Applied Economic Perspectives and Policy (2012) volume 34, number 1, pp. 119–146.
doi:10.1093/aepp/ppr039

Submitted Article

Emergency Vaccination to Control Foot-and-mouth Disease: Implications of its Inclusion as a U.S. Policy Option

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Submitted 28 October 2010; accepted 12 October 2011.

Abstract *Emergency animal vaccination has been used in recent international foot-and-mouth disease outbreaks, but current USDA policy favors emergency vaccination use only if standard culling practices alone may not be enough to control spread of the disease. Using simulation modeling, we examine implications of standard culling plus emergency ring vaccination strategies on animal loss and economic welfare loss compared to a standard culling base. Additionally, breakeven risk aversion coefficient analysis is used to examine emergency vaccination as a risk management strategy. Results indicate that response enhanced with emergency vaccination is inferior to standard culling under short diagnostic delays because it causes, on average, greater animal and national economic welfare losses. We find that emergency vaccination does have merit as a risk management strategy, as it can reduce the likelihood of an "extreme" outbreak.*

JEL Codes: H50, D60, D80.

Introduction

Decision makers are faced with many difficult choices with respect to the design of U.S. foot-and-mouth disease (FMD) control policy. Thus, these decision makers will increasingly seek analytical tools and decision criteria based on sound science, as well as lessons learned from recent outbreaks. One current animal disease policy issue is whether or not to use

Published by Oxford University Press, on behalf of Agricultural and Applied Economics Association 2011.

emergency vaccination in the event of an outbreak in the United States. The North American Guidelines for FMD Vaccine Use indicate that if FMD can be eradicated through culling alone, no vaccination should be employed. However, the U.S. Department of Agriculture's Animal and Plant Health Inspection Services (APHIS) may determine that vaccination is necessary to contain the disease after weighing factors such as the region of infection, suspected origin of the infection, estimated date of introduction, and its possible spread (APHIS, 2010). As a consequence, this decision, among others, will necessarily be made in a situation where information, time, and other critical resources are constrained.

Simulation models often used in disease policy evaluation and planning incorporate risk and uncertainty, with their output offering a distribution of possible outcomes. Based on such modeling, decision makers can identify approximately where an actual outbreak lies in the distribution of possible outcomes identified *a priori*, given the knowledge of key pieces of information such as delay to initial diagnosis and livestock movements. Still, it is highly improbable that any *a priori* scenario will match the actual disease outbreak situation exactly. Advances in the evaluation of alternative policies recognize this uncertainty in outcomes, and are moving beyond simple summary statistics in *ex ante* policy evaluation to employ more of the information available from the full distribution of outcomes.

This paper examines vaccination policy from multiple perspectives: as a means of minimizing national animal losses; a means of controlling costs and welfare loss; and as a means of risk management. The emergency vaccination policy is examined using epidemic-economic (or epinomic) modeling under the assumption of short-run, single-event epidemics in separate case studies from California and Texas. The risk management evaluation in particular can be extended and used more fully in the evaluation of response strategies for transboundary diseases such as FMD.

Foot-and-mouth Disease and Vaccination

FMD is considered a major threat to the United States due to herd destruction, trade restrictions, disease eradication costs, and market disruptions (Doel 2003; APHIS 2010). The business continuity of local farms and service providers is also threatened by potential FMD outbreaks (Doel 2003). FMD infection may cause reduced milk yield, growth rates, and fertility, as well as high mortality rates in young animals. During the past decade, large FMD events have occurred in Taiwan, the Netherlands, Japan, the Republic of Korea and the United Kingdom (U.K.). In each case, disease was eradicated through the extensive culling of all infected and dangerous contact animals, combined with controls on the movement of livestock. In some of these outbreaks, emergency vaccination was used. In the 2010 FMD outbreak in Japan, almost 300,000 animals were culled, including approximately 125,000 vaccinated animals that were eventually culled for being regarded as "at risk" (Nishiura and Omari 2010). In contrast, the use of vaccination was approved and ready for implementation within 6 days of FMD confirmation during the 2007 FMD outbreak in the U.K., but was eventually not employed because the culling and movement control policies were able to effectively contain and eradicate the disease (Anderson 2008).

North America, Europe, Australia, New Zealand and Japan maintain emergency vaccine banks against FMD. This study considers emergency vaccination similar to the programs implemented in Japan or Brazil, not a systematic vaccination program such as those implemented in Argentina and Uruguay. Emergency vaccination can protect against clinical disease and reduce the amount of virus that infected animals shed. In an emergency situation, emergency vaccination may be useful to slow disease spread and reduce outbreak size, allowing for faster control.

FMD vaccination is controversial for the following reasons: (a) risk of virus introduction via the vaccine and vaccination team; (b) potential delays in the re-opening of international markets; (c) potential of higher culling due to vaccinate-to-die policies or lack of differentiation between animals that have been vaccinated and those that are sub-clinically infected or recovered (i.e., the vaccine not being a Differentiate Infected from Vaccinated Animals, or DIVA, vaccine); and (d) the costs of implementation, plus the limited availability of key resources such as personnel and necessary vaccination equipment. That vaccinated animals are culled along with non-vaccinated animals may seem counter-intuitive. But in this particular use, vaccination is employed in the same manner that starting a backfire stops the spread of a wildfire. The vaccination-immune animals act as a living barrier that slows the spread of disease. Under vaccination, nearby herd disease spread probability is reduced. However, to avoid the trade consequences of being categorized as "FMD free with vaccination" as opposed to "FMD free without vaccination", the vaccinated animals are culled along with infected and direct contact animals.

Emergency vaccination strategies may involve inoculating animals in a ring surrounding the outbreak (the method examined here), inoculating selected high-risk animal groups, or inoculating animals in a limited area. Studies have examined different emergency vaccination strategies (e.g. Plumiers et al. 2002; Abdalla et al. 2005; Ward et al. 2009, Garner 2004, Bates et al. 2003). Results of these studies show that emergency FMD vaccination reduces the size of outbreaks, and controlled testing of vaccines shows a significant reduction in virus shedding (Rodriguez and Grubman 2009). For the remainder of this paper, "vaccination" refers to emergency ring vaccination.

Animal Disease and Economic Modeling

Integrated epinomic modeling has advanced significantly since McCauley et al. (1979) examined the cost of controlling and eradicating an FMD outbreak in the United States. Today, economists examining animal health issues recognize that the type of economic model used may vary depending on the characteristics of the disease being examined (including its spread rate, impacts on livestock, market implications and control policies). Four model types are typically used: a simple cost-benefit analysis (CBA), input-output analysis (I/O), computable general equilibrium (CGE) models and partial equilibrium (PE) (Rich, Miller and Winter-Nelson 2005). The methodological framework selected may depend on the applicable impact categories that apply to the disease in question. The primary impact categories include: production effects, market and price effects, trade effects, impacts on food security and nutrition, human health and the environment, and financial costs (Pritchett, Thilmany and Johnson 2005). Thus, the model selected should include an impact measure that captures the impact categories determined to be most critical for that disease. Within each of the four model types, there are several possible measures used to quantify economic loss including national welfare, regional welfare, producer welfare, consumer welfare, gross domestic product, trade loss, sales revenue and eradication costs.

The current stamp-out response policy will likely result in extensive culling—potentially resulting in a national supply shift, depending on the region impacted—and international trade restrictions. Countries that are FMD-free will likely not accept livestock or fresh meat products from FMD infected areas (Mason and Grubman 2009). The length of trade restrictions is bilaterally negotiated, making anticipation of trade ban lengths complicated. The World Animal Health Organization (OIE) guidelines recommend trade barriers throughout the outbreak, and for at least an additional three months if the disease is eradicated through culling alone (OIE 2009), or six months post-outbreak when vaccinated animals are allowed to live (or three months if vaccinated animals are culled). If trade partners closely follow these guidelines, emergency vaccination would not cause additional delay if a vaccinate-to-die policy is followed, and a shortened disease duration would result in faster trade market recovery. A PE economic modeling framework is employed to allow the flexibility to capture these national level effects, as well as the feedback through market mechanisms to other components of the agricultural economy.

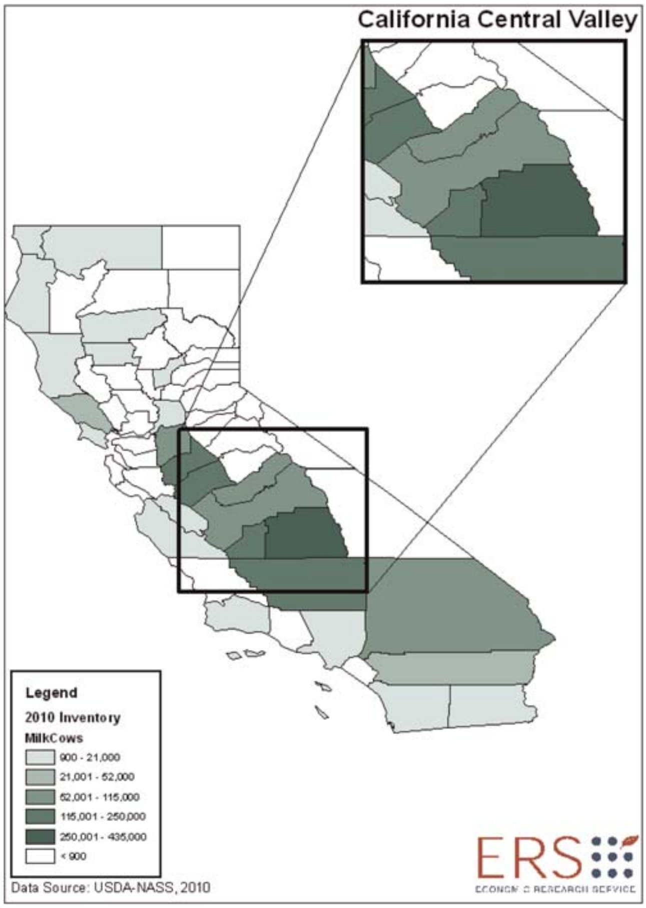
Study approach

The case studies considered in this work were designed to simulate the consequences of FMD control with and without vaccination. The case studies were undertaken in two U.S. regions with independent outbreaks, but focus on the high-value production areas of California and Texas. The California region specializes in dairy production, and the outbreak is simulated from an infection point in a 3-county region (figure 1) containing approximately 2,100 herds with 943,000 animals, although the model encompasses the entire state[1]. The 3-county region contains approximately 40% of California's dairy production, 8% of its cow/calf production, 6% of its hogs, and 20% of its sheep and goats. The second study area involves an 8-county region in the Texas High Plains (figure 2) that specializes in fed cattle production, and contains approximately 14,000 herds with over 2 million head, or approximately 43% of Texas' fed cattle and 37% of its dairy cattle[2].

[1]*Data related to California county and state level statistics are available through NASS (National Agriculture Statistical Service), United States Department of Agriculture, 2007. Available at: http://www.agcensus.usda.gov/Publications/2007/Full_Report/ Census_by_State/California/index.asp. (Accessed August 23, 2010).*

[2]*Data related to Texas county and state level statistics are available through NASS (National Agriculture Statistical Service), United States Department of Agriculture: 2007, available at http://www.agcensus.usda.gov/Publications/2007/Full_Report/ Census_by_State/Texas/index.asp. (Accessed August 23, 2010).*

Figure 1. The California study area

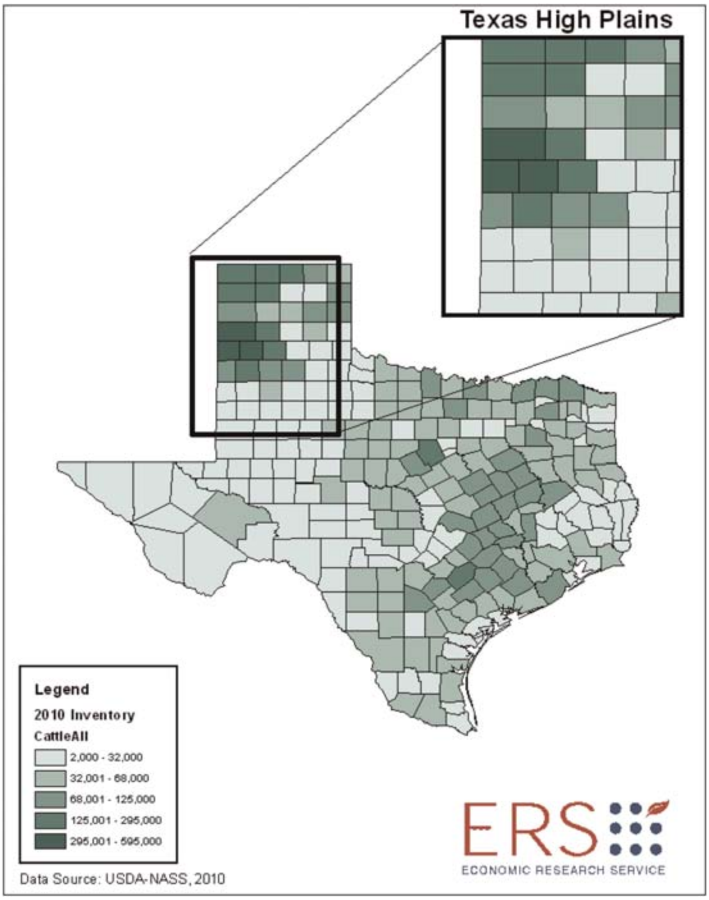


The outbreak cases were simulated with two epidemic models, each of which have been the subject of major research programs calibrating them to one of the study areas. Specifically for California, we used the Davis Animal Disease Simulation model (DADS, as described by Bates et al. (2003)) that has evolved over 10 years of studies. For Texas, we used the AusSpread-High Plains model, which arose over 5 years of studies in that region (described in Elbakidze et al. (2009)). Both models require extensive local data, and it was not feasible to adapt either model to another region. Thus, the two outbreaks are independent case studies, recognizing that differences exist in the underlying assumptions of the two models.

It was assumed that the disease is confined to the study regions through effective movement restrictions and national disease control strategies. Furthermore, we assumed that through the effective enforcement of zoning and appropriate indemnity payments, producers do not smuggle or conceal animals (following Gramig, et al. (2009) and Ferrier (2009)).

The same economic modeling structure was used in both case studies to assess national consumer and regional-level producer effects. The Agricultural Sector Model (ASM, described in Baumes (1978) and Chang et al. (1992)) is a part of the larger Forestry and Agricultural Sector Optimization Model (FASOM, described in Adams et al. (2008)). ASM

Figure 2. The Texas study area



permits the analysis of trade restrictions and regional level production. In terms of trade, no regionalization[3] is assumed in this study; as a consequence, it is assumed that the United States loses its non-pasteurized dairy and meat export markets. This could occur due to the time necessary to prove to trade partners that the disease is regionalized. The national loss expected is modeled consistent with experience from the 2003 BSE incident, where beef exports were subsequently reduced by 80% (Mathews, et al. 2006). Exports of pasteurized dairy and cooked meat products are assumed to be unaffected.

Disease Related Assumptions

Four scenarios were examined: the use and nonuse of vaccination, plus two levels of an elapsed time to diagnose the outbreak (diagnostic delay). In accordance with the FMD Redbook (APHIS, 2010), a disease stamp-out program includes culling infected and dangerous contact herds, plus

[3]*Regionalization is the containment of infection to a defined region or zone. Once regionalization has been established, production liable for trade sanctions from within the region or zone are still subject to such sanctions and normal trade can resume from other areas of the country outside that region or zone.*

surveillance and movement restrictions once the FMD-diagnosis is confirmed. This is compared to a stamp-out program modified with emergency vaccination to slaughter, as also outlined in the FMD Redbook (APHIS, 2010).

Two diagnostic delay scenarios were considered. Diagnostic delays describe how many days the disease progresses before it is first confirmed. The scenarios used were 7 and 14 days, intervals that lie within the range of observed delays in FMD outbreaks examined by McLaws and Ribble (2007). The U.S. FMD response plan indicates that this delay will be one of the factors considered in initiating a vaccination program. For outbreaks occurring from 1992 to 2003 in countries previously FMD-free, the average diagnostic delay was 14.4 days (McLaws and Ribble 2007).

Resource availability is an important determinant of the time to eradication; the resource constraint assumptions employed are summarized in table 1. The DADS model parameterization was based on literature and surveys of California livestock producers; whereas AusSpread was based on literature, and Texas livestock industry expert opinion. The density and types of operations in the region are key differences between the two case studies. Given that the epidemic simulations take weeks or months to perform, it is not feasible in the timeframe of this study to determine the level of sensitivity in the findings that arise from differences in key disease spread parameters.

Several additional assumptions merit discussion. The timely delivery and administration of vaccine − particularly in large quantities − is a concern. In addition, vaccination implementation is limited by labor availability, with all herds in a ring vaccinated as fast as the labor force allows. This was addressed by including a delay in the vaccine availability parameter − with accompanying limitations on quantity − that is relaxed over time. We assumed that 250,000 doses of vaccine are available 4 days after initial FMD confirmation, 500,000 doses after 11 days and an additional million doses each week thereafter.

Federal guidelines do not specify the exact vaccination program that would be followed, which allows it to be customized. Thus, assumptions on the ring vaccination policy differ slightly. In the DADS model, the California FMD outbreak was initiated in a 2,000+ cow dairy, randomly selected in the 3-county region. Vaccination strategies of 10 and 20km rings were simulated under a vaccinate-to-die program, and vaccination was applied only to dairy herds. The Texas outbreak was initiated in the model in a 50,000+ cattle feedlot. The vaccination program is a 5km ring vaccinate-to-die program, and vaccination is applied to all herd types.

Model and Disease Control Cost Descriptions

The Davis Animal Disease Simulation (DADS) Model: The DADS model, as reviewed by Bates et al. (2003) is a spatial, stochastic, individual-animal-based model that includes 13 herd types: small (≤250 head) and large (>250) beef herds; small (≤1000), medium (1001-1999) and large (>2000) dairies; small (≤250) and large (>250) calf/heifer raising operations; small (≤2000) and large (>2000) swine operations; goat flocks; sheep flocks; backyard (<10) herds; and saleyards. The DADS model simulates direct (animal-to-animal) and indirect (via a vector, such as human,

Table 1 Resource constraint assumption comparison in DADS and AusSpread[/1]

Control Measure	Distribution	Reference
DADS Model		
Days until vaccine was available	4	Model assumption
Radius of vaccine area	10 and 20 km	Alternative scenarios
Days until vaccine was protective	4	Cox et al. 1999
% reduction in herd infectiousness from vaccination	1-[Uniform(minimum = 80,maximum = 90)]	Hutber et al. 1999.
Days until FMD diagnosis in index herd	7 and 14	Alternative scenarios
Days from diagnosis to slaughter based on of number of animals per herd	< 250 Uniform(min = 1,max = 2) 250-1999 BetaPert(1,2,4) >2,000 BetaPert(2,2.5,5)	Expert Opinion[/2]
AusSpread Model		
Days until vaccine was available	7	Model assumption
Radius of vaccine area	5 km	Alternative scenarios
Days until vaccine was protective	4-6	Model assumption
% reduction in herd infectiousness from vaccination	5th percentile 30,60 Median 70,90 95th percentile 90,90	Model assumption
Days until FMD diagnosis in index herd	7 and 14	Alternative scenarios
Days from diagnosis to slaughter based on number of animals per herd	< 250 1 – 10 250-1999 10-14 >2,000 14-28	Ward et al. 2009

/1 Additional assumptions are outlined in Carpenter et al. (2011) for DADS and Ward et al. (2009) for AusSpread.
/2 Opinions obtained from 10 emergency-response experts familiar with intensive dairy production regions in California.

vehicle or fomite) contacts among all herd types, based on data from the literature, surveys and expert opinion.

The AusSpread Model: The AusSpread-High Plains model, as described by Ward et al. (2009), is based on the AusSpread model (as reviewed in Beckett and Garner 2007). This model is a spatial, stochastic, state-transition susceptible-latent-infected-recovered (SLIR) model that uses locations of livestock grouped into 13 herd types with 6 cattle feeding operation types: (company-owned, custom, stockholder, backgrounder, yearling-pasture, dairy-calf raiser); small ($<$1,000 head) and large ($>$ 1,000) dairies; small ($\leq$100) and large ($>$100) beef grazing operations; swine and small ruminants (sheep and goats); backyard herds ($<$10); and saleyards. A predicted contact structure, based on data collected during meetings and from surveys (Loneragan et al. 2006) plus expert opinion, is used to model disease spread (Ward et al. 2009).

Assumed Levels of Outbreak Control Costs: Estimates of FMD control and carcass disposal costs were calculated following the method used in Elbakidze et al. (2009). The cost assumptions are summarized in table 2 and are inputs for the economic model. The value of lost animals is captured through the economic analysis described below. Disease management costs include the costs of: (a) testing animals that may be infected; (b) restricting animal movements; (c) veterinarians visiting infected premises; (d) checking restricted premises; and (e) administering the vaccination program. Vaccine administration costs are assumed to have two parts: a variable cost per dose of vaccine used and a fixed inoculation cost per herd. It was assumed that all infected livestock are culled and that some additional exposed animals considered dangerous contacts are also culled. Part of the cost of restricting animal movements includes the cost of cleaning and disinfecting feed trucks, accounting for additional feed brought into the region to prevent culling animals for welfare reasons[4]. Carcass disposal costs include the cost of appraising the herd prior to culling, euthanizing animals, cleaning up and disinfecting premises, and disposing of carcasses. Indemnity payments were calculated for various animal types and operation types using the pre-disease market value of animals. However, in the estimation of the total national cost of the outbreak, which is consequently included in the ASM national welfare analysis below, the net producer costs are added to the government costs. Thus, indemnity payments acted as a transfer payment, entered as a gain in revenue to producers and as a cost of disease management to the government.

The Agricultural Sector Model: The Agricultural Sector Model (ASM) was developed by Baumes (1978) and has since been used continuously in a number of different settings. Today ASM is wholly contained in the Forestry and Agricultural Sector Optimization Model with Green House Gasses (FASOMGHG, Adams et al. (2008)). ASM simulates the allocation of agricultural land to competing crop and livestock activities and the resultant consequences for the commodity markets, in addition to welfare. Applications include climate change effects and mitigation (e.g. McCarl and Schneider 2001), Farm Program effects (e.g. Chang et al. 1992), FMD

[4]*Welfare slaughter is not related to disease control; rather, it is the depopulation of healthy, uninfected animals to prevent degraded quality of living and ethical treatment of animals under movement restrictions.*

Table 2 Eradication and carcass disposal cost assumptions[/1]

Cost Element	**Description** **Cost of Disease Management**	**Value[/2] CA and TX**
Indemnity Payments	Market value by animal type for animals slaughtered for disease control reasons, as of 2009 yearly average	Source: USDA-ERS
Foregone Income	The gross revenue per animal per day, differentiated by operation type, multiplied by the herd size and number of days from depopulation until movement restrictions are lifted	Source: USDA-ERS
Surveillance /Testing	Fixed cost of surveillance of suspect herds (regardless of number of visits)	$171 /small herd
		$122 /medium herd
		$78 /large herd
	Variable cost of surveillance of suspect herds per visit (assumed to be twice a week during a 30-day period)	$50/visit /small herd
		$75/visit /medium herd
		$100/visit /large herd
Truck Cleaning	Cost to clean a tractor and trailer on each trip (one way) into or out of the restricted zone	$130/trip
Feed Cost[/3]	$310 per ton (concentrates) delivered and delivery every other day	$4.97/cow/day quarantined
Vaccine Cost	Cost per dose of vaccine plus administration costs	$32 / head /small herd
		$29 / head /medium herd
		$13 / head /large herd
Carcass Disposal Cost		
Appraisal	Appraisal cost for slaughter	$3 / head /small herd
		$0.88 / head /medium herd
		$0.63 / head /large herd
Euthanasia	Cost to kill animals	$50 regardless of size or type
Disposal	Cost to dispose of animal carcasses	$53 / head /small herd
		$31 / head /medium herd
		$10 / head /large herd
Cleaning/Disinfecting	The cleaning/disinfection of premises that have been depopulated	$5,000 /small herd
		$7,000 /medium herd
		$10,000 /large herd

/1 The cost portion of the model closely follows the method outlined in Elbakidze et al (2009).

/2 Appraisal, euthanasia, disposal, cleaning/disinfecting, surveillance are applied to all herd types in the region and are the average cost per animal or herd across all herd types, varying by herd size unless otherwise specified, where herd sizes are small (<100), medium (100-500) and large (>500).

/3 Feed costs and truck cleaning are calculated specifically for dairies. Using a representative medium-sized dairy operation in California, it is estimated that dairy producers will only have to bring in a portion of feed from the outside; on-farm production will account for the rest. This is a cost per animal in 2009 of $4.97 per cow per day out of the total cost per cow per day of feed of $7.23. Feed costs typically are about half of the cost per hundred pounds of milk, so this number is not unreasonable, given farm milk prices at the time this study was underway.

strategy evaluation (Hagerman 2009; Carpenter et al. 2011), Rift Valley Fever vulnerability (Hughes-Fraire 2011), and work is ongoing related to avian influenza. The overview of ASM presented here is derived from the more extensive discussion presented in Adams et al. (2008) and Beach et al. (2010) [5].

ASM is an intermediate run model identifying market equilibrium where the basic modeling relations in ASM represent typical repeating activities over a multi-year time period. Endogenous variables include: (a) commodity and factor prices; (b) production, consumption, export and import quantities; (c) land use allocations (cropland, Conservation Reserve Program land, range and pastureland); (d) management strategy adoption; (e) resource use; (f) economic welfare measures (producers' and consumers' surpluses, transfer payments, net welfare effects); and (g) environmental impact indicators.

The simplified structure of FASOMGHG is as follows (Adams et al. 2008):

$$\begin{aligned}
&\text{Max} \sum_h \int_0^{Z_h} P_{dh}(Z_h)dZ_h - \sum_i \int_0^{X_i} P_{si}(X_i)dX_i \\
&s.t. \quad Z_h - \sum_\beta \sum_k C_{h\beta k}\, Q_{\beta k} \le 0 \text{ for all h} \\
&\quad - X_i + \sum_\beta \sum_k a_{i\beta k}\, Q_{\beta k} \le 0 \text{ for all i} \\
&\quad \sum_k b_{j\beta k}\, Q_{\beta k} \le Y_{j\beta} \text{ for all j and} \beta \\
&\quad Z_h,\; X_i,\; Q_{\beta k} \ge 0 \text{ for all i, h, k, and } \beta.
\end{aligned}$$

A number of different firms/farms in regions (β) are modeled, each of which has a finite set of production processes (k), that depict particular ways of combining fixed factors (j) with purchased factors (i) to produce commodities (h). The symbols in the formulation are: $P_{dh}(Z_h)$, the inverse demand function for the h^{th} commodity; Z_h, the quantity of commodity h that is consumed; $P_{si}(X_i)$, the inverse supply curve for the i^{th} purchased input; X_i, the quantity of the i^{th} factor supplied; $Q_{\beta k}$, the level of production process k undertaken by firm β; $C_{h\beta k}$, the yield of output h from production process k by firm β; $b_{j\beta k}$, the quantity of the j^{th} owned fixed factor used in producing $Q_{\beta k}$; $a_{i\beta k}$, the amount of the i^{th} purchased factor used in producing $Q_{\beta k}$ and $Y_{j\beta}$, the endowment of the j^{th} owned factor available to firm β. In the formulation above, ASM solves an objective function to maximize net market surplus, represented by the area under the product demand function (an aggregate measure of consumer welfare), less the area under factor supply curves (an aggregate measure of producer costs).

In ASM, primary and secondary commodities are consumed and exported according to constant elasticity demand functions. The areas under these demand curves represent society's total willingness to pay for agricultural products. The difference between total willingness to pay and

[5]*For a list of citations to studies performed using ASM or the FASOMGHG model, please contact the corresponding author. Moreover, consult Adams, D., R. Alig, B.A. McCarl, and B.C. Murray, 2008, FASOMGHG Conceptual Structure, and Specification: Documentation (unpublished manuscript, Texas A&M) for additional citations.*

total production and processing costs, less the area under import supply curves, is equal to the sum of producers' and consumers' surpluses (Adams et al. 2008). Maximizing the sum of these surpluses constitutes the agricultural sector objective function.

Primary variables include those associated with land allocation and transformation such as the crop production mix, tillage system, irrigation, livestock production mix, feed blending, agricultural processing mix, domestic consumption, exports, imports, and adoption of GHG mitigation options (if any). Equilibrium values are determined subject to: constraints on crop and livestock mixes; resource limits for land, water, and labor; balances on primary, secondary, and blended feed commodities; trade balances; and GHG balances (Beach et al. 2010).

ASM livestock production possibilities are defined by region, animal type (dairy, beef, swine, sheep and goats, chickens, turkeys, egg layers, horses), stage of animal production (for example, cow calf, stocker, feedlot, feeder pig, hog finishing), and livestock management alternative. Livestock production budgets use inputs as defined by livestock budgets from USDA and state extension service sources.

The variables compete for labor as well as land, which can be allocated as pasture, cropland, grazed forestland and rangeland. Land allocated to livestock uses in turn produce livestock products. Livestock production budgets use crops and processing by-products directly as feed inputs, as well as blended feeds. Livestock budgets also use intermediate animal stages as inputs to the final stage (e.g. feeder pigs are an input to finishing). The mix of livestock produced within a region falls within a convex combination of historical regional livestock production mixes to be properly aggregated (Beach et al. 2010, based on McCarl 1982).

The animal disease study introduced three additional assumptions. First, an outbreak is assumed to be a one-time, short-run event, and as such there are no shifts in the location of cow-calf, dairy, and swine production. To achieve this in the model, land use allocations for these animal classes are held constant at the pre-disease equilibrium levels. This means the shock is examined in the context of a short-run change from a pre-disease equilibrium rather than allowing the model to find a new equilibrium. Second, only a single representative year was examined rather than the full dynamic model. Third, other resources and inputs beyond land, water and labor allocations are allowed to shift, meaning inputs destined for the infected region can move to alternative uses.

Risk Aversion Analysis: Risk is considered to express the decision maker's preferences regarding the distribution of adverse consequences when the decision maker knows enough about the probability distribution to use it in decision making (Antle 1988). We consider both risk neutral and risk-averse decision making by using the breakeven risk aversion coefficient (BRAC) concept described in McCarl (1988). BRAC analysis finds a risk aversion coefficient where preferences switch between two alternative strategies, in this case stamp-out and stamp-out modified with vaccination to slaughter. Constant absolute risk aversion (CARA) utility functions are assumed. This assumption is based on analytical convenience and an inability to empirically specify the wealth dependency of the RAC (McCarl 1988), as well as the finding that if a decision maker with decreasing absolute risk aversion has a RAC (given a wealth level) at or above the BRAC, the resulting preference ordering will be consistent with the decision makers' preferences, given that distributions cross only once (Hammond 1974; McCarl 1988). The same is assumed to hold for RACS at or below the BRAC when a decision maker has increasing absolute risk aversion. McCarl (1988) shows that, with appropriate bounds, preference orderings are still consistent for multiple crossings.

One benefit of using the BRAC analysis is that, rather than assuming a risk aversion coefficient for a decision maker, we identify the RACs where preferences would shift. Other studies have offered empirically-derived RACs for producers. However, to our knowledge none have empirically examined the RACs for regulatory decision makers. Comparison with these empirical studies would be limited by the comparative scale of our wealth measure (national welfare). As McCarl and Bessler (1989) show, RACs are inversely related to the magnitude of the bet. Given that many studies use a producer returns measure, our welfare measure is orders of magnitude greater, making the RAC orders of magnitude less than what would be found in producer-level studies.

The range of RACs to be evaluated for breakeven points can theoretically run from negative infinity to positive infinity. However, we elect to bound the RAC range examined from above and below. The lower bound is set at zero, which implies an assumption that decision makers will not be risk-seeking in their response strategy selection. The upper bound is set such that the risk premium is bounded above by a confidence interval (McCarl and Bessler 1989)[6]. As detailed in McCarl and Bessler (1989), this assumes that the number of standard deviations (D) in the confidence interval is related to the risk premium. This relation is such that the risk premium can be restricted to be less than or equal to a confidence interval ($D\sigma_Y$), where σ_Y is the variance of the risky "prospect" (an FMD outbreak under a particular response strategy). Thus, the relationship among the risk premium, variance of the risky prospect and the risk aversion coefficient established by Pratt (1964) can be used to solve for the risk premium level. The resulting bound equation is a function of only the variance of the risk prospect, the RAC and the number of standard deviations. An assumption must be made on the value of D used in the bound calculation. We elect to set the value of D such that the probability of falling outside the confidence interval is equal to 1-α, where $\alpha = 0.025$. With the additional assumption of normality (made so we can equate the D value to a Z value in a standardized normal distribution), and utilizing our bound criteria based on the risk premium, this equates to a one-tailed Z value and an upper bound of RAC of $r(X) = 2^*Z_\alpha/\sigma_Y$ or, using the value of alpha above, $r(X) = 3.92/\sigma_Y$. As a result of the assumption made, and in order to allow for some comparison of similar studies, we can also interpret the results in terms of the number of standard deviations from the mean and a confidence interval, $Z_{BRAC} \geq (BRAC^*\sigma_Y)/2$, following McCarl and Bessler (1989).

Integrated Epinomic Modeling: For each scenario, outbreaks were simulated using the disease spread model (100 outbreaks per scenario for Texas and 91 outbreaks per scenario for California), and were then

[6]*McCarl and Bessler (1989) suggest 3 alternative upper bound methods. The other two not discussed here were based on: (1) restricting the risk premium to be no greater than the mean; and (2) restricting the risk premium to not exceed those found in applied MOTAD studies. An upper bound for this current study was also evaluated based on method (1), but the same qualitative results occurred.*

incorporated into the economic model, ASM. In particular, for cow/calf, dairy, farrow-to-finish, feeder pig, and small ruminant production: (1) livestock output was decreased by the animals culled (depopulated due to infection and disease control); (2) production costs were increased by disease control and carcass disposal costs; (3) feed requirements were decreased by the proportion of adult animals culled, plus 1/10 the proportion of young animals culled (to reflect the lower feed requirements of young animals); (4) labor requirement was decreased by 40% times the percentage of total livestock culled (to reflect reduced labor needs but still recognize that overhead labor remains); and (5) meat and live animal exports from susceptible species were set to zero. Pasteurized and cooked product export levels remained unaltered. These changes, both in regional supply and the trade effects with the loss of export demand, caused a ripple effect through the model, thereby affecting quantities supplied/demanded, input needs, national prices and economic surplus.

Results

Results are presented separately for the two study regions (California and Texas); within each case study, summary statistics are presented for animals culled, herds quarantined, epidemic duration, and national welfare loss. An analysis of variance (ANOVA) was used to test for statistical differences between no vaccination and vaccination, and between diagnostic delays. The full distribution is then presented in the examination of cumulative distribution functions (CDFs) and analysis of vaccination strategies as a risk management tool. In this risk management analysis we examine livestock culled (as a proxy for gross revenue) and national agricultural welfare.

California Results

Summary statistics for livestock culled, herds quarantined and duration by strategy are presented in table 3, and ANOVA results are shown in table 4. Epidemic simulation results show that heads slaughtered could reach up to 173,000, and that average slaughter is increased by vaccination. The median slaughter declines with a 10km vaccination radius under a 7-day diagnostic delay. However, ANOVA indicates that the differences between the means of the no vaccination and vaccination strategies are not statistically significant. Comparing the 7-day and 14-day diagnostic delays, mean, median and maximum livestock culled increases as detection delay increases, and that difference is statistically significant. Herds quarantined could be as high as 8,000, and this upper end of the range is reduced by vaccination. A strategy of 10km vaccination reduces mean herds placed under quarantine for both diagnostic delays, and a 20km vaccination reduces mean herds restricted under a 14-day delay. However, as with head culled, ANOVA indicates that vaccination strategies' effect on mean herds quarantined is not statistically significant. Disease duration could be as high as 88 days, which would result in a trade ban of at least 180 days. Vaccination decreases duration, but only very slightly. ANOVA results indicate that these differences are not significantly different. However, a 20km vaccination results in a reduction of 16 days in maximum duration under a 7-day diagnostic delay and an increase of 12 days for a 14-day diagnostic delay. This may be the result of an additional skew in the duration distribution for 20km vaccination.

Table 3 California outcomes under vaccination alternatives

		No Vaccination		10km Vaccination		20km Vaccination	
	Diagnostic Delay	**7-day**	**14-day**	**7-day**	**14-day**	**7-day**	**14-day**
Number Culled (Head)	Mean	10,625	66,886	11,062	67,698	11,898	73,280
	Median	8,730	62,558	7,798	67,784	10,605	72,163
	Max.	39,504	148,675	50,205	141,755	43,172	173,107
Number Quarantined (Herds)	Mean	968	3,287	926	3,005	1,049	3,064
	Median	677	2,683	767	2,783	823	2,794
	Max.	4,728	7,994	3,435	6,842	4,575	7,387
Epidemic Duration (Days)	Mean	37	53	36	52	36	52
	Median	37	52	37	51	37	50
	Max.	66	76	61	88	50	88
National Economic Welfare (Billions $2004)	Mean	2.7	16.0	4.0	19.7	5.0	21.9
	Median	2.3	15.2	3.1	19.5	4.8	22.8
	Max.	10.7	41.3	15.3	44.2	13.9	53.7

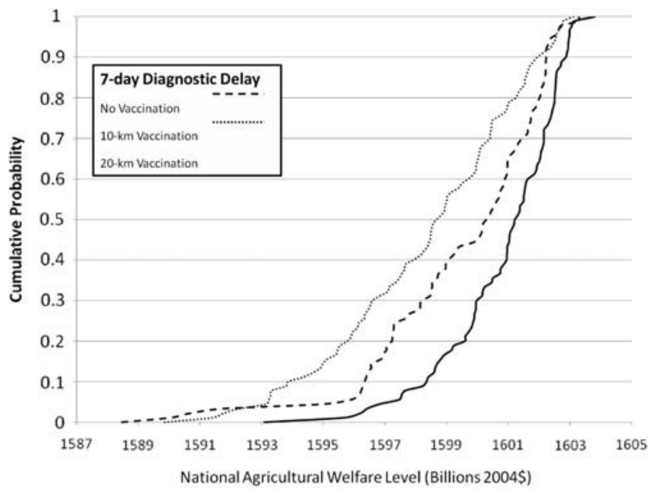
Table 4 ANOVA for California scenarios

Comparison	Measure	F-Stat	P-Value	Conclusion
No Vaccination versus 10km Vaccination				
	Animals Culled	0.16	0.6939	Vaccination does not significantly change animals culled
	Herds Quarantined	0.75	0.3862	Vaccination does not significantly change herds quarantined
	Duration	0.02	0.8847	Vaccination does not significantly change duration
	National Economic Welfare	0.28	0.5955	Vaccination does not significantly change welfare
No Vaccination versus 20 km Vaccination				
	Animals Culled	1.15	0.2833	Vaccination does not significantly change animals culled
	Herds Quarantined	0.00	0.9474	Vaccination does not significantly change herds quarantined
	Duration	0.69	0.4057	Vaccination does not significantly change duration
	National Economic Welfare	10.97	0.0010	Vaccination significantly changes welfare
7-day versus 14-day diagnostic delay				
	Animals Culled	1001.35	$<$ 0.0001	Diagnostic delay significantly changes animals culled
	Herds Quarantined	435.17	$<$ 0.0001	Diagnostic delay significantly changes herds quarantined
	Duration	660.05	$<$ 0.0001	Diagnostic delay significantly changes duration
	National Economic Welfare	984.57	$<$ 0.0001	Diagnostic delay significantly changes welfare

Finally, summary statistics for national economic welfare losses indicate that mean, median and maximum losses under vaccination (for both 10km and 20km distances) exceed losses under no vaccination, and detection delay increases losses in all cases considered. The ANOVA indicates that only the 20km vaccination strategy effect on national welfare levels is significantly different from the no vaccination case. Based on this largely risk neutral view, emergency ring vaccination would not be economically superior in California.

California Risk Aversion Analysis: Taking a slightly different approach to disease policy examination, vaccination is now evaluated as a risk management strategy. Figure 3 illustrates the cumulative density functions (CDFs) of animal losses for the three vaccination-related responses under 7-day and 14-day diagnostic delays. In both diagnostic delays, the three response strategies cross multiple times. Without prior information on the risk preferences of decision makers, stochastic dominance cannot be used to evaluate these strategies. The CDFs for national welfare levels are more spread out, and the "no vaccination" policy appears to be relatively superior.

Figure 3. Cumulative density functions for California FMD scenarios



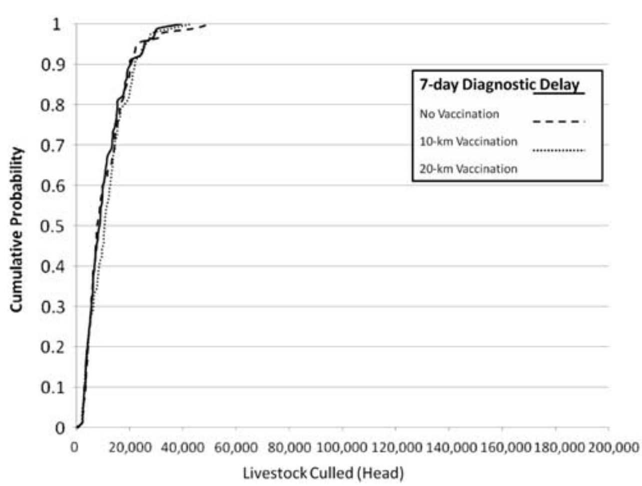
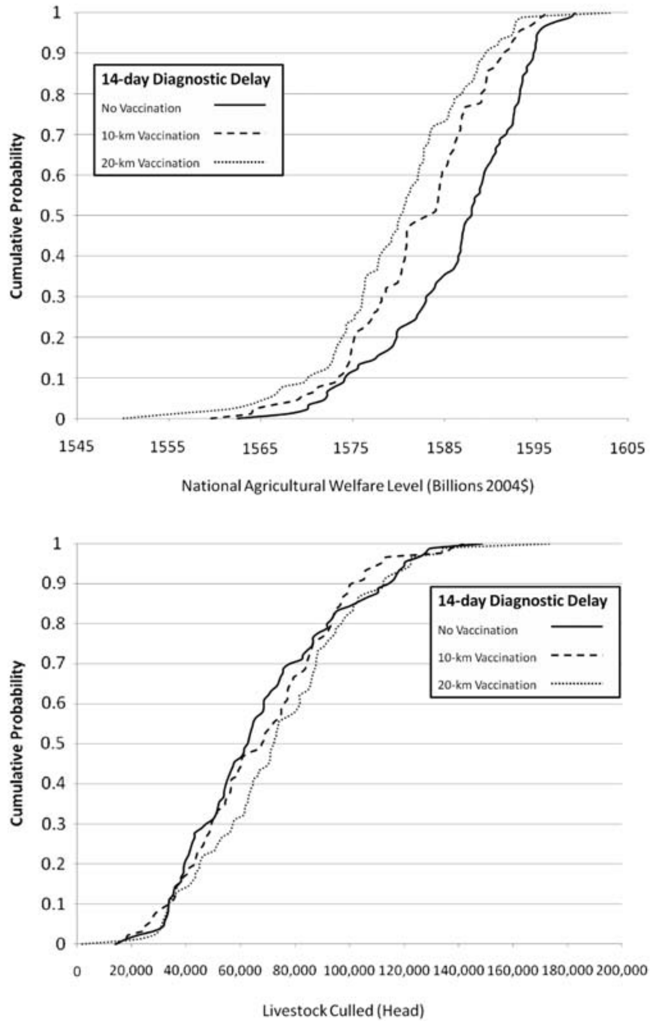


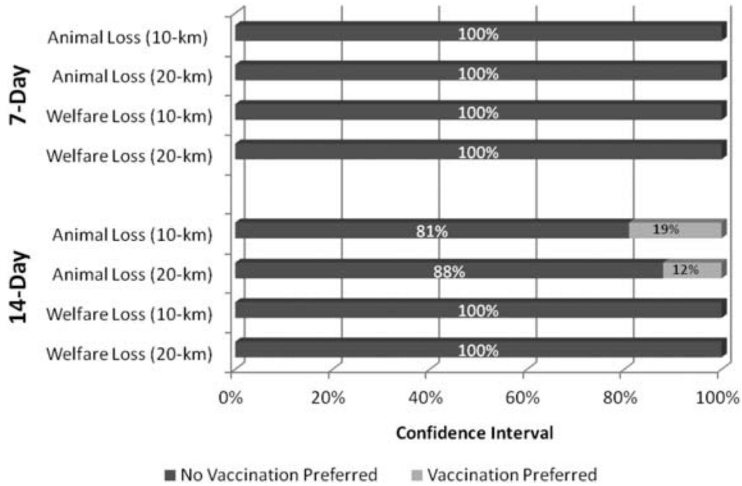
Figure 3. *Continued*



Top two CDFs are for 7 day diagnostic delay and bottom two CDFs are for 14-day diagnostic delay. Livestock culled are in number of head slaughtered for disease control and vaccinates. National welfare levels—as opposed to the change from a base level (losses) presented in Table 3—can be interpreted as the national economic surplus of the agricultural sector. The base value before any disease shock is applied is $1,603.79 billion.

Using breakeven risk aversion coefficient analysis, vaccination is evaluated as a risk management strategy, as shown in figure 4. Ranking strategies based on the distribution of national welfare losses show no risk-related preference for vaccination. Thus, a policy of culling without vaccination is preferable from the standpoint of national welfare losses from FMD in California. An alternative metric on which to base this decision is gross revenue, proxied by livestock culled. There may be interest in avoiding the right-hand tail of the distribution, or, in other words, preventing the outlier outbreak sizes and consequently higher government costs. Under a 7-day delay, no vaccination is preferred for both risk neutral and risk-averse decision makers. For the 14-day delay scenarios, a single BRAC was identified where preference switches to the use of the 10km emergency ring vaccination. Similarly, a single BRAC was identified

Figure 4. Risk aversion analysis for an FMD outbreak in California



The break-even risk aversion coefficient (BRAC) only occurs for animal loss distributions under a 14-day diagnostic delay. Following McCarl and Bessler (1988), each BRAC corresponds to a confidence interval. A standard z table is used to identify the confidence interval that is represented by the BRAC.

for the 20km emergency ring vaccination strategy. Further examining the results between the two vaccination strategies, the 20km ring vaccination was preferred to the 10km vaccination under both risk neutrality and risk aversion. For decision makers with a RAC between zero and a BRAC of $8e^{-5}$, no vaccination is the comparatively superior strategy. For RACs from the BRAC to the upper bound of $5e^{-4}$, a strategy of 20km vaccination is preferred. This BRAC corresponds to a Z_{BRAC} of 1.19 in a one-tail distribution. Using a Z table, the probability of a Z value being less than or equal to Z_{BRAC} is 0.8830, which would correspond to a RAC less than the BRAC level. Relating this back to the confidence interval (one-tailed), decision makers may elect to employ a vaccination strategy if the outbreak is anticipated to be in the 11.7% tail of the distribution of losses.

Table 5 Texas epidemic outcomes under vaccination alternatives

		No vaccination		5km vaccination	
	Diagnostic Delay	7-day	14-day	7-day	14-day
Number Culled (Head)	Mean	75,713	105,091	122,240	235,331
	Median	72,261	94,219	99,212	217,562
	Max.	149,012	231,383	339,282	451,442
Number Quarantined (Herds)	Mean	79	255	108	292
	Median	74	252	97	282
	Max.	222	504	297	541
Epidemic Duration (Days)	Mean	30	49	33	53
	Median	29	48	31	52
	Max.	62	81	60	92
National Loss in Total Ag. Surplus ($ billions, 2004)	Mean	11.2	13.5	12	13.2
	Median	11.9	10.8	12	12.1
	Max.	13.2	208.4	12.5	200.1

Table 6 ANOVA for Texas scenarios

Comparison	Measure	F-Stat	P-Value	Conclusion
No Vaccination versus 5km Vaccination				
	National Economic Welfare	0.03	0.87	Vaccination does not significantly change welfare
	Animals Culled	162.24	< 0.0001	Vaccination significantly changes animals culled
	Herds Quarantined	7.59	0.01	Vaccination significantly changes herds quarantined
	Duration	5.57	0.02	Vaccination significantly changes duration
7-day versus 14-day diagnostic delay				
	National Economic Welfare	1.15	0.28	Diagnostic delay does not significantly change welfare
	Animals Culled	92.21	<0.0001	Diagnostic delay significantly changes animals culled
	Herds Quarantined	473.69	<0.0001	Diagnostic delay significantly changes herds quarantined
	Duration	392.73	<0.0001	Diagnostic delay significantly changes duration

Texas Results: Summary statistics for Texas simulations are presented in table 5. Animals culled could be over 400,000 with up to 541 herds quarantined. Mean, median and maximum slaughter and herds quarantined is increased by vaccination and diagnostic delay. ANOVA results, as shown in table 6, indicate that vaccination has a significant impact on the number of animals culled and herds quarantined. Therefore, 5km ring vaccination in Texas does not appear to offer benefits for reducing the number of livestock culled or herds placed under movement restrictions.

Vaccination's ability to reduce the length of the epidemic is also examined for Texas. Epidemic length could reach up to 92 days, and the average epidemic duration for vaccination under a 7-day diagnostic delay or 14-day diagnostic delay is not reduced. Moreover, the median duration for either diagnostic delay is not reduced. ANOVA results indicate that vaccination has a significant impact on epidemic duration length. However, there is a reduction of 2 days in the maximum of the epidemic duration distribution for a 7-day detection delay.

Figure 5. Cumulative density functions for Texas FMD scenarios

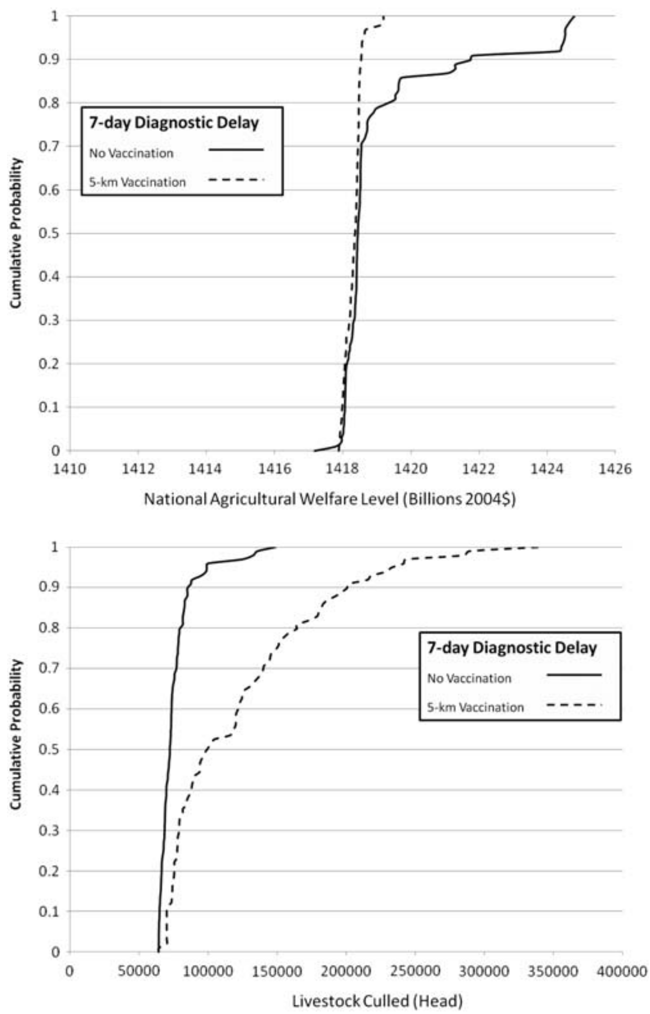
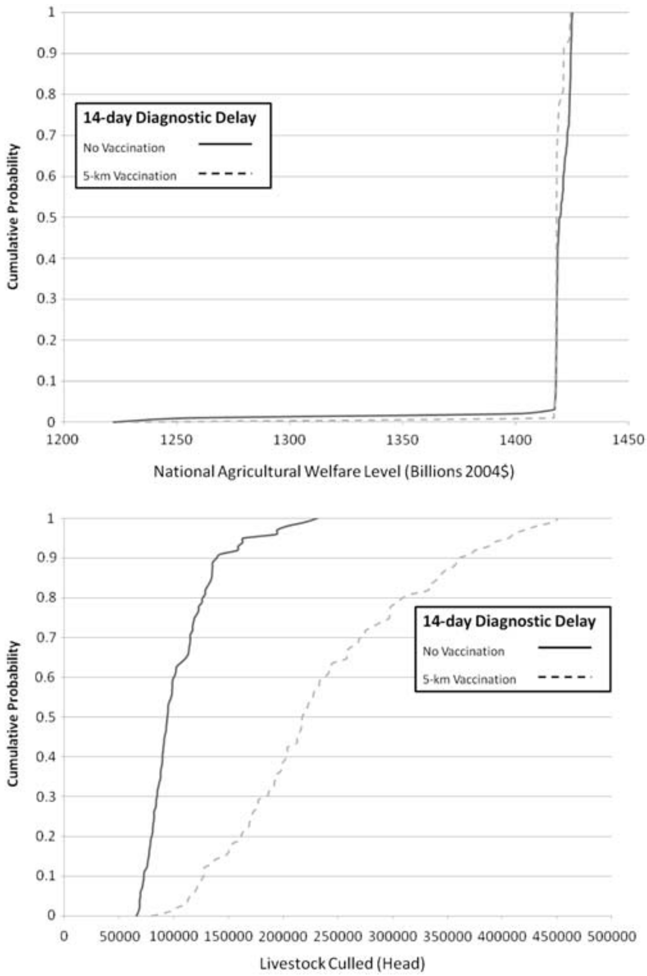


Figure 5. Continued

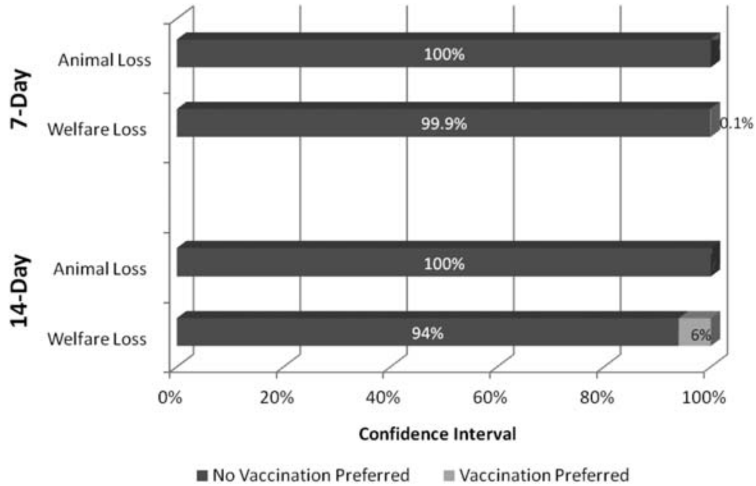


Top two CDFs are for 7-day diagnostic delay, and bottom two CDFs are for 14-day diagnostic delay. Livestock culled are in number of head slaughtered for disease control and vaccinates. National welfare levels—as opposed to the change from a base level (losses) presented in Table 5—can be interpreted as the national economic surplus of the agricultural sector. The base value before any disease shock is applied is $1,603.79 billion.

Mean and median national economic welfare losses increase under vaccination with one exception: under a 14-day diagnostic delay, mean loss is decreased. The maximum losses are lower under no vaccination for both diagnostic delays under 5km ring vaccination. However, national economic welfare is not significantly different between vaccination and no vaccination in Texas.

Texas Risk Aversion Analysis: CDFs of animals culled, as shown in figure 5, show no vaccination comparatively dominating vaccination for both 7-day and 14-day diagnostic delays. For national welfare levels, the distributions are much closer together, making interpretation difficult. Breakeven risk aversion analysis results are illustrated in figure 6. Based on the number of livestock culled, no vaccination is the preferred program for both risk neutral and risk-averse decision makers. Based on

Figure 6. Risk aversion analysis for an FMD outbreak in Texas



The break-even risk aversion coefficient (BRAC) only occurs for animal loss distributions under a 7-day and a 14-day diagnostic delay. Following McCarl and Bessler (1988), each BRAC corresponds to a confidence interval. The standard z table is used to identify the confidence interval that is represented by the BRAC.

national welfare, preference switches from no vaccination to vaccination (BRACs of 0.50 and 0.1667 for 7- and 14-day diagnostic delays, respectively). Following the same method as the California analysis, a BRAC of 0.50 corresponds to a Z_{BRAC} value of 4.72, or a 99.9% confidence interval. This confidence interval indicates that vaccination is only preferred if the outbreak is anticipated to be in the extreme 0.01% tail of the distribution of losses. Similarly, a BRAC of 0.1667 corresponds to a Z_{BRAC} value of 1.57, or a 94% confidence interval. Accordingly, vaccination would be preferred if the anticipated outcome is in the 6% tail of possible outcomes.

Discussion and Policy Implications

In the California study, anticipated mean livestock culled ranged from approximately 11,000 head to 73,000 head, and expected mean national agricultural welfare losses ranged from $2.7 billion to almost $21.9 billion, with mean epidemic duration ranging from 37 to 88 days. The California results indicate that an emergency vaccination program in dairy herds would generate mixed results for livestock culled, herds placed under movement restrictions, epidemic duration and national welfare losses. Moreover, ANOVA results indicate that only the 20km ring vaccination resulted in a significant difference in national agricultural welfare, increasing mean losses. From a risk neutral viewpoint, these results indicate that the additional slaughter from destroying vaccinated animals and the additional cost of implementing the vaccination program and depopulating those herds more than outweighs the benefits in terms of shorter quarantine and reduced duration given the assumptions made here. However, the outliers are large and there is considerable uncertainty in the outcomes. When evaluating possible risk aversion, emergency vaccination becomes preferred to a program of culling alone when the objective is to minimize the number of livestock culled. Thus, results in California indicate that an emergency vaccination program of dairy cattle reduces risk exposure.

In the Texas study, anticipated mean livestock culled ranged from approximately 76,000 head to over 450,000 head, and mean national agricultural welfare losses ranged from $11.2-13.5 billion, with a mean epidemic duration ranging from 30 to 92 days. In the Texas case study, applying a 5km emergency ring vaccination program to all susceptible herd types around the infected premises resulted in a statistically significant increase in mean levels of animals culled and placed under movement restrictions, as well as mean epidemic duration. Mean national agricultural welfare loss results were increased under 7-day diagnostic delay and decreased under 14-day diagnostic delay by vaccination. However, ANOVA results indicate the impact of vaccination on welfare loss was not statistically significant. From a risk neutral viewpoint, these results indicate that the additional slaughter from destroying vaccinates and the additional cost of implementing the vaccination program and depopulating those herds do not result in adequate reductions in mean losses. Under risk aversion, a vaccination program can be preferred if the decision maker focuses on the worst anticipated losses in the welfare distribution. In addition, the switch to vaccination occurs at a lower risk aversion level for 14-day diagnostic delay versus a 7-day diagnostic delay, indicating an important role for the estimated delay during the initial diagnosis determining whether the vaccination policy option is triggered. Thus, vaccination may also be used as a risk management strategy in Texas.

One result that has not received much emphasis up to this point is that a 7-day diagnostic delay results in consistently lower negative impacts than a 14-day diagnostic delay. Evidence from FMD outbreaks has shown that the later the disease is detected and the longer the disease is allowed to persist, the harder it is to eradicate and the more likely it is that an "extreme" outbreak would occur. When considering 15 ex-post evaluations of observed FMD outbreaks occurring between 1992 and 2003, the mean diagnostic delay was nearly 15 days, and the mean persistence was almost 116 days (McLaws and Ribble 2007 p. 1054). Thus, observed outbreaks elsewhere in the world resemble the outliers of the results from this study, and other, *ex ante* studies in the United States. Results in each case study (vaccination versus no vaccination) support the APHIS position, that vaccination be considered when there is a possibility that culling alone cannot control the outbreak, and under longer diagnostic delays. The switch in preference to vaccination as a risk management strategy under a 7-day versus a 14-day diagnostic delay in the California case study indicates that later delays in FMD detection would make vaccination more appealing. Additional work in California reveals that with a 21-day delay, 20km vaccination reduces mean national economic welfare losses, which further supports the use of vaccination in a comprehensive eradication strategy (Hagerman 2009).

This study has a number of limitations and possible extensions. Perhaps most important is the assumption made on trade bans. It is generally acknowledged that trade losses are one of the biggest implications of FMD outbreaks (Paarlberg et al. 2008, for example). However, trade ban duration was not allowed to vary with epidemic duration. Also, the model does not account for the correlation between trade ban length and the type of vaccination strategy selected. It may be reasonable to assume a long trade ban, or to assume no regionalization of trade implications, as was considered in this study. However, it must be acknowledged that these assumptions may overpower any more subtle effects from vaccination in domestic markets. Furthermore, the outbreaks considered were relatively small geographically, while larger outbreak areas may be likely to occur under an actual FMD outbreak. Examining a longer time frame would allow for the inclusion of business interruption costs and delays in trade share recovery, which is not considered here. Also, no context is provided for the BRAC estimates in the absence of further research in this area due to the lack of studies empirically estimating RACs for decision makers. Finally, although labor and vaccine availability constraints were imposed, there are other logistical issues that officials need to consider before implementing a vaccination program.

This method could be extended to include the examination of advances in FMD vaccines (commonly referred to as "second generation and DIVA vaccines"). This would include the possibility of a "stamp-out modified with vaccination to live" policy, whereby vaccinated animals would be allowed to live out their productive lives, provided the animal is not infected. Also, sensitivity analysis of results to trade ban duration may be desirable. These extensions may have significant impacts on the results presented here.

Conclusion

In examining FMD control and eradication policies in the United States, decision makers will increasingly seek analytical tools and decision criteria based on sound science and lessons learned from recent outbreaks. Recent international FMD outbreaks, such as the one Japan experienced in 2010, have been difficult to control, and vaccination has been employed to assist in control and eradication. USDA policy is that vaccination will not be used unless the outbreak could potentially become uncontrolled; policy is determined after weighing factors such as the region of infection, suspect origin of infection, estimated date of introduction, and possible spread. Here, the vaccination policy was examined from multiple perspectives—as a means of minimizing national animal losses, a means of controlling costs and welfare loss, and as a means of risk management—using epinomic modeling under the assumption of short-run, single-event epidemics in separate case studies in California and Texas.

Since decision makers consider vaccination for inclusion in FMD control and eradication policy, a few key points can be taken from this study. Animal disease eradication will be costly, both in monetary terms and in the number of livestock culled. As research is generated to aid in eradication strategy selection, our results provide support for extending the methods used for ranking strategies to include risk management evaluation. Furthermore, individual results taken from one perspective alone (e.g. mean head slaughtered) may indicate the use of one particular policy that is contradicted by examining another metric alone. By presenting the full distribution of results, it is hoped that decision makers will be better informed in *a priori* policy planning regarding livestock disease prevention and eradication.

Funding

The research was partially funded through the Department of Homeland Security National Center for Foreign Animal and Zoonotic Disease Defense from January 2009 until December 2010.

Acknowledgements

The authors thank the two anonymous reviewers and editor of *AEPP*, as well as those who offered suggestions at the three presentations of this topic at Iowa State University, Department of Economics; The USDA Economic Research Service; and the Agricultural and Applied Economics Association 2010 Annual Meeting. Also, we thank Dr. Graeme Garner at the Office of the Chief Veterinarian, Australian Government Department of Agriculture for his thoughtful and insightful comments. The views expressed in this publication are those of the authors and not those of the United States Department of Agriculture Economic Research Service.

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