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A dynamic, optimal disease control model for foot-and-mouth-disease: II. Model results and policy implications

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Abstract

A dynamic optimization model was used to search for optimal strategies to control foot-and-mouth disease (FMD) in the three-county region in the Central Valley of California. The model minimized total regional epidemic cost by choosing the levels of depopulation of diagnosed herds, preemptive depopulation, and vaccination. Impacts of limited carcass disposal capacity and vaccination were also examined, and the shadow value, the implicit value of each capacity, was estimated. The model found that to control FMD in the region, (1) preemptive depopulation was not optimal, (2) vaccination, if allowed, was optimal, reducing total cost by 3–7%, (3) increased vaccination capacity reduced total cost up to US$ 119 per dose, (4) increased carcass disposal capacity reduced total cost by US$ 9000–59,400 per head with and without vaccination, respectively, and (5) dairy operations should be given preferential attention in allocating limited control resources.
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Keywords: Optimization model; Infectious livestock disease; Foot-and-mouth disease; Disease control strategies; Economic analysis

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1. Introduction

Optimal control of exotic diseases, such as foot-and-mouth disease (FMD), is a complex problem. Also, decision makers often must base their decisions on limited information. Furthermore, the decision making process is a dynamic one, because actions, such as vaccination or quarantine, while optimal at one point in time may not be at a later date. Simulation modeling was one tool used to aid decision makers identify efficient control strategies during the 2001 FMD epidemic in the UK (Kitching et al., 2006). However, when evaluating multiple levels of alternative control strategies the options in simulation modeling often are too numerous, requiring a more efficient approach (Carpenter et al., 2006).

Previous simulation-model-based studies on cost assessment of exotic animal disease outbreaks, such as FMD in the United States, and economic evaluation of alternative disease control strategies, typically have conducted cost-accountings based on simulated outbreaks (e.g. Ekboir, 1999; Bates et al., 2003a; Schoenbaum and Disney, 2003). Each study evaluated multiple outbreaks given specific assumptions about the rate of disease spread and/or the levels of control strategies. This approach is limited in the number of scenarios that can be examined and thus the policy implications drawn from these exercises are of limited scope.

In this study, alternative FMD-control strategies were evaluated in a comprehensive manner using an optimization framework. The dynamic, optimal FMD-control model developed previously (Kobayashi et al., 2007) was used to search for daily optimal FMD-control strategies in the three-county region in the Central Valley of California (Fresno, Kings, and Tulare counties). The model minimized total regional cost for an entire epidemic duration by choosing the levels of depopulation of diagnosed herds, pre-emptive depopulation, and vaccination. The control levels were allowed to vary daily. The model was implemented with and without a vaccination option. Whether or not vaccination should be used will be determined at the federal level, and a local decision maker must optimize FMD-control strategies based on the federal policy on vaccination. The model determined optimal allocation of limited vaccine doses and carcass disposal capacity. Implicit values of the limited resources called "shadow values" were also calculated; the shadow values provide critical information for capacity building decisions, such as vaccine stockpiling, in preparation for a potential FMD outbreak.

2. Materials and methods

2.1. Model description

A previously developed dynamic optimization model was used to evaluate alternative FMD control strategies (Kobayashi et al., 2007). The model solves for daily control strategies of herd depopulation and vaccination while minimizing the total regional cost for the entire epidemic, given disease dynamics and resource constraints. In the model, the disease dynamics and the impacts of control strategies on the dynamics were characterized in a set of difference equations. Effects of animal-movement restrictions on the disease

Table 1
Industry characteristics of the three-county region of California

	Herd type					
	Beef	Dairy	Swine	Sheep and goat	Backyard	Total
Herd number[a]	664 (30%)	576 (26%)	79 (4%)	131 (6%)	788 (35%)	2238
Mean herd size[b] (head/herd)	853	1727	2519	558	5	na
Total number of animals[c] (000 head)	566.39 (31%)	994.75 (54%)	199.00 (11%)	73.10 (4%)	3.94 (0.2%)	1837.18
Total value of animals[d] (million US$)	338.70 (15%)	1660.24 (74%)	25.87 (1%)	8.84 (0.4%)	na	2033.65

Proportion to the industry total in parentheses; na: not applicable.
[a] Drawn from the three-county survey (Bates et al., 2003b).
[b] Calculated using data from 2002 Census of Agriculture (NASS-USDA, 2004).
[c] Calculated based on the data from 2002 Census of Agriculture (NASS-USDA, 2004) and the three-county survey (Bates et al., 2003b).
[d] Estimated using USDA (2005) and NASS-USDA (2005).

dynamics were also incorporated. The regional epidemic cost included value of slaughtered livestock herds, direct costs of disease control, and daily operational costs for local administration.

The model was parameterized for a three-county region in the Central Valley of California (Fresno, Kings, and Tulare counties). The epidemic relationships were specified using the information obtained from an FMD simulation model developed for the same region (Bates et al., 2003b). The model solved for optimal FMD-control strategies for six herd types: (1) beef, (2) dairy, (3) swine, (4) sheep and goat, (5) backyard herds, and (6) salesyards. Altogether, 2238 herds and 5 salesyards were identified in the region (Bates et al., 2003b). The basic industry characteristics in the region are summarized in Table 1.

The three-county region houses about 1.8 million head of FMD-susceptible livestock (cattle, hogs, sheep, and goats) (National Agricultural Statistics Service, US Department of Agriculture, 2004). More than half of the livestock population is dairy cattle (including milking and dry cows and replacement heifers). Beef cattle represent 31% of the total population, hogs 11%, and sheep and goats 4%. The region is characterized by a concentrated distribution of large-scale dairy operations. These dairy herds are considered to have high disease transmission rates because of the frequent movements of animals, people, and vehicles to and from these operations. Dairy herds also have high asset values (75% of the total livestock asset value in the region, Table 1), and thus an FMD outbreak in this population and subsequent control by slaughtering would result in significant economic losses.

2.2. Model scenarios

The dynamic optimization model was implemented under the following three scenarios: (1) without vaccination, (2) with vaccination, and (3) limited euthanasia/carcass disposal

Table 2
Model assumptions, varied by scenario

	Scenario number			
	(1)	(2)	(3a)	(3b)
Planning time horizon	100 days	100 days	100 days	100 days
Control starts	Day 21	Day 21	Day 21	Day 21
Baseline depopulation	Yes	Yes	Yes	Yes
Preemptive depopulation	Yes	Yes	Yes	Yes
Vaccination	No	Yes	No	Yes
Vaccine availability	na	250,000 doses on day 26, 500,000 doses on day 30, million doses every 7 days thereafter	na	250,000 doses on day 26, 500,000 doses on day 30, million doses every 7 days thereafter
Depopulation capacity	na	na	Animal slaughter ≤ 4000 head[a]/day	Animal slaughter ≤ 4000 head[a]/day

na: Not applicable.
[a] In cattle unit. Other species are scaled down according to relative live weights.

capacity, without (a) or with (b) vaccination (Table 2). The problem was solved for the planning time horizon of 100 days. In all cases, control strategies including movement restrictions were implemented on day 21 and after.

The model was first used to solve for the optimal FMD control strategy when the vaccination option was unavailable to the local administrators. In this case, disease control must depend on depopulation of clinically-infected herds (baseline depopulation) and preemptive depopulation of potentially infected herds. In practice, preemptive depopulation may be applied to herds that had known dangerous contacts (DC) and herds that are contiguous to infected premises (CP) (Bates et al., 2003b; Honhold et al., 2004). However, the model did not have the capacity to determine premises-specific contacts and preemptive depopulation was uniformly applied to the pool of susceptible, latently infected, and subclinically-infectious herds.

The model was then used to solve for optimal vaccine use, given the vaccination option was available for the region. The model was run with and without constraints on vaccine availability; a sufficient capacity for vaccination (e.g. delivering vaccine to premises, administering vaccination) was assumed. The following assumptions were used regarding vaccine availability (Speers et al., 2004): 250,000 doses will arrive 4 days after the index case is diagnosed (available for use on day 26); after 4 more days, 500,000 doses will arrive (available on day 30); a week later and every week after that, a million doses will arrive. It was assumed that vaccinated animals were not slaughtered afterwards (vaccinate-to-live policy).

The first two scenarios assumed unlimited capacity for depopulation while the level of vaccination was limited by vaccine availability. In reality, there will be limitations on the number of animals that can be euthanized and disposed of in a day. Thus, the model was implemented with a carcass disposal capacity constraint. Because clear estimates of the capacity could not be obtained, a conservative estimate of 4000 cattle[1]/day (5 head/h,

[1] Other species were converted into cattle unit using relative live weights based on USDA (2006): 0.267 for a hog, 0.140 for sheep or goat, and 0.468 for a backyard animal.

16 h/day, 50 sites) was used to examine the impact of limitations on depopulation control. The scenario was implemented both with and without vaccination. The vaccine availability assumptions were maintained.

The model was also used to calculate the ‘‘shadow value’’ of control constraints. A shadow value is defined as the ‘‘marginal’’ impact on the objective function when a constraint is relaxed by one unit. For example, the shadow value in this application measures how much total cost can be saved if the carcass disposal capacity were expanded by one unit to 4001 cattle/day. The information will be useful at the preparation phase of FMD management in determining desirable capacity levels (Kobayashi et al., 2006).

3. Results

3.1. FMD control with depopulation only

The model results show that while all clinically-infected herds should be depopulated, preemptive depopulation of high-risk herds was never optimal under the specified environment. The total regional epidemic cost depended on the herd type of the index case (Table 3): it was largest when the index case was a salesyard (US$ 458.1 million), followed by dairy (US$ 113.0 million), swine (US$ 87.7 million), and sheep and goat (US$ 83.7 million) operations. The financial impacts were the smallest when the index case was a beef (US$ 38.7 million) or backyard (US$ 33.4 million) operation. The epidemic duration and

Table 3
Summary results of optimal FMD management by index-case herd type

	Index case					
	Beef	Dairy	Swine	Sheep and goat	Backyard	Salesyard
1. Without vaccination						
Total cost (million US$)	38.7	113.0	87.7	83.7	33.4	458.1
Epidemic duration (days)	38	44	43	42	37	52
Cumulative incidence (day 21)						
Herds	17	41	34	33	15	170
000 Head	16.3	49.8	39.8	36.3	13.4	221.1
Cumulative incidence (total)						
Herds	22	54	45	43	19	218
000 Head	24.2	71.8	57.8	53.6	20.2	301.2
2. With constrained vaccination						
Total cost (million US$)	37.2	106.2	82.5	78.9	32.3	424.0
Epidemic duration (days)	34	38	37	38	34	38
Cumulative incidence (total)						
Herds	21	51	42	41	18	202
000 Head	22.4	66.1	53.3	49.4	18.8	277.6
Vaccinated						
Herds	172	285	252	241	145	417
000 Head	297.4	493.1	434.4	415.4	250.0	720.3

cumulative incidence exhibited the same pattern. Most infections occurred before day 21, when control measures started being implemented (Table 3): the cumulative incidence on day 21 accounted for 76–78% of total infections.

3.2. Possibility of vaccination

With no constraints on vaccine availability, the optimal strategy was to vaccinate only dairy herds on day 21. The number of herds to vaccinate varied across index-case herd types (results not shown). When vaccine availability was limited, the model again determined that the vaccine should be used only for dairy herds. The optimal extent of vaccination differed across index-case herd types (Table 3). When the index case was a backyard operation, only the first vaccine delivery was used, vaccinating 250,000 animals. In other cases, the disease was contained with partial use of the second delivery. The extent of vaccination was the largest when the index case was a salesyard.

The impacts of vaccination on the epidemic size relative to no vaccination varied by index-case herd types (Tables 3 and 4). The region would benefit from vaccination the most when the index case was a salesyard: in this case vaccination saved 16 herds from infection, shortened the epidemic by 14 days, and reduced the regional costs by US$ 34.1 million. In other cases, 1–4 herds were saved, epidemic was shorter by 3–6 days, and the cost savings was between US$ 1.1 and 6.8 million.

Across herd types, dairy herds were affected the most severely (Table 4). Dairy herds had proportionately higher infection: while dairy herds represented only 26% of the total herds in the region, 59–60% of the infected herds were dairies on average (weighted over index-case herd types). Dairy operations also accounted for a disproportionate number of infected animals because of the large average herd size. While dairy cattle represented 54% of the total livestock population, on average 86% of the total infected animals were dairy cattle. Because all the infected herds were depopulated, the economic loss to the dairy sector was substantial. With the high per-unit value of dairy cattle, the dairies accounted for 97% of all livestock costs. On average, the value of lost dairy cattle due to FMD control amounted to US$ 55 million without vaccination and US$ 51 million with vaccination, 5–6% of their total livestock asset (Table 1).

Table 4
Mean impact of FMD outbreak by herd types

	Herd type				
	Beef	Dairy	Swine	Sheep and goat	Backyard
1. Without vaccination					
Total infected herds (herds)	2.04	19.20	1.25	0.83	4.13
Total infected animals (000 head)	1.74	33.16	3.15	0.46	0.02
Value of infected animals (Million US$)	1.04	55.34	0.41	0.06	na
2. With constrained vaccination					
Total infected herds (herds)	1.96	17.65	1.18	0.80	4.00
Total infected animals (000 head)	1.67	30.49	2.98	0.45	0.02
Value of infected animals (million US$)	1.00	50.89	0.39	0.05	na

na: Not applicable (no monetary value is assigned to backyard herds in the current model).

The second largest loss was to the beef industry: about US$ 1 million, representing 2% of the value of the lost livestock in the region. The swine industry lost more animals than the beef industry, in spite of its smaller industry size, but because the unit value of a hog was smaller, the overall economic losses were smaller. The impact on the sheep and goat industry was minimal: the industry lost 1% of their livestock asset.

Finally, the model was used to calculate the implicit value of the limited vaccine doses called "shadow values." The shadow value of vaccine is higher when the resource availability constraint binds tighter, i.e., when the epidemic is larger. Therefore, the shadow value was the highest when the index case was a salesyard: an additional dose available on day 26 would reduce the total cost by US$ 119. The shadow values when other herd types were the index case were the following: US$ 34 (dairy), US$ 29 (swine), US$ 28 (sheep and goat), US$ 14 (beef), and US$ 11 (backyard).

3.3. Limited euthanasia/carcass disposal capacity

The capacity constraint of euthanasia or carcass disposal was imposed, with and without vaccination, with a dairy herd as index case. In both cases, there were 13,178 animals in clinically-infected herds on day 21, more than three times the assumed capacity (4000 head/day). Failure to quickly dispose of infectious animals results in larger epidemics. Relative to the unconstrained cases, the total cost increased by 15% with vaccination and 41% without vaccination, with an additional 7 and 20 herds infected, respectively. The patterns of optimal disease control strategies did not change under the capacity constraint. That is, preemptive depopulation was still suboptimal and the limited vaccine doses should be allocated only to dairy operations.

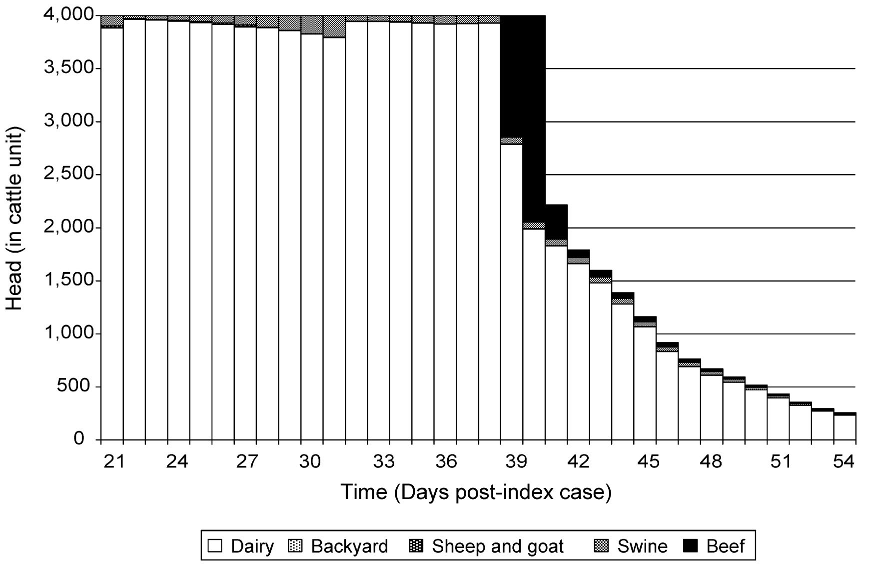

Fig. 1. Scenario 3a: Depopulation under capacity constraint (4000 head/day, index = dairy, without vaccination).

Fig. 1 illustrates the optimal capacity usage under the no-vaccination policy. During the first 20 days after the initial diagnosis, the region operated at the maximum capacity. The optimal allocation of capacity to each herd type differed by day. During the first 18 days (day 21–38), almost the entire capacity was devoted to dairy cattle, while some capacity was also allocated to smaller animals (pigs and sheep and goats). Beef herds were depopulated starting on day 39.

The calculated shadow values of the disposal capacity show that, by increasing the capacity by one unit to 4001 head/day, the total epidemic cost could be reduced by US$ 9000 with vaccination and by US$ 59,400 without vaccination. Consistent with economic theory, shadow values declined as the capacity expanded.

3.4. Sensitivity analysis

The model was also run with alternative parameter values and the impacts on the model output were evaluated. Sensitivity analyses were conducted over the following four areas: (1) disease transmission parameter (β^{ij}) values; (2) time lag between index case and initial diagnosis (high-risk period or HRP); (3) duration of subclinically-infectious period (σ_i); and (4) livestock unit values.

3.4.1. β^{ij} Parameter values

The disease transmission parameter β^{ij} values were increased by 25% both before and after initial diagnosis, i.e., with and without movement restrictions. The total cost increased by 61–120% with vaccination and 69–143% without vaccination, depending on the index case. However, the pattern of optimal strategies did not change. Even with the faster disease transmission, preemptive depopulation was suboptimal.

3.4.2. High risk period assumption (default: 21 days)

It was estimated that the UK had a 21-day lag between the index case and its identification in their 2001 FMD epidemic (Gibbens et al., 2001). If the disease were to be detected and control strategies implemented one day earlier (on day 20), the model found that the total cost would be reduced by 14–26%, depending on the index case. On the other hand, delaying control measure implementation by one day (controls starting on day 22) would increase the cost by 15–32%, depending on the index case. In both instances, however, the selection of optimal control strategies remained the same. A caveat in interpreting this result is that stochastic events in the HRP can have an extreme effect on the resulting epidemic. These perturbations were not part of the current deterministic optimization model.

3.4.3. Subclinically-infectious duration assumption (default: 7–11 days)

The latent (λ_i) and subclinically-infectious (σ_i) duration parameters taken from Bates et al. (2003b) and used in the model pertain to animal-level figures, and hence it was assumed that the disease would be detected as soon as the first animal showed a clinical sign. However, in a herd or flock, detection may not be immediate. For example, in the UK 2001 FMD outbreak, at the time of diagnosis, 2-day-old legions were found in most cattle herds and 5-day-old or older legions were found in 30% of the diagnosed sheep flocks

(Gibbens et al., 2001). In this exercise, 3 days were added to the subclinically-infectious period to evaluate the impacts of delayed diagnosis at the herd level. Note that, while only the initial diagnosis was delayed or brought forward in the previous exercise, the initial and all subsequent diagnoses were delayed in this exercise.

With vaccination, the total cost increased by 69–151% depending on the index case, while the optimal choice of control strategies did not change. On the other hand, without vaccination, the cost increased by 140–367% depending on the index case. In many cases the epidemic duration exceeded 100 days. More importantly, preemptive depopulation was now optimally adopted, except when the index case was a beef or a backyard herd. When adopted, preemptive depopulation was exclusively applied to swine herds, which had a relatively low herd asset value but relatively high disease transmission parameters.

3.4.4. Livestock unit value assumption

For demonstration purposes, the model was run with the unit value of a dairy cattle (US$ 1669) replaced by the unit value of a pig (US$ 130). Under this hypothetical situation, relatively more animals were slaughtered and fewer animals were vaccinated. For example, when a beef herd was the index case, vaccination was no longer an optimal strategy, while in aggregate 17% more animals were slaughtered. Preemptive depopulation was never found to be optimal. With dairy cattle priced at less than 10% of their true value, a stamping-out policy was less costly than an extensive vaccination campaign, even though it resulted in longer epidemic duration and more animals to slaughter.

4. Discussion

Cost-minimizing strategies to control FMD in the three-county region in the Central Valley of California were analyzed using a dynamic optimization model by Kobayashi et al. (2007). The base model results suggested that depopulation of clinically-infected herds would be largely effective as a disease control strategy, but that depopulating additional herds would not be cost effective. The model determined that preemptive depopulation would not reduce disease spread or epidemic duration sufficiently to cover the cost of lost livestock and control measures. The finding agreed with the cost-benefit analysis by Bates et al. (2003a), where preemptive depopulation was found to bring about a negative net benefit while vaccination would provide a positive net benefit.

In a sensitivity analysis, it was discovered that a delay in disease detection and diagnosis in each herd could bring in preemptive depopulation as an optimal strategy when vaccination was not an available option. This has two implications. First, this information could be used early in the epidemic once the diagnostic delay is observed. For example, if non-swine herds were subclinically infected for 7 days, preemptive depopulation is suboptimal. On the other hand, if non-swine herds were subclinically infected for 10 days, preemptive depopulation is optimal. Second, this result points out the importance of early diagnosis, which could obviate unnecessary depopulation.

It is important to remember in interpreting the model results that the concept of optimality was applied at the three-county region level and costs that may be incurred outside the region were not accounted for. Moreover, the model only considered the costs at the primary livestock production level and direct government costs. Consideration of potential disease spread into neighboring regions and potential impacts on other economic sectors, e.g., processing industry of livestock output and tourism, may mean that optimal disease control strategies may change. However, these issues are beyond the scope of this paper.

Decisions of whether or not to employ vaccination as an FMD-control strategy most importantly depend on trade impacts, as some importing countries would likely close their market to certain animal products from a country with FMD-vaccinated animals. Due to the regional cost specification, however, the current model could not determine whether FMD vaccination in the three-county region was a desirable strategy for the entire nation. Thus, in this model, it was assumed that the decision of whether a vaccination option was available for the three-county region was exogenously given. In order to quickly regain FMD-free-without-vaccination status in the international market, it may be of national interest to slaughter vaccinated animals once the outbreak is contained (vaccinate-to-kill policy). The regional cost specification also ruled out the examination of the vaccinate-to-live versus vaccinate-to-kill argument. An optimization model that encompasses a larger region or an entire nation will be able to address these issues.

The model found that vaccination under a vaccinate-to-live policy would reduce epidemic size and hence the economic damage, but the cost savings would be important only in a fast-spreading epidemic, particularly when the index case is a salesyard. The relatively small impact of vaccination suggested that baseline depopulation, combined with movement restrictions, was effective in limiting further disease spread and in ending the epidemic quickly. Again, this result was based on the regional cost specification that did not include the cost or benefit of vaccination experienced outside the region. Moreover, the implicit assumption in the model that herds with clinical signs could be immediately identified, euthanized, and disposed of overestimated the effectiveness of depopulation control.

The epidemic size depended largely on the index-case herd type; in particular, disease transmission from salesyards was the most extensive. The result highlighted the vulnerability of the livestock economy if salesyards become a target of intentional virus dissemination. However, the pattern of optimal strategies did not vary by index-case herd types: for each case, preemptive depopulation was suboptimal and vaccine should be used only for dairy herds. Only the extent of the optimal strategies varied, and hence the resources necessary to implement such strategies varied.

In specifying movement restrictions in the model, it was assumed that only animal movements were banned completely. The implicit assumption was that some feed deliveries would still be permitted during the epidemic so that, although there would be disrupted livestock marketing due to salesyard closure, producers would at least be able to continue feeding the animals and keep them alive. If tighter movement restrictions were imposed where movements of feed delivery vehicles were banned, additional animals would have to be slaughtered for animal welfare. These restrictions would result in much greater losses than those presented in this study especially on large, feed-intensive operations such as feedlots and dairy herds.

Most infections occurred prior to the initiation of control measures. This implies the importance of early disease detection and timely implementation of control measures. In the current model, all control measures were implemented on day 21 and after. While individual animals could start showing clinical signs as early as 24 h after infection (Alexandersen et al., 2004), in a non-laboratory exposure setting, it is believed that confirmation and subsequent control measure implementation would take considerably longer. The sensitivity analysis on the detection date indeed confirmed the importance of early detection.

The optimization model was also used to calculate the implicit values or ''shadow values'' of limited disease control capacities. An additional vaccine dose made available on day 26 was found to reduce the total cost up to US$ 119. The shadow value of the carcass disposal capacity at the assumed level of 4000 head/day was estimated to be US$ 9000 with vaccination and US$ 59,400 without vaccination. These estimates did not include the benefits of the additional capacity realized outside the three counties. If the benefits were considered, the value of the additional capacity would be higher. This type of information is necessary to optimally determine the level of capacity investment prior to potential outbreaks.

The model results highlighted the role of vaccination when the region faced a tight constraint in euthanasia/carcass disposal capacity. While the infected herds wait to be depopulated, they continue to shed FMD virus. Vaccination would protect susceptible herds and limit additional infections (Golde et al., 2005). The two pre-epidemic policy alternatives of vaccine stockpile and augmentation in the carcass disposal capacity are likely to compete for public funds (Kobayashi et al., 2006). Using the shadow value information, in combination with the actual cost of investment in the two alternatives, the optimal levels of each alternative can be determined.

The model determined that dairy operations would be hit hardest by an FMD outbreak in the region, and control efforts should optimally focus on these units. The optimal distribution of the available vaccine was exclusively to dairy herds, and the limited carcass disposal capacity should be allocated first to dairies before other herd types. This result was explained by two factors. First, dairy herds are important as both origin and destination in disease transmission. Constant movements of animals and feed in and out of dairy operations create frequent direct and indirect contacts between herds. Second, dairy herds have a higher asset value than other herds. As a result, the model determined that it is economically efficient to prioritize dairy herds in disease control efforts in order to protect dairy herds from infection and depopulation. Special focus on dairy herds in FMD preparation in the region is confirmed among local scientists and administrators (Dr. Richard Breitmeyer, California State Veterinarian, personal communication).

The results generated by the model were specific to the livestock industry structure in the study region. With the concentration of intensive and high-valued dairy operations, FMD control with stamping-out policy would be extremely costly in the region. In fact, the option of vaccinate-to-live policy seems highly desired by local regulatory veterinarians (Dr. Richard Breitmeyer, California State Veterinarian, personal communication). The sensitivity analysis on the livestock unit values confirmed that a set of optimal control strategies may be different in a region with a different industry structure.

The exercises presented in this paper demonstrated that the decisions on the scope and scale of FMD control strategies and the allocation of limited resources should be made with a reference to both underlying area-specific epidemic and economic characteristics. When different operation types coexist in a region, a depopulation strategy should prioritize those herd types that are important in disease transmission. At the same time, those herds that are economically valuable should be preferentially protected by vaccination. The optimization model used in this study is a useful tool to quickly evaluate epidemic and economic tradeoffs. In order to generate detailed epidemic predictions that the optimization model cannot provide, e.g., probability distributions of possible epidemic outcomes, the model should be used iteratively with the simulation model. With combined use of the two models, a set of dynamic, optimal disease control strategies for FMD can be determined efficiently and quickly. Also, with modifications, the optimization model can be used for other infectious diseases and for other livestock species.

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