of outbreaks resulted in similar outcome parameter estimates, only the *ED* derived from the simulations of 15 multiple-site CSF outbreak scenarios was used in this study. Details on the selection of most likely CSF outbreak scenarios in Indiana and the model simulations could be found in the study (Yadav *et al*., 2016).

The model algorithm was developed to compare the length of time that a swine producer could tolerate (*Tolerance_fc*; Table 1) with the three decision attributes previously described. If *Tolerance_fc* was less than the duration of any of the three attributes, a high probability of discontinuation of feed supply (*Pr_Fdc*; Table 1) was used; otherwise, a low *Pr_Fdc* was used. Following a decision to discontinue feed supply, feed interruption was modelled to emerge after passing feed storage capacity (measured in days, *Feed_storage*; Table 1). TFI was estimated as the 1^{st} day when feed interruption emerged (i.e. the day when a decision on discontinuing feed supply was made plus *Feed_storage*).

Sensitivity analyses and model simulations

Model input parameters of *Tolerance_fc*, *Pr_Fdc* and *Capacity_adj_factor* were selected for the sensitivity analyses because there was no evidence-based information to support the assigned probability distributions. A ±10% margin of the baseline value (Table 1) was used in the sensitivity analyses. A change in the estimates of median TOC and TFI of ⩾15 days was considered practically important. The software @Risk (version 7; Palisade Corporation, Ithaca, NY, USA) was used to run the simulations separately for the two pork production operations. Each simulation was run with 100 000 iterations using Latin Hypercube sampling with a Mersenne Twister generator (an algorithm/option available from @Risk) of randomly selected initial seed. The unit for model simulation was premises and the simulation proceeded in time steps of 1 day. The risk assessment model is built in MS Excel and is available by request.

Results

Overcrowding emerged in all simulated iterations (100 000/ simulation) during the 365-day simulation period for both pork production operations. In contrast, feed interruption emerged in only ~30% of the iterations. The median (5th and 95th percentiles) TOC was 24 days (10, 43) among nursery operations and 78 days (26, 134) among grow-to-finish premises (Figure 1). The overall distributions for TFI among the iterations when feed interruption occurred were similar between the two production phases with two distinguished clusters at different day ranges (Figure 2a and b). Among the iterations when feed interruption emerged, about 90% emerged within 15 days after the onset of outbreak. Overcrowding emerged before feed interruption in 71% to 72% of the iterations. The percentiles of time (days) to either overcrowding or feed interruption, whichever emerged first, by production phases is summarized in Table 2. The results showed that ~25% of the swine premises under movement restrictions would encounter either overcrowding or feed interruption in the first 2 weeks of a CSF outbreak (Table 2). Figure 3 showed the temporal distribution when the two types of pork production operations encountered either overcrowding

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or feed interruption. Overall, nursery premises under movement restrictions would encounter either overcrowding or feed interruption faster than grow-to-finish premises (Figure 3). The

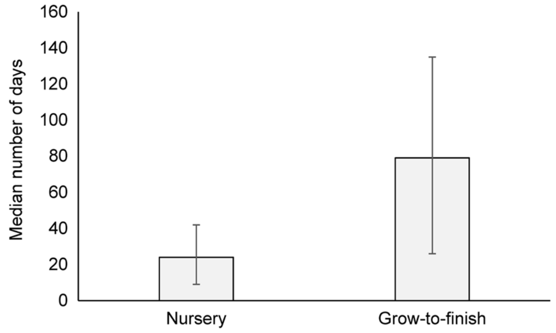

Figure 1 Median time (days) elapsed before overcrowding emerged on swine premises under movement restrictions during a classical swine fever outbreak in Indiana, USA. The estimates were generated from 100 000 iterations each for nursery and grow-to-finish pork production operations. Error bars are the 5th and 95th percentiles.

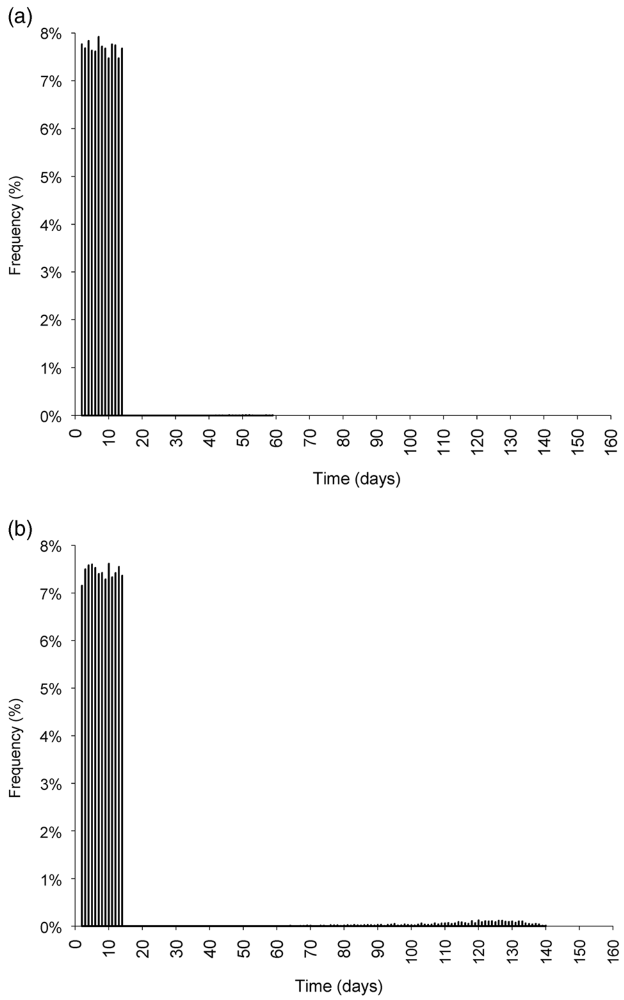

Figure 2 Histograms of time (days) elapsed before feed interruption emerged on swine premises under movement restrictions during a classical swine fever outbreak in Indiana, USA. The estimates were generated from 100 000 iterations each for (a) nursery pork production operations (19 to 65 days of age) and (b) grow-to-finish pork production operations (40 to 165 days of age).

Table 2 *Percentiles of the time (days) elapsed before overcrowding or feed interruption emerged on the swine premises under movement restrictions during a classical swine fever outbreak in Indiana, USA*

	Percentiles				
	5th	25th	Median	75th	95th
Nursery	4	10	19	29	42
Grow-to-finish	4	13	57	93	130

The estimates were generated from 100 000 iterations for each of the two different pork production operations.

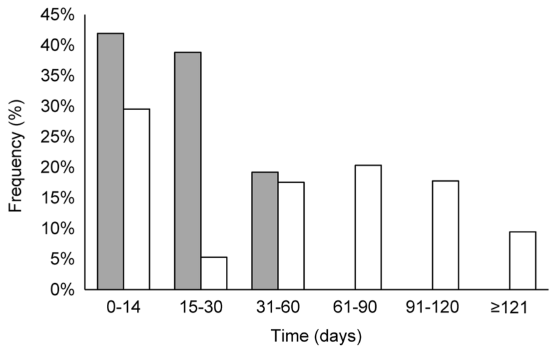

Figure 3 Percentage of the two different pork production operations under movement restrictions that would encounter overcrowding or feed interruption during a classical swine fever outbreak by time (days) of onset. The estimates were generated from 100 000 iterations each for nursery (shown as grey bars) and grow-to-finish (shown as white bars) operations.

distribution also showed that >80% of nursery premises and 35% of grow-to-finish premises under movement restrictions encountered these animal welfare implications within the 1st month of a CSF outbreak (Figure 3).

The sensitivity analyses indicated that changes in the value of *Capacity_adj_factor* resulted in a change of ⩾15 days in the estimates of TOC. Specifically, a 10% decrease in the baseline input value of *Capacity_adj_factor*, which represented 110% to 125% of the maximum capacity, led to an increase in the estimate of median TOC by 15 days in nursery premises. A 10% increase in the baseline input value of *Capacity_adj_factor* did not cause a practically important change in TOC estimates. Neither changes in *Tolerance_fc* nor *Pr_Fdc* caused a change in the output estimates in TFI by ⩾15 days.

Discussion

In this study, we aimed to develop a robust risk assessment model to estimate the TOC or TFI emerged in nursery and grow-to-finish pork production operations under movement restrictions during a CSF outbreak in Indiana, USA. These two adverse animal welfare outcomes could pose immediate challenges to swine producers and disease outbreak control personnel during a CSF outbreak as demonstrated in this study. Despite our use of Indiana swine industry data for developing the model, only two input parameters, *Intl_numb*

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and *ED*, were derived partially based on the data. Therefore, the TOC and TFI estimates from our model should be generalizable to other states in the United States and even other countries that have similar pork production systems. Our model did not take into account individual variabilities within premises. This omission might result in underestimating the uncertainty of TOC and TFI estimates (expressed by the 5th and 95th percentiles).

The finding that overcrowding occurred in all simulated iterations during a 365-day period highlights the importance of this consequence under movement restrictions. The study goal was to develop a robust, but empirically supported, risk model that can be easily adapted by decision makers (e.g. government authorities) and researchers using the available surveillance data of swine premises. To achieve this goal, the model algorithms for detecting the emergence of overcrowding on premises were constructed with the assumption that swine producers would maximize the utility of facility capacity. Specifically, overcrowding was defined as the total weight of pigs on premises exceeding 100% to 115% of the maximum capacity of the premises. This assumption aligns with modern intensive pork production operations that often utilize the maximal facility space to raise pigs. The approach also provides several advantages in building risk models over the previously published modelling approach (Bargen and Whiting, 2002). First, our models use age and weight to quantify overcrowding, which reduces errors and inconsistencies in converting between weight and occupancy space. Second, with the assumption of maximal utilization of facility capacity, our models are robust and do not require information on the dimensions or types of individual housing facilities to determine overcrowding. Because the facility-specific information on dimensions and types is not routinely collected in swine premises surveillance in the United States, our model algorithms allow a broader application to any size and type of swine premises. This robustness is critical in planning foreign animal disease outbreak control, because it must cover extensive geographic areas at a state or national level. Despite the differences in the model assumptions and algorithms, the estimated median TOC in nursery premises from our study is comparable with the estimate derived from a study of seven nursery farms in Canada (Bargen and Whiting, 2002). Both studies showed that overcrowding would occur on nursery swine premises within 1 month after implementation of movement restrictions. This finding that overcrowding could occur much faster on nursery swine premises compared with grow-to-finish premises corresponded to the difference in the age range of pigs in those two types of operations. Typically, the age of nursery pigs ranges from 19 to 65 days and grow-to-finish pigs from 40 to 165 days. Overcrowding was modelled to emerge on premises after pigs passed the harvest/transition age.

When a foreign animal disease outbreak, such as CSF, emerges, the owners of the swine premises inside a movement restriction zone need to quickly make critical decisions. To make informed decisions about how to maximize profits and minimize losses, the owners must consider the characteristics of premises (e.g. production type and how far the pigs are from the harvest/transition age) as well as different outbreak-related parameters (e.g. estimated ED and the outbreak control measures imposed). In this study, three decision attributes were incorporated into the algorithms to model the probability of a swine producer's decision to discontinue feed and euthanize the pigs. The assumption was that a longer estimated ED or a longer time interval between the age at the onset of the outbreak and the harvest/transition age or a longer progression of an ongoing outbreak would increase the probability of that producer might decide to discontinue the feed supply and euthanize the pigs. Based on these assumptions, the simulation results showed that about 90% of feed interruption, if it did occur, would result at an early stage (i.e. within 15 days) of an outbreak (Figure 2). This finding signifies the importance of including mitigation plans for alleviating animal welfare problems in outbreak management. The mitigation actions, including on-farm euthanasia and controlled movements, would compete for the same resources for other outbreak control activities, such as risk assessment, depopulation of infected premises, preemptive culling and carcass disposal. Therefore, an early onset of subsequent animal welfare issues during an outbreak could greatly hinder outbreak control if the mitigation strategy for alleviating animal welfare problems is not appropriately planned.

Our risk model estimated that all nursery premises under movement restrictions would encounter either overcrowding or feed interruption within 50 days of a CSF outbreak, whereas most of the grow-to-finish premises under movement restrictions would encounter these problems within 130 days (Table 2, Figure 3). The USDA CSF response plan states that quarantine and movement control restrictions will be maintained until at least 28 days have elapsed since the decontamination of all confirmed infected premises and negative results of surveillance activities (USDA, 2013). Furthermore, the median ED of a multiple-site CSF outbreak in Indiana was estimated to be about 200 days (Yadav *et al.*, 2016). Therefore, the movement restriction could last for >200 days during the course of CSF outbreak control in Indiana, which suggests that overcrowding or feed interruption would inevitably emerge among the swine premises under movement restrictions during a CSF outbreak in Indiana. This conclusion is likely to hold even though one of the model input parameters, *Capacity_adj_factor*, was found to have an influential impact on the estimate of TOC in nursery premises. Historical outbreaks further support these estimates by showing that the majority of animals were euthanized due to animal welfare concerns during foreign animal disease outbreaks (Edwards *et al.*, 2000; Terpstra and de Smit, 2000; Allepuz *et al.*, 2007). The current USDA foreign animal disease outbreak management manual (USDA, 2012a and 2013) states that movement restrictions are to be imposed within 7 km of the perimeter of an infected zone. This might result in a large number of swine premises falling within a movement restriction zone, indicating a demand for numerous resources to enforce movement

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restrictions and manage subsequent animal welfare problems (East *et al*., 2014). Without sufficient enforcement, illegal movements of pigs and their products outside control zones could impede the efforts towards disease confinement. However, animal welfare concerns could emerge quickly if movement restrictions were fully executed, as demonstrated in this study. The early onset of animal welfare problems during a CSF outbreak could greatly hamper outbreak management because the execution of mitigation strategies would require competing resources for other outbreak control activities. Thus, mitigation strategies for alleviating animal welfare consequences must be thoroughly formulated as part of the contingency plan for foreign animal disease outbreak controls to ensure proper distribution of limited resources for outbreak management. To aid in CSF contingency planning, the TOC and TFI derived from our risk models can be incorporated with the livestock data to estimate the number of nursery and grow-to-finish premises under movement restrictions that might encounter overcrowding or feed interruption during a CSF outbreak in a particular region. For example, we estimated that 9% to 24% of the swine premises in Indiana might encounter overcrowding or feed interruption during a CSF outbreak in another study of ours. Given an average herd size of 950 pigs, 0.7 to 2 million pigs would be affected and need to be euthanized on farm or moved to slaughter plants. These estimates can be used to assess required resources for executing mitigation strategies and to conduct a cost-benefit analysis for evaluating different CSF outbreak control strategies.

In conclusion, the study risk model reveals that overcrowding and feed interruption are likely to emerge among swine premises under movement restrictions at an early stage of a CSF outbreak. The early onset of adverse animal welfare outcomes may compete for the resources for other disease control activities and hamper outbreak control progress. The outputs derived from this study could be integrated with livestock data to estimate and evaluate different mitigation strategies.

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