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Simulation of foot-and-mouth disease spread within an integrated livestock system in Texas, USA

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ABSTRACT

We used a simulation study to assess the impact of an incursion of foot-and-mouth disease (FMD) virus on the livestock industries in an 8-county area of the Panhandle region of Texas, USA. The study was conducted in a high-density livestock area, with an estimated number of cattle on-feed of approximately 1.8 million. We modified an existing stochastic, spatial simulation model to simulate 64 scenarios for planning and decision-making. Our scenarios simulated four different herd types for the index herd (company feedlot, backgrounder feedlot, large beef, backyard) and variations in three mitigation strategies (time-of-detection, vaccine availability, and surveillance during disease control). Under our assumptions about availability of resources to manage an outbreak, median epidemic lengths in the scenarios with commercial feedlot, backgrounder feedlot, large beef and backyard index herd types ranged from 28 to 52, 19 to 39, 18 to 32, and 18 to 36 days, respectively, and the average number of herds depopulated ranged from 4 to 101, 2 to 29, 1 to 15 and 1 to 18, respectively. Early detection of FMD in the index herd had the largest impact on reducing (~13–21 days) the length of epidemics and the number of herds (~5–34) depopulated. Although most predicted epidemics lasted only ~1–2 months, and <100 herds needed to be depopulated, large outbreaks lasting ~8–9 months with up to 230 herds depopulated might occur.

1. Introduction

Foot-and-mouth disease (FMD) is a highly contagious, transboundary disease affecting all cloven-hoof species. It has long been considered the most dangerous foreign animal disease that might be inadvertently introduced into the United States (Breeze, 2004). Estimates of the cost of FMD outbreaks (approximated in $US) include ~$1.6 billion (Taiwan, 1997) (Yang et al., 1997), >$15 billion (U.K., 2001) (Kao, 2003), $5–12 billion (Australia) (Productivity Commission, 2002) and ~$14 billion (U.S.) (Paarlberg et al., 2002).

FMD has not been present in the U.S. since 1929, when there were outbreaks in California and Texas (McVicar et al., 1974). With the absence of FMD in the U.S. for >75 years, disease modeling is an essential tool for predicting the likely spread of the infection and for evaluating the effectiveness of various mitigation strategies (Bates et al., 2003). Recent outbreaks in previously disease-free countries (including Japan, South Korea, France, The Netherlands and the U.K.) have highlighted the importance of well-planned response strategies (Garner et al., 2007; Velthuis and Mourits, 2007) for regaining disease freedom following an incursion of FMD (Garner and Beckett, 2005).

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In most cases of foreign animal disease incursions, decisions regarding mitigation strategies must be made with little current or empirical data and in the context of political, economic and social pressures. Several simulation models of FMD spread within livestock populations have been developed over the last 20 years. Garner and Lack (1995) compared the impact of a hypothetical outbreak in three regions of Australia. Their model was further extended to operate within a geographic information system (GIS) framework and to incorporate real farm boundary and point-location data, and to provide a range of maps and statistics to assist with policy development and disease management (Garner and Beckett, 2005; Beckett and Garner, 2007). Bates et al. (2003) used a spatial model to investigate the spread of FMD virus within and between herds and flocks of beef, dairy, swine, goats and sheep and sale barns in an area of central California. Their model was also used to investigate hypothetical FMD spread from the California State Fair (Carpenter et al., 2007). Schoenbaum and Disney (2003) developed a national (U.S.-specific) model to investigate alternative mitigation strategies, including vaccination and slaughter. Their model (further refined) was selected by the North American FMD Vaccine Bank for use in policy formulation (Harvey et al., 2007).

FMD spread is commonly simulated using a state-transition, susceptible-latent-infectious-recovered (SLIR) framework. Generally, the motivation for developing such models is to explore the effectiveness of different mitigation strategies on the potential size and cost of an FMD incursion, rather than accurately predicting the size and duration of outbreaks (Bates et al., 2003). The use of models of FMD spread in livestock populations, applied to the 2001 FMD outbreak in the U.K., was important in that for the first time models were used during an outbreak to guide outbreak management policy (Green and Medley, 2002). Whether simulation models should primarily be used to prepare outbreak response plans – or whether they have a role in guiding response during an outbreak – is debated (Kao, 2002; Kitching, 2004; Crispin, 2005). Model simplicity vs. model realism is often at the center of such debate (Kao, 2002), and the need for high-quality empirical data (Hugh-Jones, 1976; Maragon et al., 1994; Gibbens et al., 2001; Perez et al., 2004) cannot be overemphasized.

Texas is the largest cattle-production state in the U.S., with >14 million cattle and calves produced annually (~20% of the nation's beef cattle) (USDA, 2006). Texas has an estimated 6 million cattle on feed and the feedlot industry is valued at >8 billion dollars annually (USDA, 2006). The predominant concentration of the feedlot industry in Texas is within the Panhandle region. Thus, any incursion of FMD virus in this region could have a severe impact.

Our objectives were to develop and apply a decision support system that assists policy formulation to detect and respond efficiently to incursions of FMD within the Panhandle region of Texas. We modified an existing FMD-spread model to do this. The consequences of FMD incursions and the impact of a range of mitigation strategies in an integrated intensive and extensive livestock system were investigated.

2. Methods

2.1. Study area

The study area (20,570 sq. km), comprising Bailey, Castro, Deaf Smith, Hale, Lamb, Parmer, Randall and Swisher counties, is located in the Panhandle region of Texas (Fig. 1). There were 1058 beef-cattle premises in the study area in 2002 (USDA, 2006). According to the Texas Commission on Environmental Quality (TCEQ), which is responsible for maintaining records on concentrated animal feeding operations (including feedlots and dairies), there were 92 feedlots and 76 dairies in the study area in 2006. The feedlots in the study area range in capacity from <5000 to >100,000 cattle. In feedlot operations, cattle are confined to pens and are hand-fed, whereas in large and small beef herds and backyard herds, cattle are either predominantly or solely grazed on pasture.

A spatial description of grazing beef cattle in the study area was developed using land-parcel data from the USDA Farm Services Agency (FSA) and estimated carrying capacity from the National Resources Range Capacity guides. Improved pasture, shrub land, herbaceous, rangeland and forest were the land-cover types we selected from the United States Geological Survey (USGS) 1992 National Land Cover Dataset (NLCD). The number of 30-m pixels within each land-cover type were counted and standardized by dividing by the total number of pixels. Land cover type-specific stocking rates, based on the USDA Natural Resources Conservation Service (NRCS) range condition guides, were used to weight the proportion of each land-cover type. The total number of cattle per county were multiplied by these weighting values and distributed across land-cover type at a 30-m resolution. The estimated cattle counts were then aggregated to premise boundaries. An estimated 411,019 grazing beef cattle were distributed over ~10,000 land parcels in the study area.

A quantitative survey tool, using in-person interviews, was developed to gather detailed information from owners and managers of feedlots, beef herds, dairies and swine operations on livestock movements (direct contacts off the premises, direct contact on to the premises, indirect contacts) for each of the livestock types (Loneragan et al., 2006).

2.2. Model formulation

The AusSpread model is a stochastic, state-transition susceptible-latent-infected-recovered (SLIR) model, which operates within a GIS framework (Garner and Lack, 1995; Garner and Beckett, 2005; Beckett and Garner, 2007). The model uses spatial distributions of livestock, including feedlots, dairies, beef, swine, small ruminants (sheep and goats) and backyard herds and their predicted contact structure to model the spread of FMD within a region. The AusSpread model has three options for modeling the spread of infection, depending on the amount and detail of population and movement data available: a spread-rate parameter, which is analogous to the basic reproductive ratio (R_0); modeling specific infection pathways (for example, direct and indirect contacts, local spread, spread

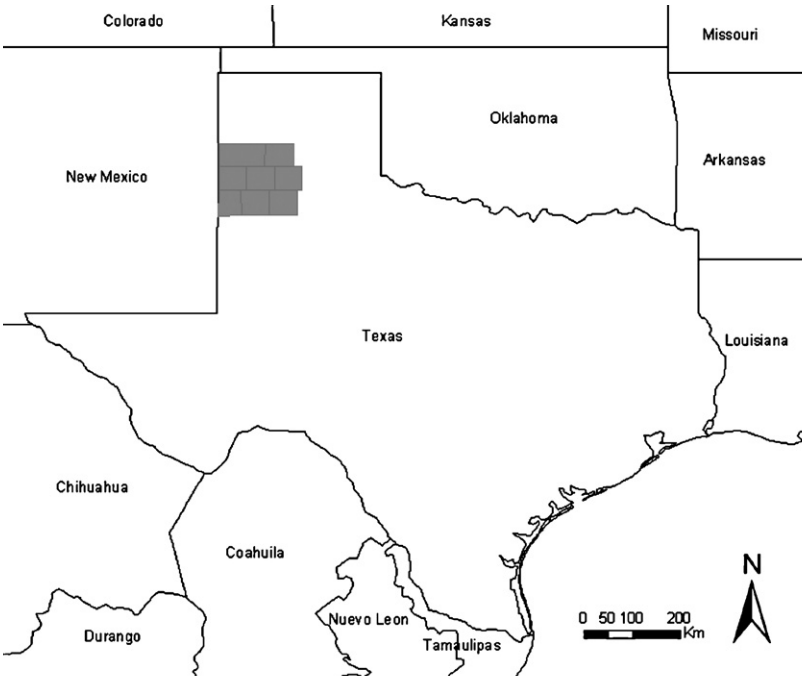

Fig. 1. An 8-county region of the Texas Panhandle, USA, selected for modeling the potential incursion of foot-and-mouth disease virus initiated in a range of index herd types. Neighboring US and Mexican states are indicated.

due to sale barns and windborne spread); and a mixed (R_0 and pathways) approach. For this study, we collected specific data to enable the second option to be used and we incorporated into the model the following infection pathways: direct contacts, indirect contacts, spread through sale barns and windborne spread.

We parameterized the AusSpread model using data collected during meetings and from surveys (Loneragan et al., 2006) and expert opinion. Through meetings with industry representatives (including the Texas Cattle Feeders Association, TCFA), we developed a qualitative description of livestock movements through various contact points in the livestock production chain of the study area. We identified 13 functional herd types, determined by contact structures that might influence FMD spread (Table 1). Six of these herd types were feedlots (confined animal feeding operations). A company-owned feedlot is an operation in which a company owns or buys cattle for the purposes of feedlotting and processing. In contrast, a stockholder feedlot is an operation in which individuals contract a feedlot to produce a pre-specified product for processing. In a custom feedlot, lots of purchased cattle are fed to pre-specified criteria. Backgrounder feedlots pre-condition cattle, usually from pasture, prior to entry into a feedlot for finishing. In a yearling-pasture feedlot, cattle <12 months of age raised on pasture are accustomed to feedlot rations. In a dairy-calf raiser feedlot, male dairy calves originating from dairy herds are accustomed to feedlot rations prior to finishing in a different feedlot. Small and large dairies herds were defined as those with <1000 and ≥1000 cows, respectively. Small and large beef herds were defined as those with <100 and ≥100 adult cattle, respectively. Backyard herds were defined as non-commercial herds, in this study using an arbitrary cut-off of 10 cattle.

We had access to data describing the 92 feedlots registered by the TCEQ (with known capacities and location information) in the study area in 2006. These feedlots were categorized as company-owned, stockholder, custom or yearling-pasture feedlots, respectively,

Table 1
Livestock industry-based opinion (company, stockholder, custom and yearling-pasture feedlots) and actual (background feedlot, dairy-calf raiser feedlot, small and large beef, small and large dairy, small ruminant, and backyard) distribution of herds types in an 8-county area of the Texas Panhandle, USA, used as input to simulate the potential incursion of foot-and-mouth disease virus and the impact of disease-mitigation strategies.

Herd type	Number of livestock	Number of herds	Mean herd size
Company feedlot[a] (≥ 50,000 cattle)[b]	348,000	5	69,600
Stockholder feedlot[a] (≥20,000 to <50,000 cattle)[b]	1,061,080	32	33,159
Custom feedlot[a] (≥5000 to <20,000 cattle)[b]	284,000	25	11,360
Backgrounder feedlot[a]	43,200	7	6,171
Yearling-pasture feedlot[a] (<5000 cattle)[b]	53,960	22	2,453
Dairy-calf raiser[a]	8,000	1	8,000
Small beef[a]	194,091	6403	30
Large beef[a]	195,964	754	260
Small dairy	8,910	14	636
Large dairy	345,830	62	5,578
Backyard[a]	9,682	2435	4
Small ruminant	13,065	913	14
Swine	5,830	2	2,915

[a] We assumed these herd types were eligible to purchase from a sale.
[b] Feedlots categorized based on capacity information.

based on their known capacity: >50,000, ≤50,000–20,000, ≤20,000–5000 and <5000. The locations of all seven backgrounder feedlots within the study area were known and therefore this information was used directly in the model without the need to infer their locations. Industry-derived information indicated there was only 1 dairy-calf raiser in the study area, and that the operation had ~10,000 cattle. A 10,000-head feedlot listed in the TCEQ database was randomly selected using a random-number generator (MapBasic 7.8. MapInfo Corporation, Troy NY, 2004; this same random-number generator was used for every instance of random number generation) and designated as a dairy-calf raiser feedlot. New code (MapBasic 7.8. MapInfo Corporation, Troy NY, 2004) was written to allow these feedlot types to be incorporated into the AusSpread model.

Two sale barns existed in the study area. Their known locations and the days of the week that sales were held were incorporated into the model. The number of buyers per sale, and their minimum and maximum travel distance were based on the knowledge of local industry groups (including the TCFA).

Periods of FMD virus latency, infectiousness and immunity in infected herds, between-herd FMD virus-dissemination rates, and vaccine effectiveness were based on expert elicitation of parameters for Texas, via an emailed questionnaire. Ten experts with field experience of FMD control were purposively chosen for this survey. These experts worked within academic and government institutions located in the United States, Argentina, and New Zealand. The experience of these experts controlling FMD had been gained mostly in South American countries, including Argentina and Colombia. To help elicit parameters of interest, the **s**elected experts were provided with the following scenario:

> "The setting is predominantly rangeland characterized by plains of thorny shrubs and trees and scattered patches of palms and subtropical woodlands. The primary vegetation includes species such as mesquite, acacia, and prickly pear mixed with areas of grasses. Seasonal variation is characterized by hot, dry summers and mild, moist winters, with average annual rainfall in the range of 20–30 inches per year. Livestock production in the area is predominantly extensive grazing with beef cattle and goats. However, there are pockets of intensive operations such as feedlots, dairies and small-scale confined swine operations. In addition, wildlife species such as white-tailed deer and feral hogs are common. Vaccination has not been previously administered in this region. Assume that FMD virus serotype specificity is not an issue."

Experts were requested to estimate the likely range (5th and 95th percentiles), and then to provide their 'best estimate' (median), of values that might be observed in an outbreak of FMD in Texas for the infection dissemination rate at the beginning of an outbreak; the period taken for control measures to fully take effect; the dissemination rate during and following implementation of control measures; the expected decrease in dissemination rate following implementation of vaccination, quarantine, or vaccination and quarantine simultaneously; seasonal dissemination rates; how many days it might take for FMD to be diagnosed in the index herd; latent, infectious, and immune periods by herd type; and the susceptibility of herd types to FMD virus infection and period of infectiousness, relative to the beef herd type. Expert's median estimates were calculated and in the model, expert opinion information was sampled from the resulting triangular (minimum, most likely, maximum) distributions.

The model was adapted to keep track of each herd (based on unique identification numbers) by model run, and to track herds under quarantine for all runs.

2.3. Model assumptions

We assumed contacts that potentially might result in the infection of a herd could be classified as direct or indirect. We defined direct contact as physical contact between ≥1 animals within an infected herd and animals within a susceptible herd. We defined indirect contact as contact that might allow the passive transfer of virus to a susceptible host via intermediate objects such as contaminated products, vehicles, equipment and other inanimate objects; or via people (for example, veterinarians, technicians, and stockmen) having contact with animals. We assumed that people or equipment (such as vehicles and veterinary and husbandry equipment, including ropes and needles) contaminated with FMD virus from an infected herd would be an indirect contact if they could come into contact with livestock or where livestock are kept. For example, if a cowboy has a backyard cattle herd that is infected, has manure from these livestock on his shoes or saliva on his clothing, and then comes to work and contacts feedlot cattle or contaminates pens, this would be considered an indirect contact. If the tires of his vehicle are contaminated, but he leaves his vehicle in a parking area away from feedlot cattle, this would not be considered a potential contact. In contrast, direct contacts essentially constituted the movement of infected livestock between premises.

Contact probabilities and number of contacts per day were elicited from survey data and local industry opinion. Direct and indirect contact rates (per day) and the probabilities of FMD virus infection, given a direct or indirect contact, are shown in Table 2. All cattle from company, stockholder and custom feedlots were assumed to be consigned direct to slaughter (resulting in no potential direct contacts). Backgrounder and yearling-pasture feedlots and dairy-calf raiser herds were assumed to have one direct contact per day, as were swine herds. Probabilities of infection, given a direct contact, were assumed to be high (≥90%) regardless of herd type. However, probabilities of infection given an indirect contact were assumed to be low (≤20%) for all herd types, with the exception of swine herds. In the model, all contact probabilities were sampled from binomial distributions.

For this study we assumed that FMD could be detected either early (7 days) or late (14 days) following an incursion. We assumed that once FMD has been detected, the number of direct contacts was reduced by 80% and the

Table 2
Livestock industry-based opinion and survey estimated direct and indirect contact rates (per day) and probability of foot-and-mouth disease infection, given contact, by herd type used as input to simulate the potential incursion of foot-and-mouth disease virus and the impact of disease-mitigation strategies in an 8-county area of the Texas Panhandle, USA.

Herd type	Contacts[a]		Probability of FMD infection	
	Direct[b]	Indirect[c]	Direct[d]	Indirect[e]
Company feedlot	N/A	45	0.95	0.20
Stockholder feedlot	N/A	33	0.95	0.20
Custom feedlot	N/A	23	0.95	0.20
Backgrounder feedlot	1.0	5	0.95	0.20
Yearling-pasture feedlot	1.0	5	0.95	0.20
Dairy-calf raiser	1.0	5	0.95	0.20
Small beef	0.01	3	0.95	0.10
Large beef	0.10	5	0.95	0.10
Small dairy	0.01	10	0.95	0.20
Large dairy	0.10	20	0.95	0.20
Backyard	0.01	5	0.90	0.15
Small ruminant	0.10	5	0.90	0.10
Swine	1.0	10	1.00	1.00

[a] Total number of contacts per day that could possibly result in transmission of FMD virus from the indicated herd type to other herds.
[b] Total number of direct contacts per day; a direct contact represents the movement of livestock between herds. For example, direct contact of 0.10 for large dairies implies that, on average, a cow/calf is introduced every 10 days.
[c] Total number of indirect contacts per day; indirect contacts are all those contacts between herds that could transmit FMD virus, other than livestock movements.
[d] Probability of FMD virus infection, given a direct contact.
[e] Probability of FMD virus infection, given an indirect contact.

number of indirect contacts was reduced by 50% the following day, to represent the effect of implementing movement-control measures.

We assumed the number of buyers per sale in the study area was 100. We assumed that 90% of sales were within-region (sampled from a binomial distribution). In-region buyers were assumed to travel to the sale a minimum of 10 km and a maximum of 150 km. We assumed the probability of sending infected livestock to sale from an infected herd, on the day a sale was held, to be 5%, adjusted for the time since the herd was infected. This function was modeled as a stochastic (binomial) event: a random number was generated using a random-number generator and if it was less than the adjusted probability of sending livestock to sale then infected livestock were sent to the sale from that herd. These calculations were performed independently each time a sale was assumed to be held. We assumed that once infected livestock were transported to a sale, the sale barn was infected. The sale barn was reset to uninfected status after each sale. We assumed that only small and large beef herds sold livestock at sales. We assumed that the probability of buying infected livestock from each infected sale was 5% (sampled from a binomial distribution) for all buyers within the specific radius of the sale (minimum 10 km, maximum of 150 km). The probability of these herd types buying infected livestock from a sale was assumed to be a uniform distribution. We assume that the probability of a herd sending livestock to a sale and purchasing livestock from a sale were independent events. All sale barns were assumed to be shut down on the day following detection of an incursion of FMD virus in the study area.

We assumed that windborne spread of FMD virus was possible only from company-owned feedlots and swine herds. The risk of windborne spread of FMD is considered highest for swine herds (Cannon and Garner, 1999; Donaldson et al., 2001). Although the risk of spread from cattle herds is comparatively low, by analogy with swine herds, we assumed that an infected feedlot with large numbers of cattle (>50,000) could function as a swine herd with respect to the windborne spread of FMD. The probability of windborne spread depended on temperature and humidity, as previously described (Garner and Beckett, 2005). The infection of a herd depended on prevailing wind speed and direction. Average monthly climatic parameters were derived from historical weather station readings in and surrounding the study area.

2.4. Disease mitigation

In all simulations, quarantine of infected premises and a ban on livestock movement was assumed. A range of additional disease mitigation strategies were modeled.

2.4.1. Herd depopulation

We assumed that depopulation of livestock on infected and dangerous-contact premises began 1 day following detection of an FMD virus incursion in the study area, and that only the index herd would be depopulated on this day. Pre-emptive depopulation of herds may also be considered—this can include dangerous-contact herds and herds within a neighborhood. Once a herd is diagnosed as infected, all of the herds exposed via direct and indirect contacts from that herd were identified and tracing (forward) of these dangerous-contact herds was initiated. We assumed that the process of tracing takes between 1 and 3 days (randomly assigned, using a random-number generator, to the identified list of herds as a uniform distribution). For trace forward, herds identified as dangerous-contact herds could subsequently be found to be infected or non-infected. Thus, the process of tracing was assumed to have an implicit sensitivity (1 – proportion of infected herds falsely excluded) and specificity (1 – proportion of uninfected herds falsely included) and sampled using a binomial distribution. For direct and indirect contacts, sensitivities and specificities of 0.95 and 0.90, and 0.85 and 0.50, were assumed, respectively. Trace back was used to identify the source of infection for a newly diagnosed infected herd and to identify buyers of infected livestock from sales. For trace back of infected herds, the same time period and sensitivities and specificities as for trace forward were assumed. For tracing sale barns we assumed the process took 1–4 days (randomly assigned, using a random-number generator [MapBasic 7.8. MapInfo Corporation, Troy NY, 2004] and a uniform distribution) with a sensitivity of 90%. Herds neighboring infected herds, within a given radius, were flagged for depopulation. In scenarios in which vaccination was used, such neighborhood (ring) depopulation could be used with a targeted-vaccination strategy, but not with a ring-vaccination strategy.

In scenarios in which ring vaccination was used to control FMD virus spread, we assumed the depopulation of dangerous-contact and neighboring herds ceased once ring vaccination began. Depopulation response policy and capacity was modeled as follows. The number of herds that could be depopulated per day was assumed to depend on resource availability, limited by the number of available depopulation teams. A response team was assigned to each herd designated for depopulation and remained committed to that herd until depopulation, disposal and decontamination were completed. The number of teams available was modeled as a linear function increasing over time until the maximum number of teams available was reached. The number of teams available was derived from information provided by local industry personnel. We assumed that initially only one team was available, increasing (as linear function over the period 1–21 days following detection of the incursion) to a maximum of 10 teams per day. We assumed that slaughter began 1 day post-detection, and that only one herd (the index herd) was slaughtered on that day. Estimates of the length of time required for depopulation, disposal and decontamination to be completed for each herd type were obtained directly through a series of meetings held with industry personnel (Table 3). In the case of feedlots, we assumed that 1 and 2 weeks following detection 1000 and 2500 cattle per day, respectively, could be slaughtered. More than 15 days post-detection, we assumed that up to 5000 cattle per day in feedlots could be slaughtered. Herds were prioritized for depopulation based on their risk category and time since diagnosis. Risk categories were formulated based on the opinions of industry personnel, together with assumed infectiousness of herd types (Table 3).

2.4.2. Vaccination

Possible vaccination strategies modeled were suppressive (or emergency) ring vaccination and targeted protective vaccination. With the ring-vaccination option, all herds within a radius of 5 km of a newly identified infected herd were vaccinated. This reduced the probability that susceptible herds within the immediate vicinity of the infected herd became infected. By decreasing the amount of FMD virus emission, this also reduced the potential for subsequent spread if the herd did become infected. The targeted protective-vaccination strategy involved selecting herds of particular types and vaccinating them before they were exposed to infection. Vaccination under either scheme was carried out according to the availability of resources. We assumed that herds were depopulated after vaccination. The AusSpread model keeps track of vaccinated herds. When using vaccine, disease-control authorities might decide to allow all vaccinated animals to remain in the population ('vaccinate-to live') or to remove all vaccinated animals at the end of the outbreak ('vaccinate-to die'). Although these options do not affect the course of the outbreak (the focus of our study), they do have important economic implications.

Table 3
Livestock industry-based opinion of the length of time (days) required for depopulation, disposal and decontamination of herds and the relative risk ranking of these herd types used as input to simulate the potential incursion of foot-and-mouth disease virus and the impact of disease-mitigation strategies in an 8-county area of the Texas Panhandle, USA.

Herd type	Depopulation, disposal and decontamination time (days), per herd	Risk category rank
Company feedlot	28	2
Stockholder feedlot	28	2
Custom feedlot	21	4
Backgrounder feedlot	14	4
Yearling-pasture feedlot	14	6
Dairy-calf raiser	14	6
Small beef	5	11
Large beef	10	10
Small dairy	5	9
Large dairy	7	8
Backyard	1	12
Small ruminant	3	13
Swine	10	1

We assumed that vaccine was unavailable until 1 week after disease detection. Furthermore, we assumed that the capacity to vaccinate herds increased during the weeks following detection of an FMD virus incursion. Estimates of capacity were derived via meetings with industry representatives. We assumed that vaccination reduced the resources available for herd depopulation by 25% because of the reallocation of staff to vaccination operations. Herds suspected (but not confirmed) of being infected and dangerous-contact herds were not eligible for vaccination. Ring vaccination caused any dangerous-contact herds that had not been depopulated to be put under disease surveillance. We assumed that it took 4–6 days for a vaccinated herd to be fully protected. To represent the range of likely situations from exposure of a herd when no animals are protected (100% susceptibility) to virtually all animals being protected (that is, 0% susceptibility), we assumed that on average a vaccinated (but not yet immune) herd exposed to infection during this period was 50% (fixed value) as susceptible as an unvaccinated, fully susceptible herd.

Scenarios in which we assumed either adequate or inadequate vaccine supply were modeled by having vaccine available for use on either day 14 or 21 of the FMD virus incursion, with a maximum vaccination capacity of 12, 25 and 50 herds during the periods 14–20, 21–27 and >27 days, and 21–27, 28–34 and >34 days, respectively, following an incursion. In addition, we assumed that in the adequate vaccine-supply scenarios, vaccination did not reduce the resources available for herd depopulation. In contrast, in the inadequate vaccine-supply scenarios, we assumed that vaccination reduced the resources available for slaughter by 25%.

2.4.3. Disease surveillance

Another mitigation considered was the type of disease surveillance activities – either passive or active – following detection of an FMD virus incursion. Passive surveillance was based on reporting of presence of clinical signs by stock owners. Active surveillance, based on targeted surveillance visits to herds around infected premises by surveillance teams, allowed earlier detection of the spread of infection and newly infected herds, thus assisting in disease control. The capacity for disease surveillance was based on the knowledge of local industry groups, including the TCFA. We assumed that this capacity increased over time to some fixed value several weeks following detection of the incursion. Herds were prioritized for surveillance visits using a user-defined risk categorization. If a herd scheduled for surveillance had not been visited within a certain time frame, then we assumed a visit to be no longer necessary and the herd was removed from the disease-surveillance list. We assumed that disease surveillance ceased when a herd was vaccinated. We also assumed that area-wide active disease surveillance stopped if a ring (neighborhood or contiguous) slaughter policy was implemented.

In scenarios with passive disease surveillance, we assumed that up to three herds were visited on the first day of surveillance. We assumed that suspect herds were visited twice a week during a 30-day period. If a herd scheduled for surveillance had not been visited within 10 days then a visit was no longer necessary and the herd was removed from the surveillance list. For active disease surveillance, we assumed that up to six herds are visited on the first day of surveillance activities. We assumed that suspect herds were visited four times a week during a 30-day period. If the herd scheduled for surveillance had not been visited within 20 days then a visit was no longer considered necessary within passive surveillance strategies.

2.5. Experimental design

Single-site incursions at a company feedlot, backgrounder feedlot, large beef and backyard herd were used to initiate the epidemic for each mitigation strategy. For each of the four incursion herd types, 16 mitigation strategies were simulated to provide a total of 64 scenarios (Table 4). For each scenario, 100 simulations were performed. In several studies, including an international model comparison (Dubé et al., 2007) and other studies using the AusSpread model (M.G. Garner, unpublished data), it has been found that a minimum of 40 simulations is needed to reasonably represent model output (for example, epidemic lengths and herds depopulated) distributions, and that the mean number of infected herds stabilizes (C.V. $<\sim 1$) around 100 simulations.

2.6. Data analysis

The AusSpread model produced summary tables of each model run, including the epidemic length, number of herds infected, number of herds depopulated and number of herds vaccinated. Summary statistics for epidemic length, number of herds depopulated and number of herds vaccinated were generated for each of the 64 scenarios. In addition, summary statistics (minimum, median, maximum) for epidemic length and number of herds depopulated were generated for all scenarios grouped by index herd type and for scenarios specific to early vs. late disease detection, passive vs. active disease surveillance, and adequate vs. inadequate vaccine availability.

Predictive data regarding epidemic length and number of herds depopulated were evaluated for normality and equality of variance using a range of techniques (frequency histograms, Gaussian kernel density estimates, Box plots, normal Q–Q plots, residual plots) prior to further statistical analysis. Box–Cox transformations were used to normalize these variables. An analysis of variance (ANOVA) was used to identify significant differences in epidemic length and the number of herds depopulated for each of the three mitigation strategies for each index herd type. The experiment was considered a complete randomized design. The experimental units were the individual simulation run. The same model was fit to both epidemic length and herds depopulated data: index herd type + mitigation strategy + (index herd type) $\times$ (mitigation strategy). Differences in epidemic length and herds depopulated were compared between scenarios including early vs. late detection (strategies 1, 5, 9, 10, and 16 vs. scenarios 2, 6, 11, 12, 14 and 15), adequate vs. inadequate vaccine supply (scenarios 3, 7, 9 and 11 vs. scenarios 4, 8, 12 and 16), and active vs. passive surveillance (scenarios 5, 6 and 7 vs. 10, 14 and 15). Tukey's multiple-comparison test was used to identify which mitigation strategies resulted in differences. All statistical tests were conducted using a type-I error of 0.05.

3. Results

Of the 10 experts selected and sent questionnaires, five returned usable information regarding FMD virus-dissemination rates and effectiveness of control strategies.

Table 4
Scenarios-of-interest simulated in a study of the potential incursion of foot-and-mouth disease virus in an 8-county area of the Texas Panhandle, USA. The 16 disease control strategies, derived using various combinations of potential mitigations, were simulated 4-times each with the index herd being a company-owned feedlot, backgrounder feedlot, large beef herd, or backyard herd to produce a total of 64 scenarios. In all scenarios, infected herds and dangerous-contact herds were assumed to be depopulated.

Mitigation	Strategy															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Ring depopulation	+	+	+	+	–	–	–	–	–	–	–	–	–	–	–	–
Active disease surveillance	–	–	–	–	+	+	+	+	–	–	–	–	–	–	–	–
Passive disease surveillance	+	+	+	+	–	–	–	–	+	+	+	+	+	+	+	+
Early disease detection	+	–	–	–	+	–	–	–	+	+	–	–	+	–	–	+
Late disease detection	–	+	+	+	–	+	+	+	–	–	+	+	–	+	+	–
Targeted vaccination with adequate supply	–	–	+	–	–	–	+	–	–	–	–	–	+	–	+	–
Targeted vaccination with inadequate supply	–	–	–	+	–	–	–	+	–	–	–	–	–	–	–	–
Ring vaccination with adequate supply	–	–	–	–	–	–	–	–	–	–	+	–	–	–	–	+
Ring vaccination with inadequate supply	–	–	–	–	–	–	–	–	+	–	–	+	–	–	–	–

Table 5
Expert-derived median (5th and 95th percentiles) dissemination-rate, disease-detection, and control-period parameters used as input to model the potential incursion of foot-and-mouth disease virus in an 8-county area of the Texas Panhandle, USA. The minimum and maximum values estimated by the five experts are shown for each of the seven parameters and three percentiles.

Parameter	5th percentile	Median	95th percentile
Initial dissemination rate	0, 2	3, 4.5	4, 8
Weeks for control to be effective	1, 1	2, 4	3, 12
Dissemination rate when control becomes effective	0, 0.4	0, 1	0, 2
% decrease in dissemination rate due to vaccination	30, 60	70, 90	90, 90
% decrease in dissemination rate due to quarantine	10, 50	50, 90	70, 95
% decrease in dissemination rate due to quarantine and vaccination	40, 70	80, 95	95, 99
Days to discover FMD in index herd	1, 7	10, 15	21, 35

3.1. Expert opinion—dissemination rates and disease control

Minimum and maximum parameter estimates are shown in Table 5.

3.2. Expert opinion—latency, infectiousness and immunity

Estimated periods of latency, infectiousness and immunity by herd type are shown in Table 6. Periods of latency, infectiousness and immunity ranged from 2 to 10, 5 to 48 and 60 to 600 days, respectively.

3.3. Livestock industry opinion—vaccination and surveillance capacity

Based on industry opinion (represented by the TCFA), a total of 12 herds per day could be scheduled for vaccination during the first week that vaccine was available. This capacity increased to 25 herds per day during the next 5 days, and then reached a maximum capacity of 50 herds per day. Only three herds could be visited for disease surveillance on the first day following detection of an FMD virus incursion in the study area. If a herd scheduled for surveillance had not been visited within 10 days, then a visit was considered no longer necessary. A herd suspected of being infected could be visited twice a week during a 30-day period.

Table 6
Expert-derived herd type-specific 5th, 50th (median) and 95th percentiles for the periods of herd-level latency, infectiousness and immunity used to parameterize (as triangular distributions) a model of the potential incursion of foot-and-mouth disease virus in an 8-county area of the Texas Panhandle, USA. Values shown are the median of the five experts responding to a questionnaire survey.

Herd type	Latency	Infectiousness	Immunity
Feedlot	2, 3, 5	7, 18, 33	60, 180, 365
Dairy	2, 3, 5	6, 15, 29	90, 210, 430
Beef	2, 3, 7	8, 19, 41	60, 180, 365
Small ruminant	3, 5, 10	11, 27, 48	60, 165, 300
Swine	2, 3, 5	6, 14, 33	60, 150, 270
Backyard	2, 3, 6	5, 11, 22	150, 272, 600

3.4. Epidemic length

Box plots of epidemic lengths, categorized by index herd type, are shown in Fig. 2. Most simulated epidemics lasted <100 days.

Predicted epidemic lengths were associated with both the index herd type and the mitigation strategy assumed (Table 7). Epidemics tended to last longer (medians, 25–52 days) for outbreaks initiated in company feedlots than for outbreaks initiated in backgrounder feedlots, large beef or backyard herd types (medians, 18–39 days). However, the range of epidemic lengths (250 days) was greatest for outbreaks initiated in backgrounder feedlots, least (99 days) for outbreaks initiated in large beef herds, and intermediate for outbreaks initiated in company feedlots and backyard herds (188 and 165 days, respectively). The longest epidemic (265 days) occurred in a simulation in which the index herd type was backgrounder feedlot.

Early detection significantly reduced the length of the epidemic for all index herd types. The greatest proportionate reduction was observed for company and backyard index herd types (Table 8). Adequate vaccine supply significantly increased the epidemic length for outbreaks with large beef index herd type (Table 8). The active-surveillance strategy did not significantly affect the length of predicted epidemics, regardless of the index herd type (Table 8).

Table 7
Analysis of variance of the association between the predicted epidemic lengths, and the predicted number of herds depopulated during control, of a potential incursion of foot-and-mouth disease virus in an 8-county area of the Texas Panhandle, USA and mitigation strategies (time-of-detection, vaccine availability, and disease surveillance during disease control) and index herd-types (company-owned feedlot, backgrounder feedlot, large beef, backyard). Data were generated from 100 simulations of each of 64 scenarios (Table 3) and were transformed using the Box-Cox method prior to analysis.

Variable	Epidemic length					Herds depopulated				
	SS[a]	DF	MSE[b]	*F*-Statistic	*P*-Value	SS[a]	DF	MSE[b]	*F*-Statistic	*P*-Value
Mitigation	3.7457	15	0.2497	314.4	<0.0001	3202	15	213.5	434	<0.0001
Herd type	1.7314	3	0.5771	726.5	<0.0001	2730	3	910.0	1849	<0.0001
Mitigation × herd type	0.0869	45	0.0019	2.43	<0.0001	148	45	3.283	6.67	<0.0001

[a] Sums-of-squares.
[b] Mean square error.

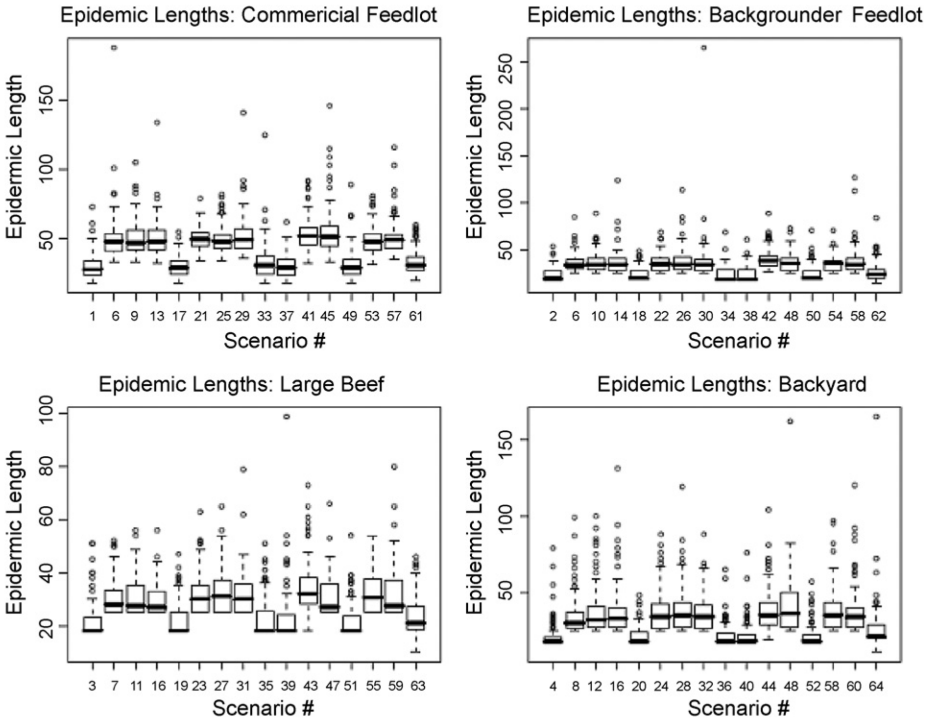

Fig. 2. Box plots of the predicted epidemic lengths of a potential incursion of foot-and-mouth disease virus in an 8-county area of the Texas Panhandle, USA for incursions initiated in four different types of index herds (company-owned feedlot, backgrounder feedlot, large beef, backyard). Data was generated from 100 simulations of each of 64 scenarios (Table 3). The box itself contains the middle 50% of the data. The thick line in the box indicates the median value of the data. The upper edge (hinge) of the box indicates the 75th percentile of the data set, and the lower hinge indicates 25th percentile. The range of the middle two quartiles is the inter-quartile range. The ends of the vertical lines ("whiskers") indicate the minimum and maximum data values, unless outliers are present, in which case the whiskers extend to a maximum of 1.5 times the inter-quartile range. The points outside the ends of the whiskers are outliers.

3.5. Number of herds depopulated

Box plots of the predicted number of herds depopulated, categorized by index herd type, are shown in Fig. 3. In several simulated scenarios with a company feedlot index herd type, >100 herds were depopulated in >25–50% of the simulations.

The predicted number of herds depopulated was associated with both the index herd type and the mitigation strategy (Table 7). More herds tended to be depopulated

Table 8

Comparison, using analysis of variance, of predicted epidemic lengths of a potential incursion of foot-and-mouth disease virus in an 8-county area of the Texas Panhandle, USA by index herd-types (company-owned feedlot, backgrounder feedlot, large beef, backyard) and mitigation strategies (time-of-detection, vaccine availability, and disease surveillance during disease control). Data were generated from 100 simulations of each of 64 scenarios (Table 3) and were transformed using the Box–Cox method prior to analysis. Comparisons were adjusted using Tukey's multiple comparison test, to provide a type I error of 0.05. Significant differences are shown in bold.

Mitigation	Mean difference	S.E.	*t*-Statistic	*P*-Value
Company feedlot				
Early vs. late detection	**0.33**	**0.0098**	**33.72**	<**0.0001**
Adequate vs. inadequate vaccine supply	0.01	0.0080	1.21	0.23
Active vs. passive surveillance	−0.0024	0.0069	−0.35	0.73
Backgrounder feedlot				
Early vs. late detection	**0.27**	**0.0098**	**27.60**	<**0.0001**
Adequate vs. inadequate vaccine supply	−0.0042	0.0080	−0.52	0.60
Active vs. passive surveillance	−0.0027	0.0069	−0.39	0.70
Large beef				
Early vs. late detection	**0.26**	**0.0098**	**27.07**	<**0.0001**
Adequate vs. inadequate vaccine supply	**−0.03**	**0.0080**	**−3.19**	**0.0014**
Active vs. passive surveillance	<−0.0001	0.0069	−0.01	>0.99
Backyard				
Early vs. late detection	**0.34**	**0.0098**	**34.96**	<**0.0001**
Adequate vs. inadequate vaccine supply	0.0060	0.0080	0.75	0.45
Active vs. passive surveillance	−0.0006	0.0069	−0.09	0.93

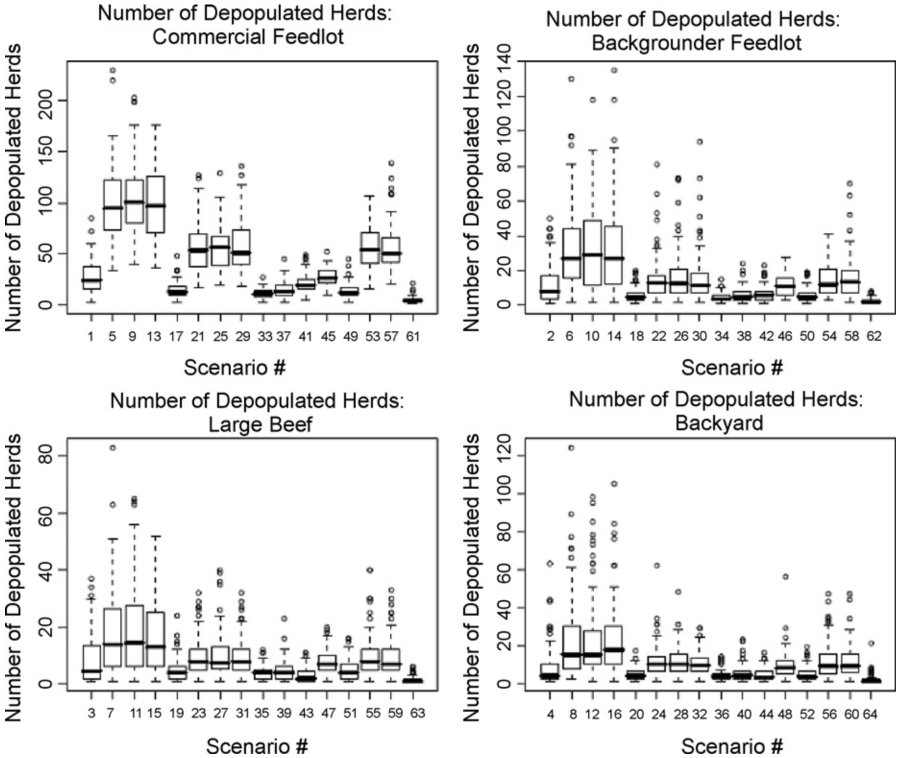

Fig. 3. Box plots of the predicted number of herds depopulated during control of a potential incursion of foot-and-mouth disease virus in an 8-county area of the Texas Panhandle, USA for incursions initiated in four different types of index herds (company-owned feedlot, backgrounder feedlot, large beef, backyard). Data was generated from 100 simulations of each of 64 scenarios (Table 3). The box itself contains the middle 50% of the data. The thick line in the box indicates the median value of the data. The upper edge (hinge) of the box indicates the 75th percentile of the data set, and the lower hinge indicates 25th percentile. The range of the middle two quartiles is the inter-quartile range. The ends of the vertical lines ("whiskers") indicate the minimum and maximum data values, unless outliers are present, in which case the whiskers extend to a maximum of 1.5 times the inter-quartile range. The points outside the ends of the whiskers are outliers.

(medians, 4–101 herds) for outbreaks initiated in company feedlots than for outbreaks initiated in other herd types (medians, 1–29 herds).

Early detection significantly decreased the number of herds depopulated for all index herd types (Table 9). Adequate vaccine supply significantly increased the number of herds depopulated for outbreaks with company feedlot index herd type. The active-surveillance strategy did not significantly affect the number of herds depopulated, regardless of the index herd type (Table 9).

Table 9

Comparison, using analysis of variance, of the predicted number of herds depopulated to control a potential incursion of foot-and-mouth disease virus in an 8-county area of the Texas Panhandle, USA by index herd-types (company-owned feedlot, backgrounder feedlot, large beef, backyard) and mitigation strategies (time-of-detection, vaccine availability, and disease surveillance during disease control). Data were generated from 100 simulations of each of 64 scenarios (Table 3) and were transformed using the Box-Cox method prior to analysis. Comparisons were adjusted using Tukey's multiple comparison test, to provide a type I error of 0.05. Significant differences are shown in bold.

Mitigation	Mean difference	S.E.	*t*-Statistic	*P*-Value
Company feedlot				
Early vs. late detection	**−8.23**	**0.24**	**−33.86**	**<0.0001**
Adequate vs. inadequate vaccine supply	**0.69**	**0.20**	**3.48**	**0.0005**
Active vs. passive surveillance	−0.07	0.17	−0.43	0.67
Backgrounder feedlot				
Early vs. late detection	**−5.80**	**0.24**	**−23.86**	**<0.0001**
Adequate vs. inadequate vaccine supply	0.05	0.20	0.26	0.79
Active vs. passive surveillance	−0.03	0.17	−0.17	0.87
Large beef				
Early vs. late detection	**−4.15**	**0.24**	**−17.09**	**<0.0001**
Adequate vs. inadequate vaccine supply	−0.11	0.20	−0.56	0.58
Active vs. passive surveillance	0.05	0.17	0.27	0.78
Backyard				
Early vs. late detection	**−5.51**	**0.24**	**−22.66**	**<0.0001**
Adequate vs. inadequate vaccine supply	−0.04	0.20	−0.21	0.83
Active vs. passive surveillance	0.03	0.17	0.19	0.85

4. Discussion

Under the assumptions that we (and our experts and livestock industries) considered realistic regarding availability of resources to manage an outbreak, the simulations suggest that typical epidemics of FMD in the study area would last from 1 to 2 months and that ~100 herds might be depopulated to control the epidemic. Although typical simulated outbreaks were small and short-lived, in some scenarios (initiated in backgrounder feedlots) outbreaks lasted up to 8–9 months and in other scenarios (initiated in company feedlots) up to 230 herds were depopulated to control the outbreak. It must be remembered however, that we confined our study to impacts on the Panhandle region of Texas. It cannot be assumed that all movements would be confined to this area. If animals were moved out of this area, secondary outbreaks in other parts of the country might occur. A delay in disease detection would be more likely to produce the latter scenario, compounding the impact of an incursion. Because of its beef-producing importance, any incursion of FMD virus in the Panhandle region of Texas could have a severe impact as a result of stop-movement orders, quarantine, and loss of disease freedom status. It is important to identify mitigation strategies that can reduce such an impact.

Overall, early detection of FMD in the index herd had the largest effect on reducing the epidemic length and the number of herds depopulated to control outbreaks. Under the assumptions used in this study, vaccination with adequate vaccine supply did not offer any significant advantages. It was associated with either increased time to eradication (scenarios with large beef herd as the index herd) or increases in average number of herds depopulated (scenarios with company feedlot as the index herd). Under other circumstances, particularly in large or rapidly spreading outbreaks, vaccination might become a more effective option. Abdalla et al. (2005) showed that vaccination is likely to be a cost effective in situations where FMD would spread rapidly and if available resources are insufficient to maintain effective depopulation. Vaccination would also be associated with additional costs depending on the policy for managing vaccinated animals. With a vaccination-to-live policy, there would be trade implications because under international guidelines (OIE, 2008) a country or zone cannot regain its FMD-free status until 6 months after the last case or the last vaccination (whichever event occurs the latest) where vaccinated animals remain in the population, compared to 3 months if all vaccinated animals are slaughtered. If a vaccinate-to-die policy is adopted there will be increased costs associated with removal of the vaccinated animals, possibly including indemnity payments for those animals with reduced or negligible market value.

The value of early disease detection has been amply demonstrated by the 2001 FMD outbreak in the U.K., where it is estimated that at least 57 farms were infected in 16 counties before the first case was reported (Gibbens and Wilesmith, 2002). We assumed early detection occurred 7 days following an FMD virus incursion in the study area, whereas late detection occurred 14 days following the incursion. The likely time-to-detection in the study area is unknown. We would expect detection to occur early in the case of feedlot, dairy and swine herds where livestock are under regular observation. However, if the incursion occurred in beef, small-ruminant or backyard herds, the time to detection (which also includes reporting delays) could be even >14 days. Efforts to increase awareness amongst owners and managers of these herd types would be beneficial. One option is to educate owners and managers to recognize the early signs of FMD.

The incubation period of FMD in the field, based on the 1967–1968 epidemic in the U.K. is ~8–10 days. Prior to clinical signs of disease, FMD virus infection can be detected via diagnostic tests. Tests based on detection of antibodies are unlikely to be useful during this period of infection; rather, tests based on antigen detection might have application within surveillance programs for early detection of FMD virus incursions (Shaw et al., 2007). Other technological advances might also assist in the early detection of an incursion. There is an opportunity to optimize surveillance systems, particularly through the application of syndromic surveillance algorithms. The economic payoff for detecting an incursion earlier is substantial: in the case of an epidemic originating in a company feedlot, the cost saving might be, on average, $150 million (Elbakidze, unpublished data).

The model we used shares many similarities with an FMD-spread model developed by Schoenbaum and Disney (2003). In the latter, the median duration of outbreaks varied among scenarios from 30 to 109 days, and vaccine and depopulation strategies significantly affected epidemic lengths. Thus broadly, and not surprisingly, outputs from these models are consistent. Using the AusSpread model and a hypothetical FMD virus incursion in southern Queensland, Australia (a region that contains 70 feedlots, >4000 beef herds, and a range of other herd types), Garner and Beckett (2005) predicted outbreaks that lasted in the range of 24–87 days with between 1 and 68 herds depopulated. Again, these results are qualitatively consistent with those we predicted. In a simulation study of FMD spread in Korea, reducing the time between disease incursion and commencement of disease control had the greatest effect on reducing the predicted number of infected farms (Yoon et al., 2006). Those authors found vaccination to be a useful control option only in some circumstances (for example, in the situation where an outbreak is still localised). Although it is tempting to compare quantitative predictions from different simulation models, the simplifying assumptions needed to be able to compare different models makes the value of such comparisons questionable. Indeed, the differences in qualitative predictions produced by different models are of more value for gaining insights into how FMD might spread through livestock populations and the best approaches to its control. Consistency in modelling approaches and broad agreement in model outputs can be used to increase end-user confidence in model predictions (Dubé et al., 2007).

This study was based on an existing, verified, stochastic spatial simulation model of FMD spread. The AusSpread model was updated based, in part, on expert and livestock industry opinion. This has inherent limitations, including the choice of experts, methods of elicitation of opinion, and lack of objectivity. Also, there was limited information available from the survey portion of the study. Despite these limitations, the model is potentially useful for exploring a range of mitigation strategies that might be applied to reduce the impact of FMD in the study area. Incorporation of such simulation results into decision-making and policy needs to be considered.

5. Conclusions

Given the study area (predominantly high density livestock) and the assumptions we made, an incursion of FMD might last up to ~50 days and ~100 herds might need to be depopulated to control the outbreak. Early detection of FMD in the index herd would have the largest impact on reducing the length of epidemics and the number of herds depopulated. In these scenarios the use of vaccine, or active disease surveillance activities following detection of an FMD virus incursion, were predicted to have little impact on further controlling the outbreak.

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