# Investment in Infectious Disease Control Capacity: The Case of a Potential Foot-and-Mouth Disease Outbreak in California

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## 1. INTRODUCTION

In the post-9/11 and post-Katrina era, society is once again reminded of its vulnerability to natural and manmade disasters. Social preparedness for the next possible disasters is a pressing concern, and the demand and pressure for emergency management planning are heightened. Outbreaks of exotic contagious diseases, whether for humans, animals, or plants, are potential disasters that call for emergency management planning. For example, arrival in the US of highly pathogenic avian influenza (HPAI) is inevitable and only a matter of time. While timely policy implementation is crucial for effective control of such diseases, physical and human capacities would largely determine the scale, scope, and effectiveness of disease control actions during an outbreak. Early disease detection by surveillance activities would also limit the size and the damage of outbreaks, especially in case of fast-spreading diseases.

An important economic question is: what is a desirable way for a society to be prepared for potential outbreaks? More specifically, what is the efficient way of allocating limited resources to alternative preparation and investment areas? In this study, we address the question in the context of a potential foot-and-mouth disease (FMD) outbreak, a highly contagious animal disease, exotic to the US, and whose economic consequences could be substantial and extensive (Ekboir, 1999; Paarlberg, Lee, and Seitzinger, 2003). We consider specific investment areas of surveillance, carcass

disposal capacity, and vaccine stockpile, and analyze their impacts on disease control strategies during an outbreak.[1]

In analyzing FMD preparation decisions, we use a dynamic optimization model of FMD management developed previously (Kobayashi et al., a). The model minimizes total regional outbreak cost by choosing herd depopulation and vaccination strategies, given epidemiologic relationships of dynamic disease spread and constraints on disease control capacity. With this model, it is possible to evaluate different preparation strategies when the resources are optimally utilized during an outbreak. Similar analyses can be conducted using epidemiologic simulation models, but the results, though possibly based on more detailed epidemiologic specifications, lack reference to optimality.

The optimal FMD management model is parameterized for a three-county region in the Central Valley of California (Fresno, Kings, and Tulare counties) (Kobayashi et al., a). The region is characterized by a concentration of large-scale dairy operations. With frequent movements of animals, vehicles, and personnel to and from these farms, FMD, should it enter the region, is expected to spread quickly among the dairy farms (Bates, Thurmond, and Carpenter, 2001). Given the high asset values of dairy cattle and the importance of dairy production in the region,[2] an FMD outbreak would result in a substantial damage to the local economy (Ekboir, 1999; Kobayashi et al., b). Accordingly, local FMD-control planning gives special attention to the dairy operations in the region (Dr. Richard Breitmeyer, California State Veterinarian, personal

[1] Disease prevention efforts, intended to reduce the probability of an exotic disease entering the system (e.g. border control and on-farm bio-security measures), are also an important investment area and pose substitutability with investments in surveillance and control capacities. However, for the purpose of this study, we focus on the types of preparation investment that are expected to limit the extent of an outbreak once it has occurred.

[2] Milk production represents about 20% of the region's gross agricultural output (30% if cattle and calves are included). Dairy farms are the major suppliers of calves and cull-cows for beef production in the region.

communication). Using the model, we find that targeted surveillance on sales yards (and possibly dairy farms) would supplement the insufficient carcass disposal capacity in this region, as outbreaks starting on these operation types are expected to expand quickly and widely and the benefits of early disease detection would be significant.

## 2. MANAGING AN FMD OUTBREAK IN THE US

### 2.1 FMD DISEASE DYNAMICS AND CONTROL OPTIONS

FMD affects cloven-hoofed animals, such as cattle, pigs, sheep, goats, and deer, but not humans. Introduced into a livestock herd, mortality is typically limited to young animals, while mature animals usually recover from the disease without intervention, though the productivity would be reduced by at least 25% (Hyslop, 1970). Since FMD is extremely contagious, the national interest would be to quickly contain an outbreak before it spreads extensively within the country. A country exporting FMD-susceptible livestock and livestock products would also have a strong incentive for quick control, as importers would typically halt importation of such products from countries with FMD outbreaks. Furthermore, FMD-endemic countries are differentiated in international markets from FMD-free countries even without recent outbreaks (OIE, 2005). Thus, in order to avoid protracted trade restrictions, a previously FMD-free country would typically take an eradication approach to controlling an FMD outbreak, primarily by depopulating infected herds.

FMD spreads mostly through direct and indirect contacts between infectious and susceptible animals.[3] Besides intentional dissemination, direct animal contacts are the most infectious mode of FMD virus dissemination, and such contacts may occur among

[3] Airborne disease transmission is also possible but relatively unimportant. In the 2001 UK outbreak, it is estimated that about 1% of the cases was through airborne transmission (Gibbens et al., 2001).

animals in a herd, at sales yards, or through shipments of animals to other herds. Indirect contacts involve other vectors such as people, vehicles, and equipment. For example, a veterinarian or a feed truck may stop at multiple farms in a day, potentially carrying FMD viruses from one farm to another. As soon as FMD is detected, therefore, movement restrictions on animals, people, vehicles, and other potential vectors of disease transmission would be imposed in order to limit the number of direct and indirect contacts and the further disease spread.

One factor that complicates FMD management is that the disease may be difficult to detect and a delay in control policy implementation is almost inevitable. An animal infected by FMD virus would become infectious after a few days (latent period), but clinical signs, if any, would appear after another few days (subclinically-infectious period). Moreover, clinical signs on an individual animal can be subtle and may not be noticed immediately. The clinical signs may also be confused with those of other diseases. Thus, it is practically impossible to detect an FMD-infected animal in its earliest stages of infection without specialized diagnostic testing. Because of its high contagiousness, by the time the first case is detected, the disease would likely have spread to other animals and to other herds. For example, in the 2001 FMD outbreak in UK, it is estimated that there was about a 21-day lag between the initial infection and confirmation of the first case and that the disease spread to at least 57 herds during this period (Gibbens and Wilesmith, 2002). Early disease detection by surveillance activities, therefore, is an important investment option in preparation for a potential FMD outbreak.

Subsequent eradication policy would be applied at the herd level, as removing visibly- (i.e. clinically-) infected animals in a herd would be insufficient facing a fast-

spreading FMD. Depopulation policy would be applied to all herds in which clinically-infected animals have been found.[4] Additional herds may be preemptively depopulated if they are considered potentially (i.e. subclinically) infected. In the 2001 UK outbreak, preemptive depopulation was applied to herds that were contiguous to, or had known recent contacts with, confirmed infected herds. In total, more than 4 million animals were slaughtered for disease control purposes,[5] of which about a third was on confirmed FMD-infected herds (NAO, 2002).

Vaccination is also a control option to slow down FMD spread, an option used regularly in FMD-endemic countries. In contrast to herd depopulation, which is intended to contain further disease spread at the source, vaccination is often used to protect susceptible herds from getting infected. However, the current technology cannot distinguish FMD-infected from FMD-vaccinated animals, and this has implications on international trade. Even after an outbreak is contained, a country that has used FMD vaccine would be differentiated from countries without FMD vaccination and would continue to face trade restrictions. In order to be free of all FMD-related trade restrictions, an FMD-free country can officially gain an FMD-free-without-vaccination status by slaughtering all FMD-vaccinated animals (Article 2.2.10.7., OIE, 2005). Thus, facing an FMD outbreak, a previously FMD-free country would have the following three vaccination policy options: 1) no vaccination, 2) vaccination without slaughtering

[4] Hereafter, we simply denote such herds as "clinically-infected herds." Short notations are also applied to herds in other disease status: a susceptible herd implies a herd with no infected animals; a latent herd has at least one latently-infected animal but no infectious animals; and a subclinically-infectious herd has at least one subclinically-infectious animal but no clinically-infected animals. Note that subclinically-*infected* herds include both latent and subclinically-*infectious* herds.

[5] In addition, 2.3 million animals were slaughtered for animal welfare reasons (NAO, 2002), where the inability of marketing output and procuring feeds due to movement restrictions raised the necessity of euthanizing such animals.

vaccinated animals ("vaccinate-to-live" policy), and 3) vaccination and then slaughter of vaccinated animals ("vaccinate-to-kill" policy).

Overall effectiveness of FMD control efforts is determined by the combined level of the control measures. While individual measures play different roles, their impacts are closely interlinked through disease dynamics. The dynamics of FMD infection, spread, and control in a population of livestock herds may be represented in a set of equations as in Table 1 (Kobayashi et al., a).[6] Subscripts *i* and *j* on variables and parameters represent herd types (e.g. beef, dairy, and swine), while all variables are indexed with *t*, representing a day. The notions of prevalence and incidence in epidemiology roughly correspond to those of stock and flow variables in economics. Prevalence variables $\left(S_{it}, L_{it}, I_{it}^{S}, I_{it}^{C}, V_{it}\right)$ denote the number of herds in each disease status (susceptible, latent, subclinically infectious, clinically infectious, and vaccinated) at the beginning of each day. Incidence variables $\left(\Lambda_{it}, \Phi_{it}^{S}, \Phi_{it}^{C}, \upsilon_{it}\right)$ denote the number of herds that advance to each disease status during the day. Parameters $\left(\beta_{ij}, \lambda_{i}, \sigma_{i}\right)$ denote disease transmission rate from herd type *i* to herd type *j*, duration of latent period, and duration of subclinically-infectious period, respectively. Disease control variables $\left(r_{it}^{B}, r_{it}^{P}, \nu_{it}\right)$ denote daily rates of baseline slaughter (depopulation of clinically-infected herds), preemptive slaughter, and vaccination, respectively. Note that preemptive slaughter and vaccination are applied to the total of susceptible, latent, and subclinically-infectious herds because the status of these herds cannot be identified by the decision makers.

[6] Actual disease transmission processes may be more realistically characterized with spatially explicit and stochastic representation as, for example, in the FMD simulation model by Bates, Thurmond, and Carpenter (2003). These features are to be incorporated in an optimization model in development.

## 2.2 ECONOMICS OF FMD CONTROL AND PREPARATION

An economically efficient combination of FMD control strategies would be one that balances its marginal costs and benefits. The challenge for the decision makers is to appropriately define and quantify the costs and benefits of different control strategies so that they can be internalized in the decision-making process. However, the task is extremely difficult. On the one hand, the decision makers face complex local disease dynamics. On the other hand, locally-applied FMD control measures could have wider impacts, and the tradeoffs of alternative strategies would not necessarily be straightforward.[7] For example, aggressive eradication policy by herd depopulation would hurt local livestock industry but reduce the probability that the disease spreads outside the region. Aggressive controls would also shorten outbreak duration and hence the duration of trade restrictions. If the FMD-infected region is a major supplier of livestock output, tight movement restrictions on such commodities would disrupt the national livestock/food economy. A local FMD vaccination policy may also induce trade restrictions applied at the national level.[8]

Previous studies on FMD economic impacts faced the same difficulty of incorporating disease dynamics and various aspects of FMD impacts in a single, comprehensive framework. For example, Paarlberg, Lee, and Seitzinger (2003) measure welfare impacts of an FMD outbreak in the US by incorporating domestic and

[7] Sumner, Bervejillo, and Jarvis (2005) view a disease-controlled state as a public good, and discuss various problems arising in management of infectious diseases from the angle.

[8] An FMD-infected or vaccinated zone can be established within a country if the conditions specified by the World Organisation for Animal Health are met (OIE, 2005). The FMD-free zone will be treated differently from the rest of the country.

international[9] market effects, but the assumption on the aggregate supply shock due to an FMD outbreak (a million head of cattle slaughtered for FMD control) is exogenously given with no reference to disease dynamics.

Other FMD market impacts analyses use supply shocks generated by epidemiological simulation models (Ekboir, 1999; Schoenbaum and Disney, 2003). The simulation models are run under alternative assumptions about disease spread rates and disease control strategies, and the impacts of simulated outbreaks on the regional and national economy are evaluated in a partial equilibrium or multi-sector framework. While producing useful results, these studies can characterize epidemiologic and economic tradeoffs of alternative disease control strategies only for selected scenarios, and the number of scenarios examined in each study is typically limited.

The model by Kobayashi et al. (b), which is used in the present analysis of FMD preparation, explicitly incorporates local disease dynamics in an optimization model and evaluates all possible combinations of control strategies simultaneously. While this model overcomes the limitation of the simulation approach, it does not internalize the impacts of local disease control strategies outside the region. We are not aware of a comprehensive optimization model that internalizes both disease dynamics and wider market impacts. Given the difficulties, we continue our discussions and analysis by focusing on tradeoffs at a local level that can be captured by local disease dynamics, while acknowledging the limitations of the approach and noting the need for a larger, more comprehensive model.

[9] The focus is placed on US beef imports, as imported and exported beef are treated as perfect substitutes and the US is a net beef importer in this sense. Thus, the issues of market losses due to FMD-related trade restrictions are not examined.

An optimal set of local FMD control strategies may be defined as the one that minimizes net costs for the entire outbreak. Since control strategies on a given day would affect the future course of disease spread, decision makers would like to balance the overall benefits and costs of disease control strategies by applying them timely and effectively. The scale and the timing of strategies that the decision makers can choose each day, however, would be restricted to a large extent by the level of preparation investment made prior to the outbreak. Capacity constraints would have a greater significance for the control of highly contagious exotic diseases such as FMD, since capacity augmentation during an outbreak is often impossible faced with the unexpected introduction of a fast-spreading disease.

Potential constraints local decision makers may face during an FMD outbreak include the following. First, although the decision makers would like to start implementing control policies as soon as the disease is introduced in the region, the disease would not be detected immediately. Second, on a given day, there may be more animals that the decision makers would wish to euthanatize and dispose of than the region has the capacity to do so. Third, vaccination scale would depend on the vaccine stockpile as well as vaccination manpower. Fourth, manpower for enforcing movement restrictions would also affect the effectiveness.

All of these constraints would affect disease dynamics differently, and there would be certain extent of substitutability and complementarity in investments intended for relaxing potential constraints. For example, vaccination may relieve a bottleneck in carcass disposal capacity by slowing down disease spread and hence reducing the number of animals that need to be disposed of each day. Alternatively, the bottleneck may be

relieved by early disease detection achieved through routinely-implemented surveillance activities. In making decisions about allocating resources to alternative investment areas in preparation for a potential FMD outbreak, understanding the disease dynamics and potential impacts of such investments on the disease dynamics is essential. With the use of a dynamic optimization model, we address such questions and provide information useful for FMD management in California.

The US has been free of FMD since 1929 and has enjoyed access to export markets for beef and other livestock commodities without facing FMD-related restrictions. However, the concerns over a potential FMD outbreak are rising, especially following the UK's experience in 2001 and an elevated threat of bio-terrorism since September 11, 2001. USDA and other federal and local agencies have conducted FMD simulation exercises (Riggs and Waldrup, 2000; Speers et al., 2004) and drafted emergency response guidelines (PL 107-9 Federal Inter-agency Working Group, 2003; CDFA, 2006). According to these documents, vaccination decisions would be made at the federal level in case of an FMD outbreak in the US, and the option of "strategic vaccination" would be used if it is determined necessary and feasible. The policy on whether to slaughter vaccinated animals after the outbreak is contained is unclear. The official FMD vaccine stockpile is controlled at the federal level at the North American FMD Vaccine Bank.[10]

The exact federal vaccination strategy, therefore, would be specific to each outbreak. Accordingly, local decision makers would have to make preparation decisions without knowing whether or not vaccination would be an option. To reflect the situation,

[10] Private international markets for FMD vaccine exist, and local governments could invest in their own vaccine stockpile. We are not aware of such cases in the US.

we analyze expected impacts of investments in surveillance efforts and carcass disposal capacity under different assumptions about vaccination policies. In this study, we assume sufficient manpower to implement control policies, i.e. manpower for euthanasia, vaccination, and enforcement of movement restrictions would not be a limiting factor.

## 2.3 THREE-COUNTY CALIFORNIA OPTIMAL FMD MANAGEMENT MODEL

In evaluating alternative preparation investment policies, we use a dynamic optimization model previously developed by Kobayashi et al. (a). The model is a numerical implementation of a discrete-time optimal control problem of local decision makers, with the objective of minimizing total outbreak cost and subject to the disease-dynamics equations of motion in Table 1. The regional outbreak cost consists of: 1) value of slaughtered livestock assets for disease control, 2) direct costs of disease control measures (depopulation and vaccination), and 3) daily operational costs during outbreak that the local administration incurs (including costs of enforcing movement restrictions). The state variables are the prevalence variables $\left(S_{it}, L_{it}, I_{it}^{S}, I_{it}^{C}, V_{it}\right)$, and the control variables are disease control variables $\left(r_{it}^{B}, r_{it}^{P}, \nu_{it}\right)$.

The model was parameterized for a three-county region in the Central Valley of California (Fresno, Kings, and Tulare counties). The epidemiologic parameters $\left(\beta_{ij}, \lambda_i, \sigma_i\right)$ were taken from, or estimated using the output of, an FMD epidemic simulation model developed for the same region (Bates, Thurmond, and Carpenter, 2003). The disease transmission rates $\beta_{ij}$ were estimated with and without movement restrictions on animals and other vectors (e.g. humans and vehicles). Disease control policies would be implemented as soon as the first case is discovered. Thus, the reduced $\beta_{ij}$ values are applied from the day the initial case is discovered until the end of the outbreak.

The model treats six operation types (beef, dairy, swine, sheep and goat, backyard, and sales yards), and daily optimal strategies are solved for herds in each of the six types. Altogether 2,238 herds and 5 sales yards were identified in the three-county region (Bates, Thurmond, and Carpenter, 2003). In this model, a sales yard is considered as a transitory destination, where animals do not stay for an extended period, and thus depopulation and vaccination policies are not applied to sales yards. However, sales yards are considered to have an important role in disease dissemination, as they attract animals from various farms, let them interact and have direct contacts, and then send them off to various destinations. Sales yards in the region would be closed as soon as the first case of infection is detected, thus in this model they do not contribute to disease transmission following the initial detection. For backyard operations, preemptive depopulation and vaccination are not considered.

The region houses about 1.8 million head of FMD-susceptible livestock (cattle, hogs, sheep, and goats) (NASS-USDA, 2004). More than half of such livestock population is dairy cattle (including milking 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 (Bates, Thurmond, and Carpenter, 2001). Dairy herds also have high asset values, and thus an FMD outbreak and subsequent depopulation control in the region are expected to cause disproportionate damage to the local dairy industry. Selected model parameters are listed in Table 2.

## 3. EVALUATING ALTERNATIVE FMD PREPARATION POLICIES

### 3.1 BENCHMARK MODEL RESULTS

Kobayashi et al. (b) use the same model to analyze the optimal FMD control policies in the three-county region. Here, we summarize their results and use them as the benchmark for our analyses on FMD preparation investments. They run the model with and without vaccination, where vaccination scale is limited by the limited federal vaccine stockpile.[11] The model is run for a planning horizon of 100 days. They initialize model runs by infecting one herd (index case) on the first day, which may represent an accidental introduction of FMD into the region. The procedure is repeated for all six herd types. All control measures including movement restrictions are implemented on day 21 and after, the estimated lag between the initial infection and detection in the 2001 UK outbreak (Gibbens and Wilesmith, 2002).

Kobayashi et al. (b) find that preemptive slaughter is never optimal in the modeled environment. It would cost more to depopulate herds additional to those identified infected, even though doing so would limit potential disease spread. Vaccination is found never optimal under a vaccinate-to-kill policy, where vaccinated animals are subsequently slaughtered. Vaccination is found to reduce the regional cost if a vaccinate-to-live policy is taken. In this case, vaccination is applied only to dairy herds. Because of the high asset value of dairy cattle, it is found economically efficient to protect dairy herds from infection by vaccinating them.

[11] They use estimates provided by the North American FMD Vaccine Bank (Speers et al., 2004). It is estimated that 250,000 doses would arrive 4 days after control strategies are put in place (available for use on day 26); after 4 more days, 500,000 doses would arrive (available on day 30); a week later and every week after that, a million doses would arrive.

The outbreak size and cost vary significantly by index-case herd types (Table 3). The outbreak is by far the longest, largest (in terms of total number of infected animals), and costliest, when it starts on a sales yard, followed by dairy, swine, and sheep and goat herds. The outbreak is the least extensive when a beef or backyard herd is the index case. The results reflect the different rates of disease transmission across source and destination herd types, which are represented in the $\beta_{ij}$ values. For example, on a given day, a sales yard or a dairy herd likely has higher probabilities of both receiving and shipping out infectious animals than an extensive beef operation. Vaccination reduces the total regional cost, but its impact is substantial only when the index case is a sales yard. The extent of vaccination (the number of animals vaccinated) also varies by index-case herd types.

### 3.2 VALUE OF CARCASS DISPOSAL CAPACITY

The base results predict that there would be 20-300 thousand head of animals to slaughter and dispose of during an FMD outbreak in the region. The results assume an unlimited carcass disposal capacity, while there would be a capacity limitation in reality. During the 2001 FMD outbreak in the UK, concerns were raised over various carcass disposal methods and their negative impacts on public health and environment (NAO, 2002). Should an FMD outbreak occur in the US, carcass disposal procedures would face a closer scrutiny (NABCC, 2004), which may result in limiting the scope and scale of resources available for carcass disposal.

To address the issue, we run the model with a constraint on carcass disposal capacity, where the number of animals that the three-county region can dispose of each

day is limited, while maintaining the other specifications.[12] Since clear estimates on actual capacities in the region are unavailable, we consider a range from 4,000 head/day (5 head/hour, 16 hours/day, 50 sites) to 30,000 head/day, and associated shadow values are estimated. The shadow values reported here are the sums of daily shadow values on carcass disposal capacity constraint over the entire duration of each outbreak. The sign is then reversed to make the values positive (a larger capacity reduces the total cost, hence each original shadow value is negative). Note that the number of clinically-infected animals on day 21 (Table 3) represents the number of animals that the local decision makers would like to dispose of on the day FMD is first confirmed in the region.[13] Without prior intervention, the demand for carcass disposal capacity is expected to be the greatest on day 21. Since the figures for beef and backyard as the index-case herd type are below 4,000 head, it is expected that the capacity constraint would never bind for these cases.

When the option to vaccinate is not available, the shadow values differ substantially by index-case herd types (Figure 1).[14] The shadow values are by far the highest when the index case is a sales yard. An outbreak that starts in a sales yard spreads most rapidly and extensively, and having a sufficient capacity to control the outbreak is most important in this case. Note that the shadow values at low capacity levels are much smaller than the maximum (found at 13,000 head/day). This is because

[12] In Kobayashi et al. (b), it is found that, when the region faces a binding constraint in carcass disposal capacity, it is optimal to give priority to dairy herds. That is, by depopulating and disposing of dairy herds before other herd types, additional infections, primarily of dairy herds, would be minimized.

[13] The model assumes that clinically-infected herds are immediately identified once the first case is discovered.

[14] Because of the high complexity and non-linearity of the model, the numerical solutions are sometimes sensitive to the starting values, and the obtained solutions can contain local minima. While the shadow values should monotonically decrease as the capacity expands, the results presented in the figures contain non-monotonic parts. In such cases, one should be concerned about the trends. Gaps between points (missing lines) represent extreme values and are not shown in the figures.

the outbreak becomes so large[15] that marginal increases in capacity at such low capacity levels contribute minimally to a faster disease control and hence cost reduction. The marginal benefit of additional carcass disposal capacity is especially high between 12,000 and 15,000 head/day.

The shadow values of carcass disposal are the second highest when a dairy herd is the index case (Figure 1). Dairy herds are important as both the source and destination on disease transmission. Once a dairy herd is infected, it quickly spreads to other dairy herds. The shadow value declines rapidly as the capacity expands, and it practically becomes zero at 9,500 head/day. As expected, when a beef or a backyard herd is the index case, the shadow values are zero for all capacity levels.

When a vaccination option is available under a vaccinate-to-live policy, the shadow values are much lower than under no-vaccination policy (Figure 2). The vaccination option reduces the shadow value of carcass disposal capacity most dramatically when the index case is a sales yard: the highest shadow value declines from $632,874 without vaccination (found at 13,000 head/day) to $6,702 with vaccination (at 7,000 head/day). Again, the lower shadow values at the lower end of the capacity range suggest the difficulty in timely disease control when carcass disposal capacity is severely limited, even with the option of vaccination.

Vaccinate-to-kill policy, where vaccinated animals are slaughtered once the outbreak is contained, is never optimal at the three-county level when a *non*-sales yard operation is the index case. In these cases, even if a vaccination option is available, the advantage of vaccination in controlling the outbreak would not compensate additional

[15] Practically all herds in the region would be infected.

losses in the livestock assets, and the sole use of baseline depopulation would be more economical.

A vaccinate-to-kill policy is optimal only when the index case is a sales yard and when the carcass disposal capacity is limited to below 18,000 head/day. In these cases, even if additional animals have to be slaughtered, vaccination would limit the outbreak cost lower than relying only on depopulation. Investigation at selected capacity constraint levels suggests that, compared to under a vaccinate-to-live policy, the optimal number of animals to vaccinate under a vaccinate-to-kill policy is smaller, and it declines more quickly as the carcass disposal capacity expands. The incentive for local decision makers under a vaccinate-to-kill policy is to vaccinate fewer animals as the necessity to vaccinate diminishes. For larger capacity levels than 18,000 head/day, the solutions are essentially identical to the results under no-vaccination policy (Figure 3).

The examination of the shadow values on carcass disposal capacity reveals several important policy implications. First, a limited carcass disposal capacity does affect the course of FMD control strategies, and this aspect needs to be considered in FMD preparation at the local level. Especially, estimation of the existing capacity is essential in evaluating the regional preparedness to a potential FMD outbreak. Second, local carcass disposal capacity and federal vaccination policies interact. If the option to vaccinate is not available, having sufficient carcass disposal capacity is especially important.

Third, the impacts of a limited carcass disposal capacity vary depending on where the outbreak starts, which determines the future disease spread and the eventual outbreak size. If the outbreak was expected to start only on a beef or backyard herd, existing

capacity might be sufficient. On the other hand, it is estimated that, if a sales yard was the expected index case, a capacity below 12,000 head/day would result in infection of practically all herds in the region without vaccination. In reality, it is uncertain where the outbreak would start. There may be multiple index cases, which is especially likely in case of an intentional introduction of the disease into the region. Therefore, decisions about desirable level of carcass disposal capacity may be made in reference to likely scenarios of disease introduction into the region and the associated probabilities.

### 3.3 VALUE OF SURVEILLANCE

The above analysis suggests that the three-county region of California may be better prepared for a potential FMD outbreak by strengthening carcass disposal capacity. Such capacity may have some alternative usage, including outbreaks of other livestock diseases that involve slaughter and disposal of animals (e.g. avian influenza and Exotic Newcastle disease). However, the scope of alternative usage of the capacity would be limited, and a large capacity would not be necessary for many of the scenarios for an FMD outbreak in the region. Thus, investment in a large carcass disposal capacity may not be unanimously supported by decision makers.

We argue that investing in a targeted routine surveillance as well as in a moderate carcass disposal capacity would be an alternative strategy to prepare for an FMD outbreak. Surveillance activities would enable early disease detection and early implementation of movement restrictions and other control policies, which in turn would relieve a bottleneck of carcass disposal capacity in a large outbreak. There are several potential surveillance techniques that differ in terms of the sensitivity and report-time specifications and in the implementation and running costs. For instance, the

Autonomous Pathogen Detection System (APDS) provides timely and accurate results, sometimes within 15 minutes (Fitch, Raber, and Imbro, 2003), but it is estimated to cost $15,000 per unit (The Athena Project) and requires a continuous and high level of maintenance.

The substitutability between investments in carcass disposal capacity and routine surveillance are illustrated in the iso-cost curves (Figures 4 and 5). The model is used to generate total outbreak cost[16] under 1,115 different combinations of carcass disposal capacity and surveillance level. We assume no vaccination and either a sales yard (Figure 4) or a dairy herd (Figure 5) is specified as the index case, since the bottleneck of a carcass disposal capacity constraint would be the tightest in these cases. For surveillance, we consider a generic technique that reduces the duration between the index case and detection. We consider a range of detection lag between zero days (immediate detection) to 28 days. Note that the detection lag thus far assumed in the analysis is 21 days.

The figures confirm the existence of substitutability. For example, when a sales yard is the index case (Figure 4), for the iso-cost curve for 800 million dollars, detecting the disease half a week earlier (as opposed to on day 21) would result in the same cost saving effect as augmenting the carcass disposal capacity from about 8,000 to 14,500 head/day. To achieve the same outbreak cost under unlimited carcass disposal capacity ($458.4 million, Table 3) with a low level of carcass disposal capacity of say, 5,000 head/day, the detection lag would have to be shortened by a week. This may be possible with a different technology or with more frequent testing with the same technology.

[16] Costs of investment in carcass disposal capacity or surveillance activities are not included in the calculation.

Our earlier results suggest that surveillance activities may be appropriately targeted for sales yards in the region, as they are expected to act as the major disseminators of the virus. Alternatively, dairy farms may be a desirable surveillance target, as proportionately more dairy herds would be infected in the region and a higher detection rate would be achieved if the surveillance system would be installed only on selected farms. Targeting dairy herds would also be desirable because the surveillance system could serve for early detection of subsequent cases, whereas all sales yards would be closed and the system would not be utilized after the first case is detected in the region.

Results of the FMD simulation model (Bates, Thurmond, and Carpenter, 2003), with which the optimization model used in this paper was parameterized, sugges that implementation of the above mentioned air-"sniffer" device (APDS) in the region has a potential of relieving the carcass disposal capacity bottleneck in the region (Dr. Bradley Dickey, CADMS, personal communication). According to the simulation results, for example, installing APDS at all of the five sales yards in the region, with continuous monitoring, would allow average disease detection on day 18 rather than on day 21. The unit cost of implementation would be $15,000 (The Athena Project), and the annual maintenance cost is estimated to be around $10,000 (JASON, 2003).

## 4. CONCLUSIONS

Using a previously developed dynamic optimization model (Kobayashi et al., a), we analyze the impacts of alternative preparation investments on potential FMD outbreaks in the three-county region in the Central Valley of California. Given different assumptions about federal vaccination policies, we estimate the cost-saving effects of investments in different levels of carcass disposal capacity and surveillance efforts. We

find that a limitation in carcass disposal capacity would affect the feasible set of FMD control strategies in the region. The impacts of the capacity constraint would vary depending on where the first infection occurs, which affects the extent of disease spread and the eventual outbreak size. While additional carcass disposal capacity may not provide benefit if a beef or a backyard herd is the index case, cost savings would be substantial if an outbreak starts on a sales yard and, to a lesser degree, on a dairy herd.

We also find substitutability between investments in carcass disposal capacity augmentation and surveillance activity. The carcass disposal bottleneck could be relieved by routine surveillance activity targeted at sales yards (and possibly dairy farms) via early disease detection and early implementation of control strategies. While carcass disposal capacity would have limited alternative uses, surveillance equipments may be calibrated for detecting other diseases and pathogens. Our results do not include values of such alternative uses of the capacities. With these included, a higher overall value of surveillance efforts is expected.

Another important finding is the strong interactions between depopulation and vaccination policies especially when the carcass disposal capacity is limited. Without a vaccination option, local disease control policy would have to depend on depopulation, which increases the burden on the carcass disposal capacity. In the current federal policy, whether or not vaccination is available would be determined case by case and thus unknown prior to an outbreak. Thus, the incentive of local decision makers may be to prepare the region for a potential FMD outbreak with a sufficient capacity of carcass disposal capacity and routine surveillance activities. Alternatively, local decision makers may wish to secure their own vaccine stockpile. With a potential of local FMD

vaccination resulting in trade restrictions applied at the national level, coordination of vaccination policies at different decision-making levels would be appropriate.

The optimization model used in this study is a unique combination of epidemiology and economic concepts and techniques. The model enables economic analyses based on reasonably detailed disease dynamics that are locally and disease specific. Shadow values on limited resources and substitutability of alternative investment areas suggested by the model are crucial for informed decision making in preparation for potential FMD outbreaks. The approach is readily applicable to other diseases, especially where data on actual outbreaks are available or where a sophisticated epidemiologic simulation model is developed.

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Table 1. Daily FMD Disease Dynamics

| | Prevalence (Stock) | Incidence (Flow) |
|---|---|---|
| Susceptible | $S_{i,t+1} = \left(1 - r_{it}^{P} - v_{it}\right)\left(S_{it} - \Lambda_{it}\right)$ | NA |
| Latent | $L_{i,t+1} = \left(1 - r_{it}^{P} - v_{it}\right)\left(L_{it} + \Lambda_{it} - \Phi_{it}^{S}\right)$ | $\Lambda_{jt} = S_{jt} \sum_{i} \beta_{ij} \frac{I_{it}^{S} + I_{it}^{C}}{S_{it} + L_{it} + I_{it}^{S} + I_{it}^{C} + V_{it}}$ |
| Subclinically infectious | $I_{i,t+1}^{S} = \left(1 - r_{it}^{P} - v_{it}\right)\left(I_{it}^{S} + \Phi_{it}^{S} - \Phi_{it}^{C}\right)$ | $\Phi_{it}^{S} = \left(\prod_{k=1}^{\lambda_i}\left(1 - r_{i,t-k}^{P} - v_{i,t-k}\right)\right)\Lambda_{i,t-\lambda_i}$ |
| Clinically infectious | $I_{i,t+1}^{C} = \left(1 - r_{it}^{B}\right)\left(I_{it}^{C} + \Phi_{it}^{C}\right)$ | $\Phi_{it}^{C} = \left(\prod_{k=1}^{\sigma_i}\left(1 - r_{i,t-k}^{P} - v_{i,t-k}\right)\right)\Phi_{i,t-\sigma_i}^{S}$ |
| Vaccinated | $V_{i,t+1} = V_{it} + \upsilon_{it}$ | $\upsilon_{it} = v_{it}\left(S_{it} + L_{it} + I_{it}^{S} - \Phi_{it}^{C}\right)$ |

Notes:

$\beta_{ij}$ : disease transmission rate from herd type *i* to herd type *j*

$\lambda_i$ : duration of latent period

$\sigma_i$ : duration of subclinically-infectious period

$r_{it}^{B}$ : rate of baseline slaughter (depopulation of clinically-infected herds)

$r_{it}^{P}$ : rate of preemptive slaughter

$v_{it}$ : vaccination rate

Source: Kobayashi et al. (a).

Table 2. Selected Parameters Used in Optimal FMD Management Model

| Herd type (*i*) | Herd number (herd) | Average herd size (head/herd) | Livestock unit value ($/head) | Euthanasia/ disposal cost ($/head) | Cleaning/ disinfection cost ($/herd) | Vaccination cost ($/head) | Vaccination cost ($/herd) |
|---|---|---|---|---|---|---|---|
| Beef | 664 | 853 | 598 | 16.5 | 9,513 | 6 | 885 |
| Dairy | 576 | 1,727 | 1,669 | 16.5 | 31,710 | 6 | 664 |
| Swine | 79 | 2,519 | 130 | 16.5 | 9,513 | 6 | 664 |
| Sheep and goat | 131 | 558 | 121 | 16.5 | 9,513 | 6 | 885 |
| Backyard | 788 | 5 | 0 | 16.5 | 5,000 | na | na |
| Sales yard | 5 | na | na | na | 31,710 | na | na |

na: Not applicable

Source: Kobayashi et al. (a).

Table 3. Summary Results of Optimal FMD Management by Index Case Herd Type

(No carcass disposal capacity constraint)

| | Index case: | | | | | |
|---|---|---|---|---|---|---|
| | Beef | Dairy | Swine | Sheep/ goat | Backyard | Sales yard |
| Total regional cost (million dollars) | | | | | | |
| No vaccination | 38.7 | 113.1 | 87.8 | 83.8 | 33.4 | 458.4 |
| Vaccination | 37.3 | 106.1 | 82.6 | 79.2 | 32.3 | 424.3 |
| Outbreak duration (days) | | | | | | |
| No vaccination | 38 | 44 | 43 | 42 | 37 | 52 |
| Vaccination | 35 | 38 | 37 | 38 | 34 | 38 |
| Number of clinically-infected animals on day 21 (000 head) | | | | | | |
| | 2.7 | 13.2 | 8.9 | 6.5 | 1.8 | 75.1 |
| Total number of infected animals for the entire outbreak (000 head) | | | | | | |
| No vaccination | 24.2 | 71.8 | 57.8 | 53.6 | 20.2 | 301.2 |
| Vaccination | 22.6 | 66.0 | 53.3 | 49.5 | 18.8 | 277.6 |
| Total number of animals vaccinated (000 head) | | | | | | |
| | 250.0 | 518.7 | 434.4 | 397.8 | 250.0 | 720.5 |

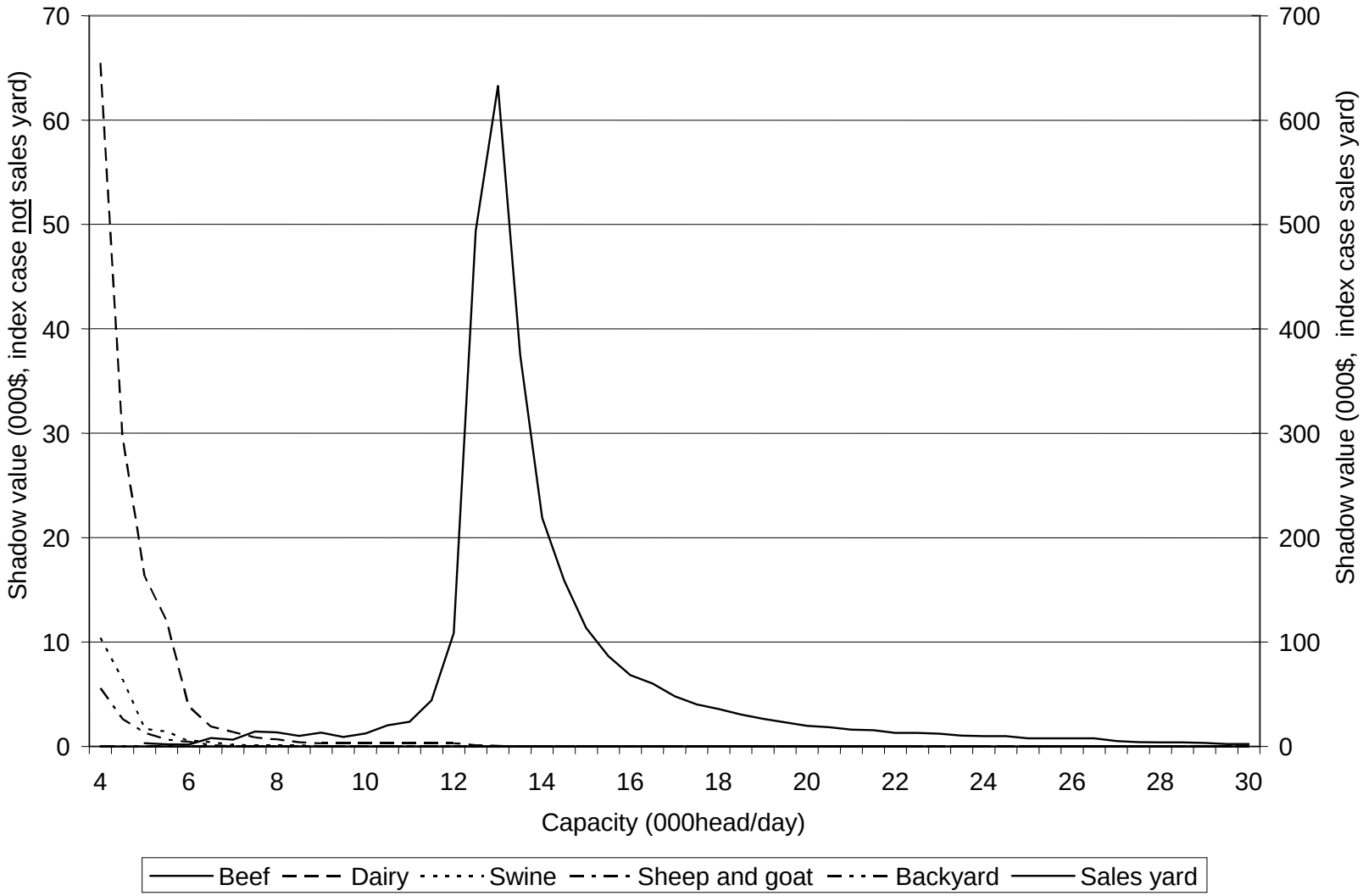


**Figure 1. Shadow value of carcass disposal capacity by index case: Without vaccination**

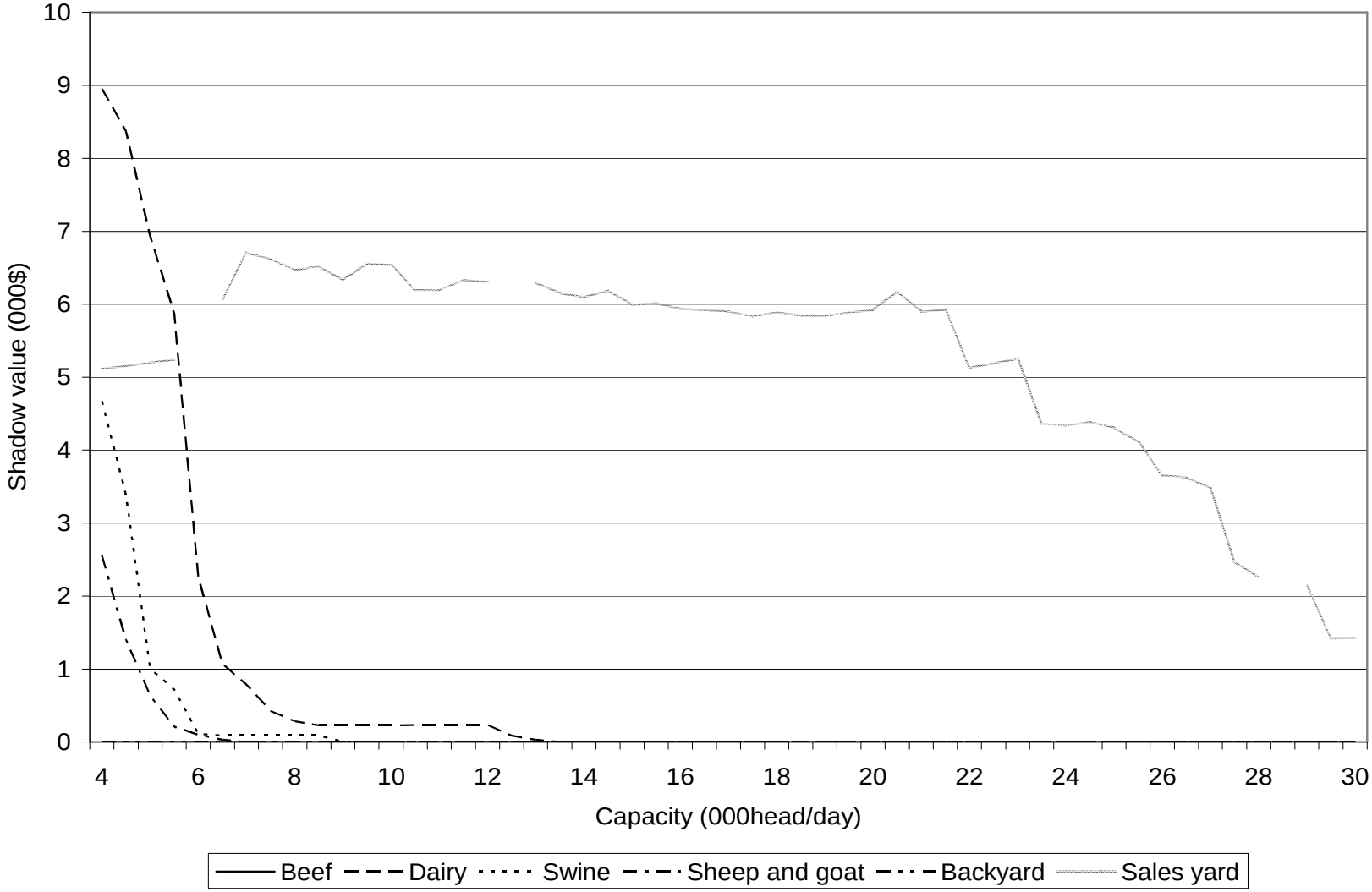


**Figure 2. Shadow value of carcass disposal capacity by index case: With vaccination (Vaccinate-to-live policy)**

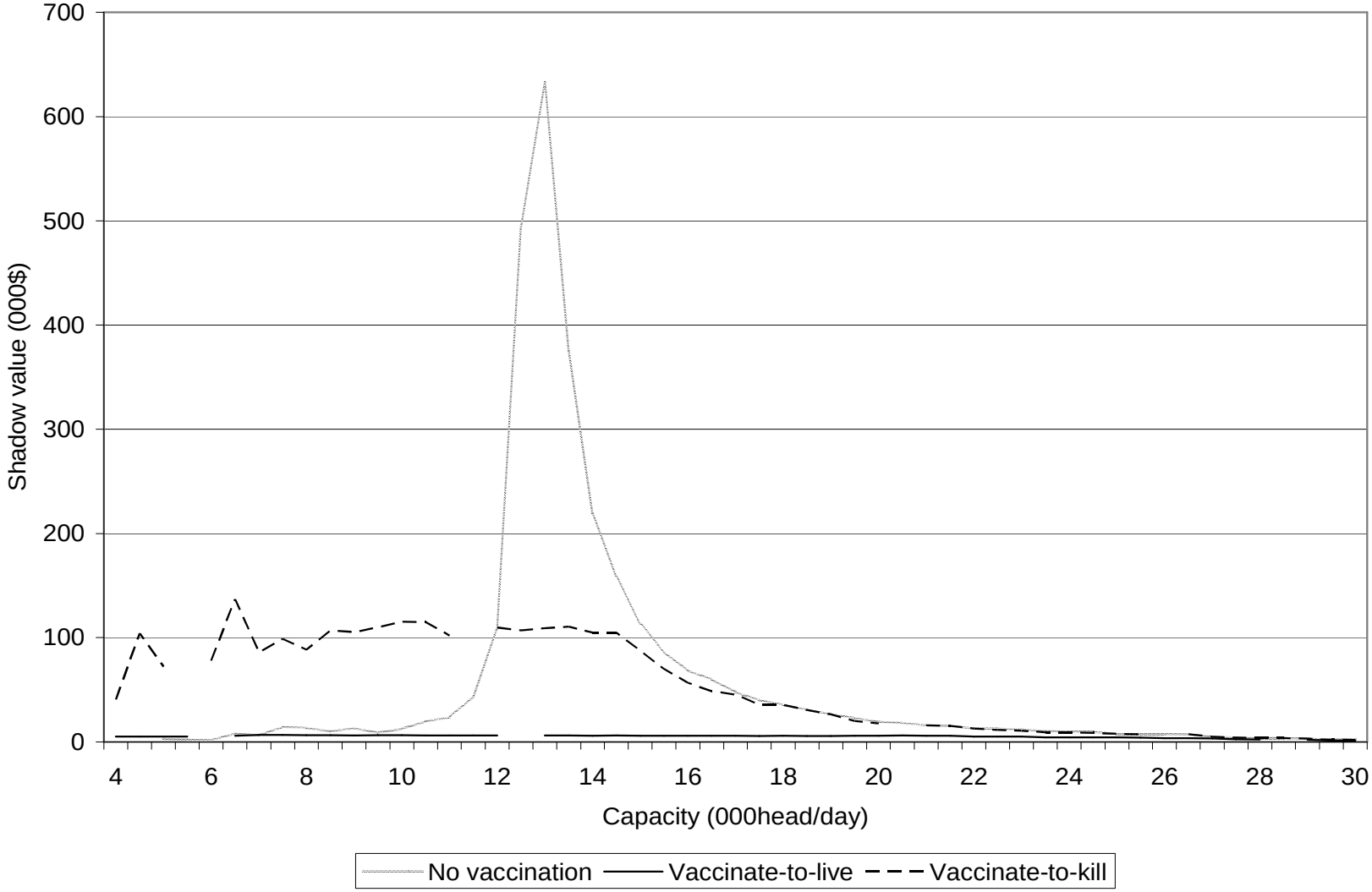


**Figure 3. Shadow value of carcass disposal capacity by policy: Index case sales yard**

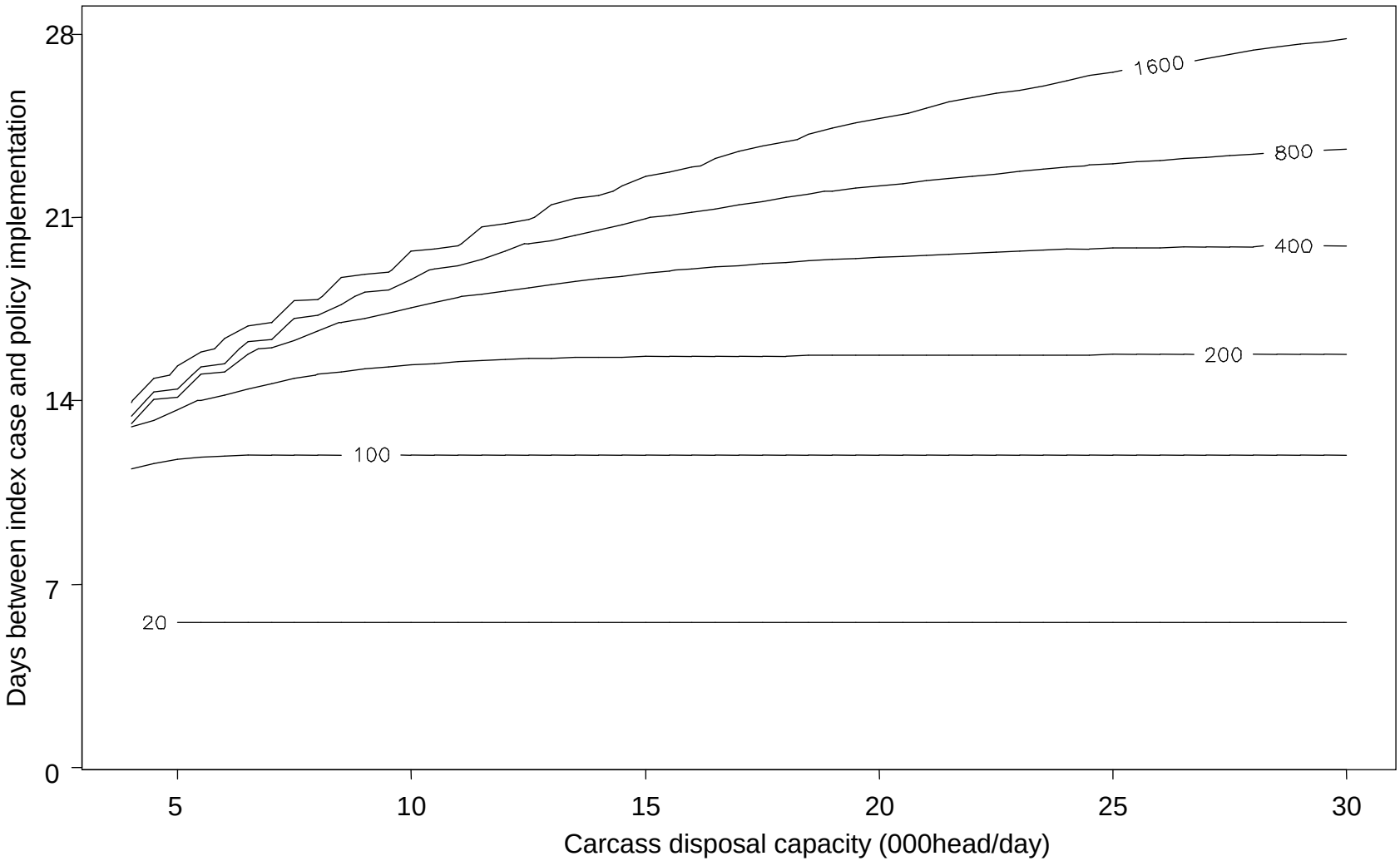


**Figure 4. Iso-cost curves (Million dollars, Index case sales yard, No vaccination)**

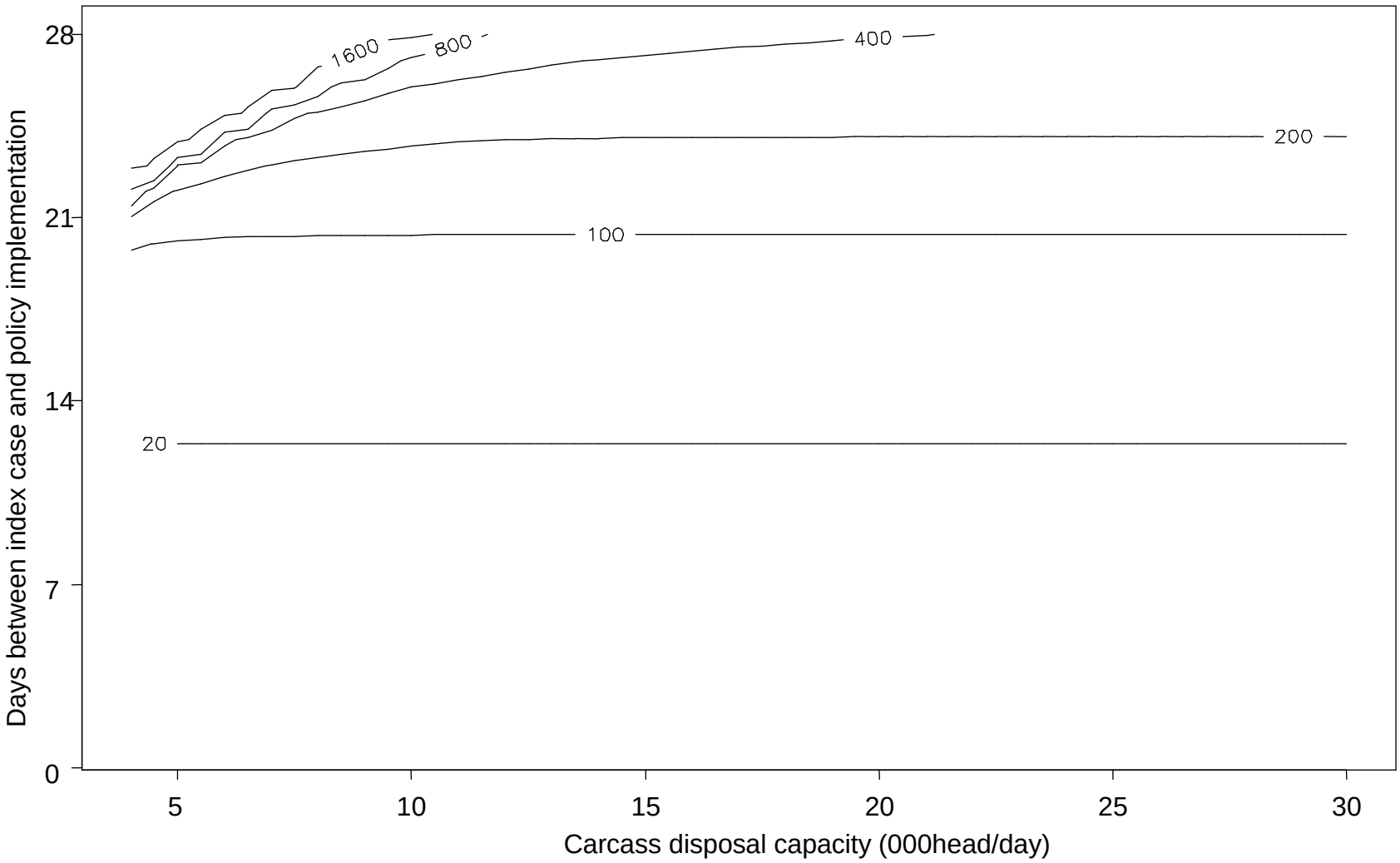


**Figure 5. Iso-cost curves (Million dollars, Index case dairy, No vaccination)**