Invasive Species Management: Foot-and-Mouth Disease in the U.S. Beef Industry *

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Abstract

A conceptual bioeconomic framework that integrates dynamic epidemiological-economic processes was designed to analyze the effects of invasive species introduction on decision making in a livestock sector (e.g., production and feeding). The framework integrates an epidemiological model, a dynamic livestock production model, domestic consumption, and international trade. The integrated approach captures producer and consumer responses and welfare outcomes of livestock disease outbreaks, as well as alternative invasive species management policies. Scenarios of foot-and-mouth disease are simulated to demonstrate the usefulness of the framework in facilitating invasive species policy design.

Keywords: livestock, invasive species, foot-and-mouth disease, beef cattle production

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Introduction

Invasive species in livestock pose a serious threat to agriculture and to human health. The introduction of an invasive species in livestock can be devastating to a country's agricultural and food sectors. For example, the 1997 outbreak of foot-and-mouth disease (FMD) in Taiwan resulted in the loss of 38 percent of their hog inventory. A single mad cow found in Alberta in 2003 cost Canada $25 million per day (New Zealand Veterinary Association, 2003). The 2003 incident of mad cow disease (BSE) in Washington State virtually stopped all exports of U.S. beef, and the United States has since then lost approximately $3—5 billion a year in exports because of this one incident (Coffey et al. 2005). The beef ban lasted two years, until December 2005, when Japan announced that it would resume imports of products from U.S. beef, aged 20 months or less. In January 2006, Japan reimposed the ban. Moreover, the introduction of an invasive species is a threat to food supplies, security, and safety, especially for livestock production, where a foreign disease could disseminate quickly, easily contaminating meat and meat products.

Economic analysis of disease outbreaks has typically focused on static input-output models and static partial equilibrium analysis to study the effects of invasive species (e.g., Garner and Lack 1995, Mahul and Durand 2000, Ekboir, Jarvis, and Bervejillo 2003). Computable general equilibrium (CGE) modeling has also been used to study the potential economic impact of FMD (e.g., Blake 2001, Schoenbaum and Disney 2003). One limitation of these studies is that they do not address the dynamic nature of livestock inventories inherent in the reproduction process. Berentsen, Dijkhuizen, and Oskam (1992) recognized that the time needed by the livestock sector to adjust to a new equilibrium is much longer than the one-year adjustment period assumed by standard I-O models. They introduced a dynamic model that prolongs the time needed for adjustment, but that has nothing to do with the population dynamics of breeding inventories. Another recent study, by Rich (2004), also recognized the importance of dynamic effects in modeling livestock production by adopting adhoc equations that relate current livestock inventories to lagged slaughter price, where a one-period lagged number of newborns and the number of newborns was exogenously determined. Although the inventories evolved over time, there was no guarantee that the dynamics would agree with profit maximization behavior constrained by the biological process of aging and reproduction capacity of breeding inventories.

Invasive species introduction in livestock can be appropriately modeled as a renewable resource problem. Renewable resource theory has previously been used to study cattle cycles (Rosen, Murphy, and Scheinkman 1994, Aadland 2004), achieving results similar to historical data and disease control in agricultural production (Marsh, Huffaker, and Long 2000), recognizing certain diseases themselves as renewable stocks. Consequently, an important advantage of modeling the invasive species problem in livestock production as a renewable resource problem is that it allows introduction of an invasive species and examination of alternative mitigation measures (e.g., ring vaccination, border control, or quarantine) to alter the dynamics of the breeding stock while maintaining consistency with profit-maximization behavior constrained by the population dynamics, which is essential to more accurately predicting outcomes and economic impacts.

Our interest is in a conceptual bioeconomic framework that integrates dynamic epidemiological-economic processes to analyze the effects of an invasive species introduction on decision making in a livestock sector. The framework provides important extensions and contributions relative to previous studies. Because consumer and producer behaviors are key in the event of an invasive species introduction, and because trade bans are typically imposed on countries suffering outbreaks in livestock sectors, the dynamic bioeconomic model is linked to both domestic markets (e.g., demand and supply) and international trade components (e.g., imports and exports). This model also offers the opportunity to estimate consumer and producer welfare effects. In addition, the invasive species introduction and dissemination itself is modeled as a Markov-Chain State Transition process (Miller 1979), and is integrated as a component in the bioeconomic model. The conceptual framework was applied to the beef sector in the United States to investigate the effects of a hypothetical outbreak of FMD. Results are provided for comparing alternative mitigation measures (e.g., border control or quarantine) for FMD.

The Conceptual Framework

The livestock sector uses animals as renewable resources to produce meat for domestic or international consumption. The production process can be conceptualized into two processes: breeding and feeding. Producers choose the retention rate of available stock of animals that can be used to reproduce breeding stock. This is a joint decision that also determines the number of animals that can be used to produce meat. Feeding operations take feeder calves and choose appropriate feeding programs. This decision determines the slaughter time and weight (i.e., the rate at which the number of feeders is converted to meat supply). Profits can be realized by selling meat products on domestic and international markets.

The overall structure of livestock production and the consumption model is based on Aadland's (2004) and Jarvis' (1974) modeling methods. We extended these models to include imports and exports of live animals and meat products. In addition, the profit-maximization behavior of feeding operations was explicitly modeled to account for possible shocks affecting the profitability of feeding operations. The conceptual model consists of four major components: breeding decisions, feeding decisions, domestic and international markets and market-clearing conditions, and invasive species dissemination. These components are presented in the order listed in the following sections.

Breeding Decisions

Conceptually, the representative breeder's objective is to maximize the sum of the present values of all future profits by choosing the culling rates,[1] imports, and exports of breeding stock, subject to the constraint of population dynamics. We assume that the representative breeder operates in a perfectly competitive market environment so that she is a price taker in both input and output markets. The breeder solves the following optimization problem:

(1) $$\max_{\{E_t^j\},\{M_t^j\},\{KC_t^j\}} \left\{ \sum_{t=0}^{\infty} \beta^t E_0(\pi_t) \right\},$$

subject to the constraints

(2) $$K_{t+1}^{j+1} = (1-\delta^j)(K_t^j - KC_t^j + M_t^j - E_t^j)$$

(3) $$B_t = \sum_{j=m}^{s} K_t^j$$

(4) $$K_{t+1}^0 = 0.5\theta B_t, \;\; Moff_{t+1}^0 = 0.5\theta B_t .$$

Following Aadland (2004), breeding stock is differentiated by age (in general, age could be in months, quarters, and/or years). Each age group evolves according to

[1] The term "culling rate" includes feeder calves as well as stock culled for productivity concerns.

equation (2), where K_t^j, M_t^j, and E_t^j are the number of domestic, imported, and exported age *j* breeding females, respectively, and KC_t^j is the number of breeding animals to be culled (choice variable) for that group. In equation (2), δ^j is the death rate for animals of age *j*. This equation implies that female animals of age *j*+1 are comprised of female animals of age *j* that are not culled and survive the period plus the imported minus exported animals of age *j* in period *t*. Equation (3) provides the total number of female animals B_t that can be bred, where *m* is the age at which a female is ready to be bred, and *s* is the age the productive life ends. These females could be bred and give birth in the next period. Instead of birth rate, "weaning rate," the probability of weaning a healthy offspring, θ, better describes the productivity of a breeding animal. The newborns are given in (3), with K_{t+1}^0 and $Moff_{t+1}^0$ being the female and male offspring, respectively.

In (1), total profit for period *t* is

(5) $$\pi_t = R_t - TC_t .$$

In equation (5), total revenue, which consists of meat sales, live animal exports, and salvage value of culled breeding animals, is given by

(6) $$R_t = P_t^0 (KC_t^0 + Moff_t^0) + \sum\nolimits_{j=0}^{s} PE_t^j E_t^j + \sum\nolimits_{j=1}^{s} P_t^j KC_t^j ,$$

where PE_t^j is the export price per head for a breeding animal of age *j*, and P_t^j is the market value per head of a culled animal. It is assumed that the culled newborn females become feeders. Their market value P_t^0 is determined as described later in the feedlot section. Once a newborn is retained for breeding purposes, future culling would render it unsuitable for feeding, and a salvage value P_t^j, $j \geq 1$, is awarded if the breeding animal is culled at age j.[2]

The total cost of the breeding herd consists of maintenance, imports, and a quadratic inventory adjustment cost of breeding stock:

(7) $$TC_t = \sum_{j=0}^{s} (W_t^j K_t^j + PM_t^j M_t^j) + \frac{1}{2} MAC \cdot \left(\sum_{j=0}^{s} KR_t^j - \sum_{j=0}^{s} KR_{t-1}^j\right)^2,$$

where W_t^j is the maintenance cost per head for a breeding animal of age j, PM_t^j is the price of imports per head, MAC is the coefficient of marginal adjustment cost, and $KR_t^j = K_t^j - KC_t^j + M_t^j - E_t^j$ is the number of animals retained for breeding purposes. It is assumed that an increasing adjustment cost is applied when the total inventory changes from the previous period. The adjustment cost reflects the increasing difficulty in securing/liquidating necessary resources.

The complete set of Kuhn-Tucker conditions for profit maximization of breeding operations is specified below. Let $dK_t = \sum_{j=0}^{s} KR_t^j - \sum_{j=0}^{s} KR_{t-1}^j$ be the total change in inventories from the previous period. The Kuhn-Tucker conditions are

(8a) $$P_t^j \geq \psi_t(j) \quad \perp \quad KR_t^j \geq 0,$$

(8b) $$PE_t^j \leq \psi_t(j) \quad \perp \quad E_t^j \geq 0,$$

(8c) $$PM_t^j \geq \psi_t(j) \quad \perp \quad M_t^j \geq 0,$$

(8d) $$KR_t^j + E_t^j \leq K_t^j + M_t^j,$$

where $\psi_t(j)$ denotes the capital value of an age j breeding animal, given by

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[2] If the breeding animal can be salvaged for products of significant market value, then a separate demand for the salvaged products must also be defined to determine the equilibrium salvage values. For example, Aadland (2004) defines a separate demand equation for "non-fed" beef produced by slaughtering culled breeding cows. The salvage value is determined by clearing the non-fed beef market.

(8e)
$$\psi_t(j)=\beta^{10-j}\left(\prod_{i=j}^{9}(1-\delta^i)\right)P_t^{10}-\sum_{k=j}^{9}\beta^{k-j}\left(\prod_{i=j}^{k-1}(1-\delta^i)\right)W^k$$
$$+\sum_{k=j+1}^{10}\beta^{k-j}\left(\prod_{i=j}^{k-1}(1-\delta^i)\right)\theta^k P_t^0-MAC\cdot dK_t \quad .$$

An interpretation of the conditions above is that when an age j animal is retained for breeding, it must be true that its market value equals its capital value, consisting of its future salvage value at the end of its productive life, minus the total cost of keeping it until then, plus the revenue it brings about by producing calves, and minus the marginal adjustment cost it incurs. On the other hand, if the retention is zero, then the market value must be greater or equal to the capital value. Export of breeding animals will increase as long as the price of export is greater than the capital value. The increase in exports will continue until the price of exports is reduced to equal that of the capital value. If no export occurs, then it must be true that the price of export is less than or equal to the capital value. The number of imported breeding animals behaves very much like retention. Import value will increase as long as the price of import is less than the capital value, and the increase will continue until the price of import catches up with the capital value.

To complete the breeding decisions, foreign market supply and demand for breeding animals are defined. Let $fbs^j(\ )$ denote the foreign supply function for breeding animals of age j, and $fbd^j(\ )$ denote the foreign demand function for breeding animals of age j.[3] The relationship between total breeding animal imports

[3] For the sake of completeness, a separate foreign supply and foreign demand for each age group is defined, while it may not be necessary to do so in actual implementation. For example, almost all of the import and export of beef cattle for breeding purposes are yearling heifers, so only one pair of equations is essential.

and import price, and the relationship between total breeding animal exports and export price, are given by

(9a) $QM_t^j = fbs^j(PM_t^j)$,

(9b) $QE_t^j = fbd^j(PE_t^j)$.

For a given set of expected prices and costs, and available stock of female animals, the system of equations composed of (8a)—(8e), (9a), and (9b) can be solved for the number of retention, imports, and exports of breeding animals for the representative producer.

Feeding Program and Meat Production

While price expectations for all other inputs and outputs in the breeding decision problem can be formulated based on their respective final markets, the price expectation for feeders, P_t^0, is still conditional upon the profit-maximization behavior of feeding operations. Furthermore, we assume that all of the male newborns and females that are not retained for breeding purposes and not exported will go through a feeding program to produce meat. Meat production per feeder, hence the final meat supply, is influenced by the feeding decision.

In general, the producer can choose different feeding methods, such as limiting intake and/or changing ration composition, according to the life stage and body condition of the feeders, to maximize his profit. Most often, feeders will be put through a fixed "optimal" feeding program, as suggested by animal scientists. Thus, to simplify matters, we assume that all feeders go through a typical feeding program and that only the producers choose when to slaughter. Under the feeding program, let the growth function and expected cost based on information available at time *t* be

(10a) $WT_d = w(d)$

(10b) $C_{t,d} = c_t(d)$,

where WT_d is a feeder's live weight, which is a function of days on feed d, and $C_{t,d}$ is the cost of feeding the feeder, also a function of days on feed. Let $PMeat_{t,d}$ be the expected price of meat d days later, based on information available at time t, while the expected profit realized d days later is given by

(11) $$FP_{t,d} = PMeat_{t,d} WT_d - C_{t,d} - P_t^0 .$$

Since there is only one choice variable d, the feedlot optimization problem is a linear search for the d^* that gives the maximum unit profit $FP_{t,d*}$

(12) $$\max_d \{FP_{t,d}\} \text{ s.t. (10a), (10b), and (11)}$$

(Amer et al. 1994). If we assume that the feeder market is perfectly competitive, then the feeder price will be bid high enough to make maximum feeding profit 0. The feeder price at time t is then given by

(13) $$P_t^0 = PMeat_{t,d*} WT_{d*} - C_{t,d*} .$$

We also assume that the feeding operations engage in international trade of feeders. The feedlot owners would import feeders as long as the maximum profit from feeding an imported feeder is greater than zero. The number of imported feeders will increase until the price of import is driven up to P_t^0, at which point it is no longer profitable to import them. Feedlot owners would export feeders as long as the profit from exporting is greater than the maximum profit of feeding them out. The number of feeder exports will increase until the price of export decreases to P_t^0 so that the profits from exporting and feeding them out are equal. Let $ffs(\ )$ denote the foreign feeder supply function, and $ffd(\ )$ denote the foreign feeder demand function. The equilibrium feeder imports FM_t and feeder exports FE_t at time t are determined as

(14a) $$FM_t = ffs(P_t^0)$$

(14b) $$FE_t = ffd(P_t^0).$$[4]

Since finishing the feeders out is the only way to produce fed meat, total domestic supply of fed meat is given by

(15) $$S_{t+D} = WT_{d*}\prod_{j=0}^{t}(1-\mathrm{d}^{j})(KC_t^0 + Moff_t^0 + FM_t - FE_t)$$

where D denotes the nearest integer when the optimal days on feed is converted to the same time interval as t.

The feedlot module introduced above provides the linkage between breeding decisions and final meat demand. Equation (13) describes how feeder price can be influenced by the profit-maximization behavior of feedlot operations. It also allows the feeder price to be affected by potential disease outbreaks, by changing the growth function and by modifying the optimal days on feed. Introducing imports and exports of feeders here can help to account for potential impacts of bans on live animal trade due to changes in disease status. The feeder price derived here then feeds into the representative breeder's first-order conditions for determining the market value of feeders and the capital value of breeding animals.

Meat Markets and Equilibrium Conditions

Meat markets are where the feeding operations and breeders obtain information to form their expectations, and where expected production profits can be realized. To capture the potential impact of an invasive species outbreak on market

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[4] Given that in most countries the volume of live animal trade for breeding is very small, and most of the imports and exports are for the purpose of genetic improvement, it does not severely impair the model to set the import and export terms in equation (1) as exogenous variables. However, as important pathways for invasive diseases, they cannot be totally ignored.

environment in a broad spectrum, both domestic and international markets are included. Domestic demand for meats is defined using inverse demand relationships. Let D_t be the demand for meat, $PMeat_t$ be the price, and IN_t be the income. Domestic demand for meat in price-dependent form can be expressed as

(16) $PMeat_t = d(D_t, IN_t)$.

In the case of free trade, and assuming that the exchange rate is fixed over time,[5] the export demand for meat is a function of the domestic price,

(17) $ME_t = ed(PMeat_t)$,

and the import demand for foreign meat products, assuming that the imported meat and domestically produced meat are homogeneous, is also a function of the domestic price,

(18) $MM_t = md(PMeat_t)$.

Assuming a perfectly competitive market, the equilibrium price is given by solving the market-clearing condition (Varian 1992):

(19) $S_t + MM_t = D_t + ME_t$.

Under appropriate assumptions, for a given price expectation scheme and initial stocks of all relevant inventories, the system of equations consists of equations (8a)—(8e), (9a), (9b), and (13)—(18), and can be solved for relevant equilibrium prices and quantities. The bio-economic model was kept as general as possible so that it could be adapted to model specific types of livestock production in an open economy. With the appropriate choice of time interval, mature age, length of productive life, feeding pattern, growth function, and other biological parameters, the

[5] The main reason to assume fixed exchange rates is that we are not interested in the effect of exchange rate fluctuations on meat trade. The imbalance in the meat trade alone is not likely to impact exchange rates significantly.

simulation model can be used to evaluate the effects of various events and agricultural policies on different aspects of livestock production. It can also interact with epidemiological information to study the effects of an animal epidemic.

Invasive Species Processes and Policies

Invasive species processes or management policies tend to alter the population dynamics of the breeding stock, change the yield function of feeders (including changes in input requirements), and/or impact domestic/international trade. The dissemination of invasive species can be modeled as a Markov-Chain State Transition process. While changes to market environment and productivity parameters of infected animals are treated as exogenous, we allow the disease dissemination process to interact with livestock production and feeding decisions. After a disease introduction, the state-transition model describes the number of animals in different disease states in each inventory group. When time progresses to a point where production decisions need to be made, as described in the bioeconomic model, this information is passed to livestock producers. The producers can then formulate their optimal production plans with respect to both infected and non-infected animals, with updated constraints and production parameters. The economic decisions made by these producers will also modify the number of animals in different disease states and different inventory groups. These modified values are passed back to the state transition model. As such, we allow the production environment to be modified by the introduction of an invasive species, and the course of the invasive species dissemination to be modified by rational choices of economic agents. The interaction also enables us to investigate the indirect effects of invasive species control policies on livestock producers' rational choices so that corresponding policies can be made to keep those private choices in alignment with the overall mitigation goal.

We chose to use a deterministic state transition model derived from a Markov Chain to describe the disease dissemination process. Deterministic state transition models built from a Markov Chain have been used by several authors in previous studies of FMD (e.g., Miller 1979, Berentsen, Dijkhuizen, and Oskam 1992, Mahul and Durand 2000, Rich 2004).[6] In each period, an animal transfers from one state (susceptible, infectious, immune, or dead) to another state with corresponding probabilities. While all of the transition probabilities depend on the epidemiological characteristic of the epidemic being investigated, the probability of transition from susceptible to infectious also depends on the prevalence of the disease. Let INV_t^k denote the inventory of category k at time t with $INV_t^0 = K_t^0, \ldots, INV_t^s = K_t^s$ and $INV_t^{s+1} = Moff_t^0$, i.e., the inventories include all stocks of female and male animals available at time t.[7] Let τ denote the time index for which the dissemination process is defined. Let S_t^k and I_t^k be the number of susceptible and infectious individuals in inventory k, and $\varepsilon_t^{k,i}$ be the number of effective contacts made by animals in the k^{th} group with those in the i^{th} group. Assuming that all contacts have the same probability ρ of disseminating the disease, then the probability of one susceptible animal in the

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[6] Another often used approach for disease spread is the stochastic Markov-Chain state transition model achieved by using Monte-Carlo methods (e.g., Garner and Lack 1995, Ekboir, Jarvis, and Bervejillo 2003, Schoenbaum and Disney 2003). Because we focus on integrating aspects of feeding, as well as import and export markets, we chose a deterministic approach. We encourage future research into alternative stochastic approaches in the disease spread component of the model.

[7] i could be further expanded to include any other relevant inventories. For example, it is usually necessary to include male and female yearling feeders in a typical beef cattle production system. In that case, we can let INV_t^{s+2} denote the number of female yearling feeders, and INV_t^{s+3} denote the number of male yearling feeders.

k^{th} group becoming infectious is given by $\rho \frac{\sum_i \varepsilon_t^{k,i} I_t^i}{INV_t^k}$. The expected number of susceptible animals in the k^{th} group becoming infectious is then given by $\rho \frac{\sum_i \varepsilon_t^{k,i} I_t^i}{INV_t^k} S_t^k$. Let R_t^k denote the number of animals that exit the infectious cohort, including recovered susceptible, recovered immune, and dead. The dynamics of the infectious herds that characterizes the outbreak of an epidemic can be described by the following system:

(19) $$I_{\tau+1}^k = \rho \frac{\sum_i \varepsilon_t^{k,i} I_t^i}{INV_t^k} S_t^k + I_t^k - R_t^k \text{ for all } k.$$ [8]

The epidemiological process can be influenced by government agencies through the mitigation/eradication effort variable R_t^k. For example, the number of infectious herds can be reduced through depopulation and application of appropriate treatments. By making R_t^k a function of the infected herd and mitigation effort, efforts in identifying the infected and susceptible contacts can be sufficiently represented in the dynamic process. Another policy variable is $\varepsilon_\tau^{k,i}$, the number of effective contacts an infectious herd can make, which can be reduced by measures such as restricting live animal movement and the establishment of quarantine zones.

In order to evaluate the effectiveness of invasive species prevention measures and to generate implications on resource allocation among prevention and mitigation

[8] The modeling method of disease dissemination we adopted is a standard S-I-R (susceptible-infectious-removed) type model. Interested readers can refer to Miller (1979) or Rich (2004) for a complete description of the dynamic system.

measures, we further introduced an invasive species introduction mechanism that initiates the dissemination process, as described by the following equation:

(20) $$I_0^k = \mu_t^k ,$$

where μ_t^k is a non-negative random variable representing the number of infectious animals introduced from outside the production system. Either direct imports of infectious live animals or domestic live animals contacting pathways could carry the pathogen. For ease of presentation, we refer to the number of imported hosts. μ_t^k is assumed to follow a binomial distribution with density function:

(21) $$f(\mu_t^k) = \binom{H_t^k}{\mu_t^k} p^{\mu_t^k} (1-p)^{H_t^k - \mu_t^k} ,$$

where p denotes the probability that a host is not successfully excluded from the production system, and H_t^k denotes the number of hosts introduced into the k^{th} group. The hosts can be thought of as undergoing identically independently distributed Bernoulli trials. The number of successes then follows a binomial distribution, as described in (21). This introduction mechanism provides two policy variables for analysis of preventative measures, such as implementing better detection methods, increasing inspection efforts, and preventing imports from high-risk countries. By implementing better detection methods and increasing the sample size of inspection, the probability of a host entering the country, p, can be reduced. Another way to reduce the probability of invasion is to prevent imports from high-risk countries so that fewer hosts are imported. Both methods can be used to reduce the expected number of introductions, $H_t^k p$.

The integrated epidemiological bioeconomic model described in this section recognizes the importance of dynamic effects in the livestock sector when evaluating economic impacts of introducing exotic diseases. A variety of ways in which an invasive species and corresponding management policies could impact livestock production, domestic demand, and international trade, are taken into account in the economic analysis. The conceptual model can be implemented for specific species to simulate potential disease outbreaks and to generate implications for alternative prevention and mitigation strategies. As an illustrative example, we implemented the model to simulate potential FMD outbreaks in beef cattle production.

Implementation of Beef Production with the Introduction of FMD

The United States is the largest beef producer in the world and is currently FMD-free. Given the highly contagious nature of FMD, along with the zero tolerance policy of high quality beef importers, FMD is considered the most economically devastating type of disease outbreak in the livestock sector.

Various assumptions were implemented in this study to empirically optimize the bioeconomic model in the presence of an FMD outbreak. In the production component, fixing some of the generic variables such as mature age and reproduction life was necessary. For the feedlot component, yearling feeders were fed and their optimal slaughter weight determined. Adjustments were made to the market environments to accurately represent the imports and exports of beef, feeders, and breeding animals. Details are presented in the following sections.

Population Dynamics

An annual model can best describe beef production due to the annual reproductive cycle of the breeding herd. A heifer becomes productive at age 2 and the average productive life as a breeding animal ends at age 10 (Aadland 2004). Thus, we set $m = 2$ and $s = 10$ in equation (2). Typically, weaned calves not retained for breeding purposes will go through a backgrounding phase and enter feedlots when they become yearlings, at which time they are fed a ration with high grain content. Additional inventories are specified to track the number of female and male yearlings:

$$Fyg_t = (1-\delta^0)KC_{t-1}^0$$
$$Myg_t = (1-\delta^0)Moff_{t-1}.$$

Feedlot Optimization

The equations for predicting the intake and growth of the feeders on feedlots were adopted from the *Nutrient Requirements of Beef Cattle* (National Research Council 1996), and are listed below (t denotes days on feed throughout the feedlot section):

$$DMI_t = DMA * BW_{t\text{-}1}^{0.75}(0.2435NE_{ma} - 0.0466NE_{ma}^2 - 0.0869)/NE_{ma}$$

$$NE_{rm} = 0.077BW_{t\text{-}1}^{0.75}$$

$$FFM_t = NE_{rm}/NE_{ma}$$

$$NE_g = (DMI_t - FFM_t)NE_{ga}$$

$$G_t = 13.91NE_g^{0.9116}WE_{t\text{-}1}^{-0.6837}$$

$$BW_t = BW_{t\text{-}1} + G_t,$$

where DMI_t is the predicted dry matter intake, DMA is the dry matter intake adjustment factor,[9] BW_t is the current body weight (shrunk weight), NE_{ma} is the net energy for maintenance of the feed, NE_{rm} is the predicted net energy required for maintenance, FFM_t is the predicted feed required for maintenance (dry matter), NE_g

[9] Dry matter intake is adjusted according to the feeder's equivalent weight. Refer to Fox, Sniffen, and O'Connor (1988) for equivalent weights and corresponding adjustment factors.

is the predicted net energy for gain, and WE_t is the equivalent weight (body weight adjusted by factors corresponding to breed frame codes).[10]

Since the profit of feedlots depends on final quality of the meat products (the quality grade and yield grade in the context of a grid marketing system), we use the equations from Fox and Black (1984) to predict the body composition, quality grade, and yield grade:

$$EBF_t = 100 * (0.037 EBW_t + 0.00054 EBW_t^2 - 0.61) / EBW_t$$

$$CF_t = 0.7 + 1.0815 EBF_t$$

$$QG_t = 3.55 + 0.23 CF_t$$

$$YG_t = -2.1 + 0.15 CF_t ,$$

where EBF_t is the percentage of fat in the empty body, $EBW_t = 0.891 BW_t$ is the empty body weight, CF_t is the percentage of fat in the carcass, and QG_t and YG_t are the quality grade and yield grade, respectively. The QG_t value is related to U.S. Department of Agriculture standards as follows: Select^0 = 8, Select$^+$ = 9, Choice$^-$ = 10, etc.

While all of these equations predict the mean values of certain traits, the actual values may vary for a particular feeder. To get the expected discounts for the whole population of feeders under a grid marketing system, we took into account trait variability. Following Amer et al. (1994), traits are modeled as random variables that follow normal distributions (empirical distributions can also be used for better results), with the mean predicted by the model and estimated variances. The proportion of cattle marketed in a certain grid cell corresponds to the probability mass between the

[10] Refer to Fox, Sniffen, and O'Connor (1988) for frame codes and adjustment factors.

boundaries of the cell. The expected total discount/premium for cattle marketed after t days on feed can be calculated, denoted as Dis_t.

The intent is to calculate the revenue, costs, and profit of the feedlot when the feeders are marketed at day T. The current value of selling the feeder at time T is given by

$$R_T = EP_T * CW_T * \exp(-r\frac{T}{365}),$$

with R_T being the present value revenue, EP_T being the expected price adjusted by the total expected discount Dis_T, CW_T being carcass weight, and r being the discounting rate. The cost accrued at the slaughter point T includes ration cost and yardage cost:

$$Ration_T = \sum_{t=0}^{T}(DMI_t * RC * \exp(-r\frac{t}{365}))$$

$$Yardage_T = \sum_{t=0}^{T}(0.25\exp(-r\frac{t}{365})),$$

where RC is the unit ration cost and where yardage cost is assumed to be \$0.25 per day. The expected profit from one feeder is then given by

$$Profit_T = R_T - Ration_T - Yardage_T.$$

Since profit is a function of only the integer variable T, linear search within its domain yields the optimal slaughter point and the maximum profit derived from the feeder. Let T^* be the optimal solution; the corresponding profit is used as the current market value for feeder calves in the breeding decisions. The corresponding finishing weight *FW*, finishing cost *AFC*, and expected discount *OptDis* are used in calculation of total meat supply and total profit.

Beef Supply, Demand, and Total Profit

The total supply of fed meat FMS_t is the number of feeders coming out of the feedlots multiplied by their finishing weight FW_t:

$$FMS_t = (1-\delta^1)FW_{t-1}(Fyg_{t-1} + Myg_{t-1}).$$

The supply of non-fed meat is determined by the number of culled breeding animals multiplied by the average slaughter weight ASW :

$$NFS_t = ASW\sum_{j=1}^{m}(1-\delta^j)KC_{t-1}^j.$$

Since we are dealing only with beef production of two products, fed beef and non-fed beef, that have limited substitutability, we used single-equation constant elasticity demand equations for fed and non-fed beef. The mid-point own price elasticity ranges from -0.5 to -0.8 in the literature. Using beef disappearance per capita and beef retail price obtained from The Red Meat Yearbook (USDA 2004), we estimated the elasticity to be -0.8116. Because the demand for non-fed beef is usually less elastic, -0.5 is used in the non-fed beef demand. The two demand equations are

$$P_t = C_0 FMS_t^{-1.232} \quad \text{and} \quad SV_t = C_1(NFS_t / ASW)^{-2},$$

where C_0 and C_1 are two constant terms.

Total profit is calculated in the following manner. The revenue from fed meat is the market price minus the discount at the optimal slaughter weight, multiplied by the total supply. The total feed cost FC_t is the average feeding cost per feeder AFC_{t-1} (determined in the last period), multiplied by the total number of feeders. The total breeding cost TBC_t is the average breeding cost ABC , which is assumed to be constant, multiplied by the total number of animals retained for breeding purposes.

Total profit equals the sum of the revenues from fed meat Rfm_t and from non-fed meat $Rnfm_t$ minus the feeding cost, total breeding cost, and inventory adjustment cost

$$\pi_t = Rfm_t + Rnfm_t - FC_t - TBC_t - \frac{1}{2} MAC \cdot (\sum_j KR_t^j - \sum_j KR_{t-1}^j)^2$$

where

$$Rfm_t = (Pm_t - OpDis_t) * FMS_t$$

$$Rnfm_t = SV_t * NFS_t / ASW$$

$$FC_t = AFC_{t-1} * (Fyg_{t-1} + Myg_{t-1})$$

$$TBC_t = ABC * \sum_{j=1}^{m} KR_{t-1}^j \ .$$

International Markets

Four primary beef export markets—namely Mexico, Canada, South Korea, and Japan—are included in the model. These four countries accounted for about 90 percent of total beef exports in recent years according to data obtained from The World Trade Atlas (U.S. Department of Commerce 2005). To estimate export demand elasticities, annual series dated from 1983 to 2003 of beef and veal exports to Canada, Mexico, and Japan, along with U.S. beef prices, were obtained from The Red Meat Yearbook (USDA 2004). Historical population, real exchange rates, and real income per capita were obtained from the International Macroeconomic Data Set (USDA 2003). Export data were converted to export per capita. U.S. prices were converted to real U.S. beef prices in the importing countries by multiplying real exchange rates and then dividing by the consumer price index (CPI) of the importing country. Export demand elasticities for Mexico, Canada, and Japan were obtained by regressing export demand per capita on real U.S. beef price and real income per capita in log-log form using OLS. Since the data needed to estimate the elasticity for South Korea were not available, it was set to -1.[11]

There are also three foreign countries supplying beef to the United States: Canada, Australia, and New Zealand. These three countries accounted for about 85 percent of total beef imports by the United States in 2000 (USDA 2004). The import demand elasticities for these countries were also estimated using import and U.S. beef price data from The Red Meat Yearbook (USDA 2004). The elasticities were obtained by regressing per capita imports on real beef price and real per capita income in log-log form using OLS. The estimated export and import demand elasticities are listed in Table 1. The constants in the export demand and import demand equations are set to the value that makes the quantities match those of the year 2000.[12]

Other Biological and Production Parameters Used in Calibration

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[11] We are not aware of any previous study that provides estimates for the export demand elasticity of U.S. beef to South Korea. Different values for this parameter were tried in the simulated scenarios; the results for inventories, prices, and welfare measures did not change significantly. For example, when -0.5 instead of -1 was used in scenario 6 of the first set, consumer surplus decreased by 0.0177 percent and producer surplus increased by 0.478%; when -2 was used in the same scenario, consumer surplus increased by 0.36 percent and producer surplus decreased by 0.81 percent. Different values did not change the conclusion drawn about the different scenarios.

[12] The U.S. also engages in live cattle trade with Canada and Mexico. The imports from Canada are primarily cattle for feeding and slaughter. Imports from Mexico are mostly feeders. Imports of beef cattle for breeding purposes are negligible. Because the available data is too sparse and erratic to estimate import supply equations for live cattle, and since imports do not affect the breeding decision directly, we set the imports exogenous in the empirical model ahead and assumed U.S. producers derive zero economic profit from importing. The U.S. also exports a small quantity of breeding cattle to Mexico. As before, it was not possible to estimate a demand equation for breeding stock, and we set it exogenously. It was assumed that exported live cattle are all yearling heifers, and the unit value was set to the marginal value of a yearling heifer, determined by production decision.

Table 1. Parameter Definitions and Values

Parameter	Description	Unit	Value
Breeding			
d^{j}	Death rate of age *j* cattle	%	0.0324a
q	Birth rate	%	0.85a
ABC	Average maintenance cost	$/year	400b
mac	Marginal adjustment cost coefficient	$/head	0.001c
b	Time rate of preference		0.95c
Feeding			
NE_{ma}	Net energy for maintenance	Mcal/kg	2.03
NE_{ga}	Net energy for gain	Mcal/kg	1.28
BGC	Backgrounding cost	$/head	100b
YARD	Yardage cost	$/head/day	0.25b
RC	Ration cost	$/ton	100b
r	Interest rate	%	9b
Demand Elasticities			
U.S.	U.S. domestic DE for beef		-0.81a
CAN	Canada DE for U.S. beef		-3.00a
MEX	Mexico DE for U.S. beef		-1.68a
JAP	Japan DE for U.S. beef		-0.42a
KOR	Korea DE for U.S. beef		-1c
Supply Elasticities			
CAN	Canada SE for U.S. beef market		-1.86a
AUS	Australia SE for U.S. beef market		1.44a
NZL	New Zealand SE for U.S. beef market		0.57a

[a] Estimated using historical data.
[b] Approximate estimates based on various literature and expert opinion.
[c] Assumed value.

Relevant parameters of the bioeconomic model are listed in Table 1. The death rate and birth rate were estimated from the cattle inventory data obtained from the USDA's Foreign Agricultural Services Production, Supply and Distributions (PS&D) Database. Death rates and birth rates were assumed to be $\delta^{j} = 0.0324$ and $\theta = 0.85$,respectively. Production cost parameters are rough estimates taken from various budget forms from different USDA extensions. The maintenance cost of breeding cows is $400/year. Marginal adjustment cost was assumed to increase at the rate of \$0.001/head when the change in breeding stock increased by one.[13] The time rate of preference was assumed to be $\beta = 0.95$. The backgrounding cost was \$100. The ration we used consisted of 70 percent corn, 25 percent alfalfa silage, and 5 percent soybean meal ($NE_{ma} = 2.03$ Mcal/kg and $NE_{ga} = 1.28$ Mcal/kg). The price of the ration was roughly \$100/ton. Yardage cost was assumed to be \$0.25/head/day. Interest rate was set at r = 0.09. The starting inventories were also estimated from cattle inventory data obtained from the PS&D database. The grid pricing system is presented in Table 2.

Table 2. A Typical Grid of Discounts and Premiums for Fed Cattle

	YG1	YG2	YG3	YG4	YG5
Prime	10	9	8	-12	-17
Choice	2	1	0	-20	-25
Select	-5	-6	-7	-27	-32
Standard	-33	-34	-35	-55	-60
Out Cattle	<500	<550	>950	>1000	
Discount	30	10	10	30	

*Values are calculated using the method described by Feuz, Ward, and Schroeder (1989), representing discounts/premiums for \$100 per carcass weight.

The standard deviation of carcass weight was assumed to be constant at 20 kg. The standard deviation for quality grade (1.4) and yield grade (0.8) were estimated using grading data obtained from the USDA Agricultural Marketing Service. The model was calibrated to the inventories and prices of year 2000. Constants in the demand and supply equations were calculated so that the demand and supply quantities match those of the year 2000.

Specifications for FMD and Dissemination

[13] Marginal adjustment cost is a key parameter affecting the stability of the model's solution. Larger value allows the model to tolerate larger sized shocks. We chose the minimum value that allows stable solutions in the FMD scenarios.

FMD is a disease caused by an airborne virus, *Aphtovirus*, which attacks all cloven-hoofed animals. Cattle are highly susceptible to FMD because they inhale a large quantity of air. There is no known cure for the disease. Despite painful symptoms, most of the infected cattle make a full recovery after three weeks. Although some cattle may stop eating for a few days because of the pain, FMD usually does not significantly affect the productivity of beef cattle. The mortality rate in adult cattle is low, rarely exceeding 2 percent. The mortality in young cattle is much higher, but rarely exceeds 20 percent. In our simulations, it is assumed that FMD causes 2 percent death in infected adult cattle and 20 percent death in calves. No other productivity parameters are changed.

The dynamics of dissemination are defined on weekly intervals. Cattle herds are classified into six states: susceptible, latent infectious, second week infectious, third week infectious, immune, and dead. Cattle become infectious for three weeks after effective contact with infected animals. The incubation period of FMD averages three to eight days. During this period, an infected animal is capable of shedding the virus, but does not display symptoms. Thus, we call the first-week infectious herds "latent infectious." After the incubation period, most infected animals will display foot and mouth lesions. The course of an FMD infection is rarely longer than three weeks. Animals become immune to the disease after recovery. Although most recovered cattle remain carriers of the virus, infection caused by contact with carriers is rare, and hence is not considered here. Cattle that are dead or depopulated exit the spread process.

The dissemination rates for FMD are estimated based on the parameters found in the computer-simulation model of FMD by Schoenbaum and Disney (2003).[14] A herd on average makes 3.5 direct contacts with other herds per week, and 80% of them are effective in transmitting the disease. Average indirect contacts are 35 per week, and 50 percent of them are effective. Thus, a herd can infect about 20 other herds per week. This dissemination rate is used for the first two weeks after FMD is introduced, during which the government and producers are unaware of the FMD presence. After the second week, movement control and quarantine measures are in place, and producer awareness increases. From the third week on, the dissemination rate is halved each week until it reaches 2.5 in the sixth week. From the seventh week on, a dissemination rate of 0.7 is used.

Scenarios and Results

The current U.S. policy for dealing with FMD outbreak is to totally stamp it out. This policy involves depopulation of all identified infected herds, cleaning and disinfecting exposed premises, banning the movement of all susceptible animals that might have been in contact with the infected herd within two weeks, rigid control of the movement of animals and animal products around the outbreak area, and surveillance of suspected herds (Ekboir, Jarvis, and Bervejillo 2003). The effects of movement control have been addressed previously in the discussion of decreasing dissemination rate. There is little policy variation in the identification and depopulation of the infected herd. Under the stamping out policy, all herds identified

[14] This parameterization, as indicated in Scheonbaum and Disney's (2003) presentation, is based on published parameters and European experience with FMD. It should be noted that under alternative parameterization the simulation results may vary. However, the characteristics of breeding stock dynamics in response to an FMD outbreak do not change significantly.

as infectious must be depopulated. Thus, the depopulation rate of the infectious herd is dictated by the probability of an infectious herd displaying symptoms of FMD. In other words, the proportion of the infected herd being depopulated is dictated by the proportion that is identifiable. Since latent infectious herds do not display symptoms, it is hard to identify and remove them from the dissemination process. In the simulation scenarios, we allow the identification and depopulation rate of latent infectious herds to vary with different levels of effort in controlling the disease spread. Because most of the second and third week infectious herds display symptoms, we assume that 90 percent of the second and third week infectious herds are depopulated in all scenarios regardless of the effort levels.

We define a set of scenarios to explore the effects of different effort levels in tracing and surveillance of susceptible contacts. Assumptions include the following: i only infected herds are depopulated, ii 90 percent of the herds that are in the second and third week of the infectious period are depopulated, iii once a herd is under surveillance, it will be depopulated in the first week if it becomes infectious so that it cannot infect others, iv all beef exports and live cattle exports halt for three years, v domestic demand decreases by 5 percent for three years, and vi there is no recurrence after eradication.

Scenarios of the empirical model are simulated to determine the impact from changes in initial stocks and other parameters in the model. Following Standiford and Howitt (1992), the model is solved as a mathematical programming problem using GAMS software (Brooke, Kendrick, and Meeraus 1988). This approach is flexible in systematically linking and integrating model components, including allowing the nesting of the invasive species process with weekly time steps into the annual bioeconomic model and the use of complex switching functions.

Depopulation Scenarios

The analysis proceeded in the following manner. A base scenario without FMD was simulated to calculate welfare changes for the scenarios of interest. Next, effort levels in tracing and surveillance were represented by different levels of identification and depopulation rate of latent infectious herds: 30—90 percent, with increments of 10 percent (labeled scenario 1 through 7 in Table 3).

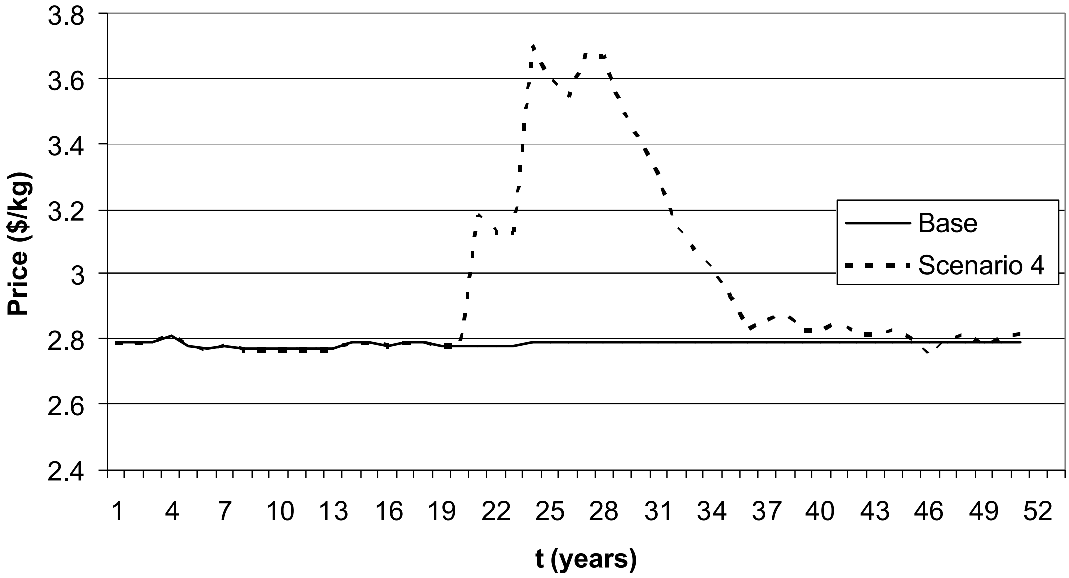
Table 3. Welfare Changes for Scenarios with Improvement in Traceability

Scenario	*Depop Rate**	*Depopulated (% of total inventory)*	*Cost (Billion$)*	*Consumer Surplus (Billion$)*	*Producer Surplus (Billion$)*	Total **(Billion$)**
1	30%	76.92	-6.83	-186.22	-73.26	**-266.31**
2	40%	55.27	-4.91	-123.93	-9.90	**-138.74**
3	50%	39.46	-3.50	-91.87	16.54	**-78.84**
4	60%	27.94	-2.48	-66.46	18.64	**-50.30**
5	70%	19.51	-1.73	-47.36	14.80	**-34.29**
6	80%	13.41	-1.19	-33.51	10.01	**-24.68**
7	90%	9.04	-0.80	-23.53	5.79	**-18.54**

* Depopulation rate of the latent infectious herds.

In all scenarios, the FMD outbreak is eradicated within one year. Since production decisions are made on annual intervals, the effect of the outbreak can be thought of as a one-time shock to inventories, due to death and depopulation. In the following three years, domestic demand is reduced and export markets are closed. For illustrative purposes, the price response to scenario 4 (60 percent depopulation rate of latent infectious herds) is presented in Figure 1. The outbreak is introduced in the 20th period. In this scenario, about 28 percent of the total inventory is lost due to death and depopulation.

Figure 1. Beef Price Response to FMD Outbreak



Although demand is also suppressed, the excessive loss of beef supply causes a jump in beef price. When demand shifts back to normal and export markets reopen three years later, another price spike is created. High prices stimulate buildup of breeding inventories. As breeding inventory increases, beef supply increases over time. Price then drops until it reverts back to the long-run equilibrium. In scenarios 1—5, similar price responses are observed. In scenarios 6 and 7, the initial price response is negative because the shift in demand outweighs the loss of beef supply. The trend in price is similar to those in the first 5 scenarios after demand relationships shift back.

The percentage of total inventory depopulated (including death), depopulation cost, change in consumer surplus, change in producer surplus (as measured by changes in profit), and total welfare loss due to the outbreak are listed in Table 3. In all scenarios, the loss in consumer surplus constitutes the biggest proportion of total welfare loss. Considering all producers together, there was a gain in scenarios 3-7, primarily due to the inelastic demand for beef. In the first two scenarios, the adjustment cost outweighs the gain. As the depopulation rate of latent infectious herds increases, the total welfare loss decreases dramatically, but at a decreasing speed. In the most optimistic scenario, a total welfare loss of $18.54 is expected. At a more reasonable level of traceability, the depopulation rate of latent infectious herds is assumed to be 60—70 percent, where a total welfare loss of $34 to $50 billion can be expected.

The results shown above indicate that it is beneficial to increase the effort to track direct and indirect contacts that an infectious herd has made. This provides rationale for implementing animal ID systems to track the movements of live cattle, improving the information infrastructure, and increasing personnel for active surveillance. However, such efforts are not free. The marginal effect of such endeavors will inevitably decrease as the effort level increases. The marginal cost of increased traceability will eventually exceed the marginal gain in welfare. The optimal level of investment in effort can be achieved when marginal cost equals marginal gain.

Vaccination Scenarios

To further illustrate the model's usefulness in determining the optimal mitigation policy, a second set of scenarios were evaluated. As mentioned earlier, ring vaccination is often used to contain rapid spread of diseases. We assumed that ring vaccination has to be used to achieve a depopulation rate of latent infectious herds beyond 60 percent in this set of scenarios. Ring vaccination involves vaccinating all cattle herds within a certain radius of a discovered infected herd. The vaccinated cattle are eventually depopulated to regain an "FMD free country where vaccination is not practiced" status.[15] Scenario 1 is a base scenario, where a 60 percent depopulation

[15] According to Article 2.2.10 of The Terrestrial Animal Health Code-2005, a country can be declared an FMD-free country where vaccination is not practiced if (i) there has been no outbreak of FMD during the past 12 months, (ii) no evidence of FMD infection has been found during the past 12 months, (iii) no vaccination against FMD has been carried out during the past 12 months, and the country has not imported since the cessation of vaccination any animals vaccinated against FMD.

rate for the latent infectious herds is achieved *without* the need for ring vaccination. When this depopulation rate is increased to 70, 80, and 90 percent in scenarios 2, 3, and 4 (listed in Table 4), we assume that ring vaccination must be used, and that the size of the vaccination rings are set in such a way that the number of susceptible herds vaccinated are exactly 1, 2, and 3 times the number of latent infectious herds that are depopulated. Again, these susceptible herds are subsequently depopulated. That is to say, taking scenario 2 as an example, we end up depopulating twice as many herds as would have been necessary if the 70 percent depopulation rate had been achieved through improving traceability. The welfare changes corresponding to this set of scenarios are listed in Table 4. Since all costs—including depopulation and vaccination costs—are accounted for in the total welfare changes, it is apparent that the base scenario, 60 percent depopulation rate without ring vaccination, results in the best social welfare outcome.

Table 4. Welfare Changes for Scenarios with Ring Vaccination

Scenario	*Depop Rate*[*]	*Depop (% of total inventory)*	*Depop&Vacc Cost (Billion$)*	*Consumer Surplus (Billion$)*	*Producer Surplus (Billion$)*	Total **(Billion$)**
1	60%	27.94	-2.48	-66.46	18.64	**-50.30**
2	70%	32.91	-2.92	-77.65	18.99	**-58.66**
3	80%	34.25	-3.04	-80.62	18.79	**-61.83**
4	90%	36.32	-3.23	-85.12	18.17	**-66.96**

[*]Depopulation rate of latent infectious herds.

Comparison of Simulations with and without FMD Affecting Breeding Stock Dynamics

To emphasize the importance of including breeding stock dynamics in the previous analysis, we make a comparison between scenario runs with and without biological constraints on the breeding stock being affected by FMD outbreaks. Two scenarios are developed. In both scenarios, all the previous assumptions apply and we assume that 60 percent of the latent infectious herds are identified for depopulation without using vaccination. In the first scenario, the model is run with its full integrity, which includes the biological constraints on breeding stock dynamics. In the second scenario, without biological constraints on breeding stock dynamics, we assume that any death loss in the breeding stock due to FMD or depopulation can be replaced immediately at a cost equal to its capital value. This setup allows us to temporarily relax the biological constraints on population dynamics—i.e. the FMD outbreak has no direct effect on breeding stocks.

Not surprisingly, results from the two scenarios are very different and offer interesting comparisons. Figure 2 shows the dynamic response of total breeding stocks. When the biological constraints on population dynamics are in place, depopulation causes a sharp drop in breeding stock. It takes a long time to rebuild inventories to the original levels. On the other hand, when there is no biological constraint on the breeding herd and thus no direct effect on breeding stocks, total breeding stock slightly increases due to higher price expectations, and then gradually drops back down. Price responses in the two scenarios are shown in Figure 3. The temporary shortage of beef supply due to depopulation of feeder calves and yearlings raises beef prices in both scenarios. The difference comes after the third year when export markets are reopened and calves born after the outbreak can be slaughtered. In the first scenario, the low breeding stock levels sustain the shortage of beef supply for a long period. The beef price suddenly rises due to the increase in total demand and then gradually returns to its long-term equilibrium level. In the second scenario, where FMD does not directly affect breeding stocks, beef supply returns to about the same level as before the outbreak, and so does total beef demand. Beef price also drops back to around the long-term equilibrium.

Figure 2. The Effects of A FMD Outbreak on Breeding Stock with/ without Biological Constraints on Breeding Herd Dynamics

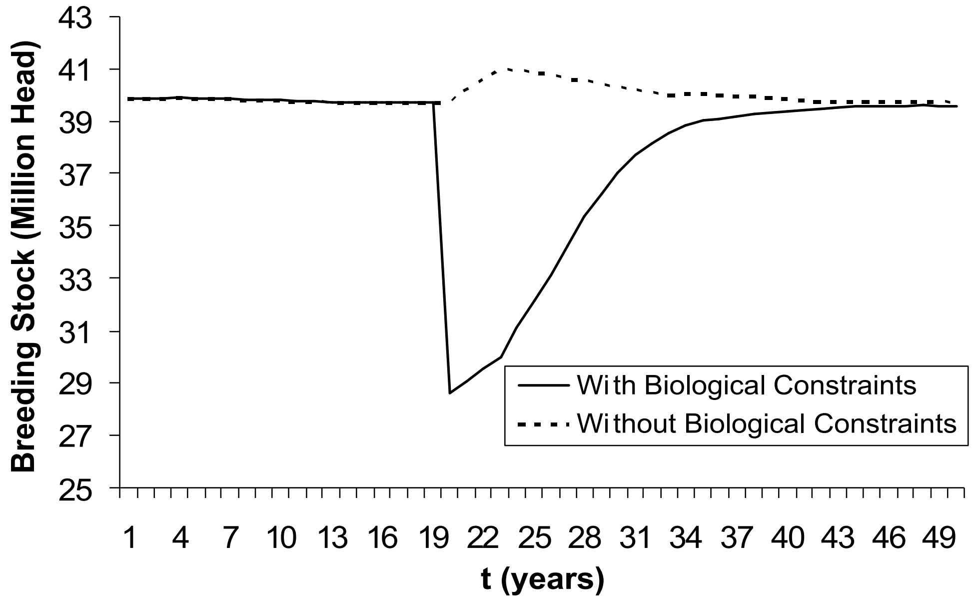
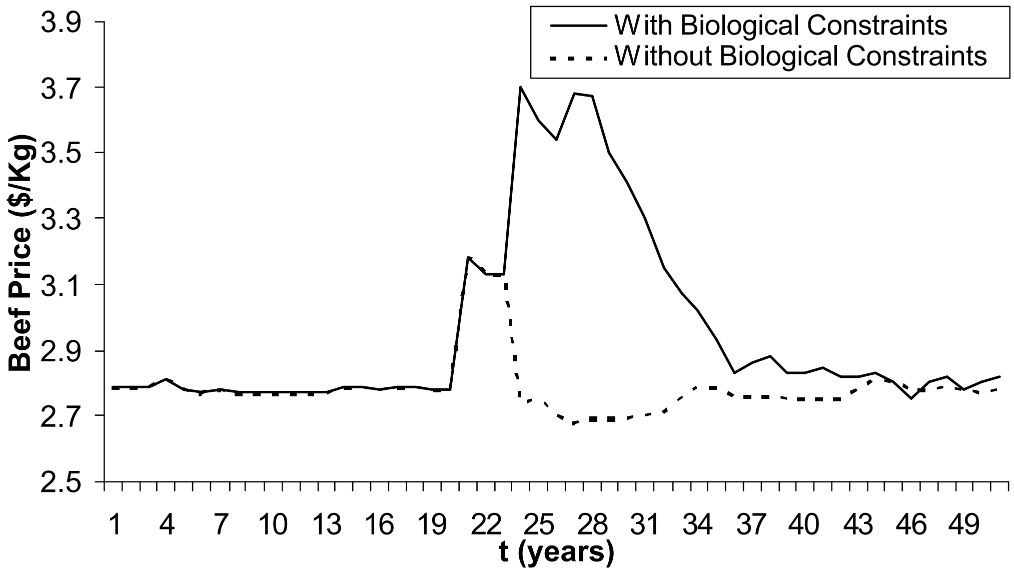


Figure 3. The Effects of A FMD Outbreak on Price Response with/without Biological Constraints on Breeding Stock Dynamics



Welfare results are also very different between the two scenarios. With biological constraints on the breeding stock dynamics, total welfare loss is $50 billion; without biological constraints, total welfare loss is reduced to $36 billion—an underestimation of $14 billion. More interesting, while beef producers gain $18.6 billion when breeding stocks are reduced by the FMD outbreak, they lose $21.7 billion when the biological constraints on breeding herd dynamics are not considered.

At the same time, consumer welfare loss is reduced from $66.5 billion to $11.8 billion. We can see that with the constraint of breeding stock dynamics, the FMD outbreak creates a *de facto* "supply management" scheme where consumers not only bear the whole loss of the outbreak but also, due to inelastic beef demand, bid beef price high enough for beef producers as a whole to be better off. When the constraint is completely relaxed, such a "supply management" scheme cannot exist because one can also obtain additional breeding stock as long as it is profitable to do so.

The comparison above clearly shows the importance of including breeding stock dynamics in evaluating potential invasive species outbreaks and alternative invasive species management policies. Ignoring breeding stock dynamics not only neglects the long-term economic effects caused by an invasive species outbreak, but also can lead to incorrect conclusions about welfare distributional effects.

Conclusion

The dynamic epidemiological-economic model presented in this paper proves to be a useful tool for analyzing the effects of an invasive species introduction on decision making in a livestock sector. The integrated epidemiological dynamics and population dynamics provide essential pathways for an exotic disease to impact the production process through modification of production parameters and dynamic constraints, thus capturing the producer's response to a disease outbreak. International trade components not only capture the effect of the changing market environment when an outbreak occurs, but also endogenize important disease pathways essential for assessing the probability of such an occurrence. Linking together breeding, feeding, consumption, and trade, the framework can be used to explore a wide range of economic effects of an exotic disease.

The value of the bioeconomic model lies in its capability of capturing effects of invasive species policy alternatives. Implementing invasive species management policies is always about balancing gain and loss. Even if we do not consider the direct cost, creating a disease-free zone is never a “free lunch.” Tighter prevention measures usually mean less gain from trade. Eradication of a disease usually leads to heavy depopulation, sacrificing short-term benefits for long-term gain. Our model is designed to address different aspects of an invasive species policy to capture its overall value. For example, segmenting imports and exports by country allows us to investigate the effects of an emergency shutdown of imports from a certain country due to disease discovery, which, in conjunction with the potential loss if the risk were not eliminated, helps us to more accurately evaluate welfare changes associated with the invasive species policy. Furthermore, dynamic effects on welfare levels and welfare distributions allow policymakers to choose among alternative methods of eradication, such as eradication by depopulation or eradication through vaccination, and to decide how the effort should be financed.

The implementation of beef production with introduction of FMD is used as an example of how the conceptual model could be implemented to evaluate the economic impact of a potential exotic disease outbreak and to examine alternative prevention and mitigation policies. Although the use of a deterministic disease dissemination process limits the interpretation of simulation results, more sophisticated stochastic state transition models could be used in its place with minor modifications.

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