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The Economics of Bovine Viral Diarrhea Virus Control in United States Cow–Calf Production

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This study evaluates the costs associated with bovine viral diarrhea virus (BVDV) control strategies for cow–calf producers and aims to identify minimum viable premiums to induce control measures. Monte Carlo simulations were used to estimate the cost of control strategies, risk of BVDV outbreak, and BVDV-attributed production losses. We find that the price premiums needed to induce enhanced BVDV control by cow–calf producers range from $8.41 to $35.95 per head. Additionally, management of larger herds are more likely to adopt rigorous control protocols due to the increased likelihood of PI exposure and ability to absorb additional costs.

Key words: animal health economics, bovine viral diarrhea virus, cow–calf production, risk analysis

Introduction

Bovine viral diarrhea virus (BVDV) is an infectious pathogen that can cause adverse health effects in beef cattle. BVDV infection can be divided into three broad categories: transient, fetal, and persistent infection (PI), with the latter being the most harmful. Fetal infection during days 50–125 of gestation leads to PI, which persists through their life (Grooms et al., 2009). Consequently, PI animals are considered the primary source of BVDV exposure in a cattle operation. For a cow herd, economic losses from BVDV infection have been estimated to be $50–$100 per head (US Department of Agriculture, 2007), stemming from reproductive complications and heightened calf morbidity (Houe, 2003). For stockers and feedlots, the immunosuppressive properties of BVDV increase the likelihood of subsequent respiratory diseases in cattle that are exposed to a PI animal. Loneragan et al. (2005) found that the risk of initial respiratory tract disease was 43% greater in cattle exposed to a PI animal. Correspondingly, the estimated economic losses to the beef cattle industry attributable to PI animals are between $500 million and $1.5 billion annually (Miles, 2009; Ishmael, 2016).

Because PI animals the result of fetal infection, their prevalence in the supply chain is largely determined by the BVDV control practices implemented in the cow–calf sector. In the United States, approximately 9% of cow–calf operations have at least one PI animal (Wittum et al., 2001; US Department of Agriculture, 2010b). Multiple epidemiological studies of beef cattle have estimated the within-herd prevalence of PI animals to be less than 1% (Wittum et al., 2001; US Department of Agriculture, 2010b). In the United States, increasing BVDV control within the cow–calf sector has the potential to reduce losses to cattle producers and the wider industry. Hurt (2018) concluded that the cow–calf, stocker, and feedlot sectors would each experience net gains due to enhanced

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BVDV management within the cow–calf sector, with feedlot gains substantially outpacing those of the other sectors. However, uninfected herds would experience a net loss due to increased BVDV management costs. Since more than 90% of cow–calf herds fit this category, this constitutes a large barrier to adoption. Further, the uneven distribution of costs and benefits and the subclinical nature of BVDV infection make incentivizing BVDV management challenging.

The limited management of PI cattle in the cow–calf sector generates a negative externality for other sectors in the beef cattle market, with stockers and feedlots experiencing most of the productivity losses and treatment costs associated with PI cattle. Hence, the cow–calf sector has little incentive to engage in enhanced BVDV control because it does not experience the total costs attributed to PI animals. This negative externality leads to less than optimal efforts to control BVDV within the cattle industry. This is particularly true, as we will show, of smaller operations, where the risk of loss to the firm is low and the risk can be transferred downstream in the supply chain. A potential solution to the PI externality is rooted in the compensation principle. If the benefit of PI reduction to feed yards is greater than the cost of achieving that level of reduction for cow–calf producers, then feed yards can compensate cow–calf producers for reducing the prevalence of PI cattle, leading to net social gains. In other words, feedlots can provide premiums for tested PI-free cattle to ensure that they do not incur losses attributable to PI exposure, potentially constituting net gains for both parties.

While some PI-free premiums exist, the volume of producers that market cattle under these programs has been low. According to the US Department of Agriculture (2020), only 2% of operations marketed calves as PI free. The National Cattlemen's Association 2022 policy book indicates that the organization has been encouraging efforts to develop economically efficient mechanisms to control and/or eliminate BVDV in beef cattle herds (National Cattlemen's Beef Association, 2022). Therefore, evaluating necessary PI-free premiums to induce enhanced BVDV management would aid in advancing stakeholder objectives.

Traditionally, BVDV research, among other types of livestock disease research, has been confined to veterinary medicine, epidemiology, and animal science. However, animal health economics is increasingly being incorporated to help develop concepts and models that support the decision-making process in optimizing animal health (Dijkhuizen, Huirne, and Jalvingh, 1995). Most economic studies of BVDV have focused on the cost of disease for the private and public sectors (Bennett, Christiansen, and Clifton-Hadley, 1999; Chi et al., 2002a), or the value of eradication programs (Lindberg, 2003; Thomann et al., 2017). These studies estimated the magnitude of the economic cost of disease; however, without accounting for the cost and efficacy of control strategies, they do not provide direction for disease management. The few economic studies that have considered the economics of BVDV management were either modeled within dairy production (Chi et al., 2002b) or did not account for the natural variability in clinical manifestations and spread of the disease. Correspondingly, incorporating biological and epidemiological knowledge into an economic evaluation of BVDV management for cow–calf producers would prove beneficial.

The objectives of this study are to (i) analyze the cost effectiveness of eight BVDV control strategies for three herd sizes in the cow–calf sector and (ii) estimate the PI-free premiums required to induce a PI-testing plus vaccination strategy to be the most cost-effective control option for herds infected and uninfected with BVDV. The aim of a control strategy is to minimize the total cost of BVDV, which is defined as the sum of the control costs and expected production losses. We expect that control inputs exhibit diminishing marginal benefit associated with disease control. Thus, the optimal level of disease is likely to not be 0%. Correspondingly, we first hypothesize that the strategy with the lowest total cost will not minimize either the risk of an outbreak or expected production losses. It is likely that the probability of exposure to a PI animal will differ depending on herd size. Accordingly, our second hypothesis is that the cost-effectiveness of strategies will differ depending on herd size. Finally, because we expect the cost-effectiveness of these strategies to differ conditionally on herd size, we hypothesize that the PI-free premium per head needed to encourage greater BVDV management will differ depending on herd size.

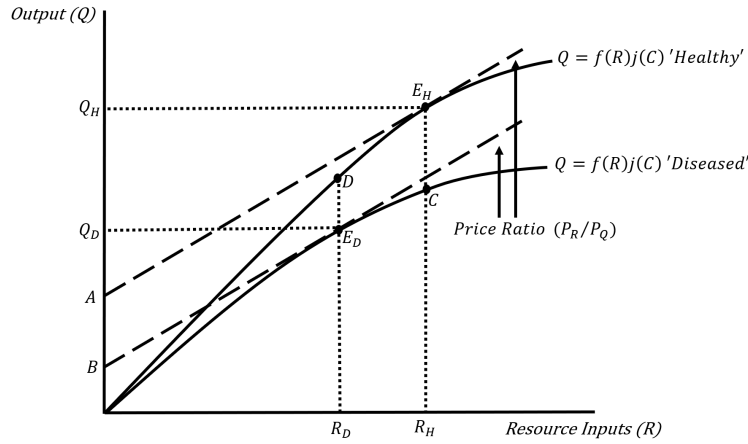

Figure 1. Production Function of a Diseased and Healthy Herd

Notes: Adapted from Mclnerney (1996).

Conceptual Model

Modeling the Impact of Disease

Following Chi et al. (2002b) and Hennessy and Marsh (2021), we present a model that incorporates the economics of damage control (Lichtenberg and Zilberman, 1986), and a disease management model (Mclnerney, 1996). The direct effect of a disease is represented by the following production function:

$$Q = f(R)j(C), \tag{1}$$

where

- Q = quantity of output (calves, measured it total cwt),
- R = quantity of regular variable inputs used (feed, labor), and
- C = quantity of disease control inputs used.

Disease can lower output by increasing the mortality rate or by reducing the efficiency of the inputs in production, R. The level of disease within a herd depends on the quantity of disease control inputs used, C. Figure 1, adapted from Mclnerney (1996), illustrates the effect of disease on the production function: Disease presence in a herd shifts the production function from "healthy" to "diseased" status. In both production functions, the operation uses inputs as efficiently as possible. The downward shift in the "diseased" function is due to a reduction in output for a given level of input associated with the presence of disease. The input price, P_R, to output price, P_Q, ratio curve is indicated by the dashed curves. The point where the price ratio curve is tangent to the production function indicates the level of input use that will maximize profits (i.e., where the marginal value of product is equal to the marginal cost of inputs). For a healthy herd and diseased herd, the optimal levels of production occur at points E_h and E_d, respectively.

Modeling Disease Control

The level of disease in a herd, D, is influenced by the quantity of disease control inputs used in production. Disease control inputs are unique compared to other factors of production in that they do not increase potential output. Rather, the purpose of such inputs is to reduce the difference between potential output (i.e., the maximum level of output attainable from a given combination of directly productive inputs) and actual output (Lichtenberg and Zilberman, 1986). This characterization suggests that the proper way to think about disease control inputs is through a two-step process:

(i) the impact of disease control inputs on the level of disease and (ii) how the resulting level of disease influences production and treatment expenditures (Fox and Weersink, 1995).

In the first step, herd level disease (D), depends on prevalence of the untreated disease (D_o) and the proportional reduction in disease due to a given level of control inputs, (C). This is summarized by the control function, $\zeta(C)$:

$$D = D_o[1 - \zeta(C)]. \tag{2}$$

The control function is assumed to have the same properties as a cumulative probability distribution because it is constrained on the interval $\zeta(C) \in [0,1]$. When $\zeta(C) = 0$, the control inputs have no effect on the level of disease, resulting in $D = D_o$. In contrast, complete eradication ($D = 0$) would be realized if $\zeta(C) = 1$. It is assumed that the proportion of the disease remaining after control inputs are used monotonically decreases with increases in the level of control ($\partial\zeta/\partial C \geq 0$). The rate of change in the marginal product of control inputs is unknown but is assumed to be concave (Fox and Weersink, 1995).

In the second step, the effect of remaining disease on output is estimated as a fractional reduction in potential production if disease were not present, $f(R)$. The fraction of these potential production losses is referred to as the damage function:

$$\delta(D), \tag{3}$$

which is assumed to possess the properties of a cumulative distribution function. With no disease ($D = 0$) there is no reduction in output, $\delta(D) = 0$, and actual output will equal potential output, ($Q = Q_o$). As the level of disease approaches infinity ($D \to \infty$), the proportional losses in output approach 1 and actual output approaches some minimum output, Q_{min},which cannot be less than 0 (Fox and Weersink, 1995). It is assumed that the marginal impact of disease on output is nonnegative ($\partial\zeta/\partial D \geq 0$) and that the damage function could exhibit various curvature properties; however, it is assumed to be concave (Fox and Weersink, 1995).

By substituting equation (2) into equation (3), the fraction of potential output that is produced is described as

$$Q = f(R)j(C) = f(R)\{1 - \delta(D_o[1 - \zeta(C)])\}. \tag{4}$$

With an output price of p, regular input cost of k, and disease control input cost of w, the profit maximization problem becomes

$$\pi_{\max} = p\left[f(R)\{1 - \delta(D_o[1 - \zeta(C)])\}\right] - kR - wC. \tag{5}$$

The first-order optimality conditions are defined as

$$\pi_R = pf'(R^*)\, j(C^*) - k = 0, \tag{6}$$

$$\pi_C = pD_o f'(R^*)\,\delta'(D^*)\,\zeta'(C^*) - w = 0. \tag{7}$$

Primes represent the first derivative. The optimal quantity of disease control inputs to use will depend on price of output, initial presence of disease, disease-free level of output, the severity of output reduction due to disease, the effectiveness of control inputs in reducing disease prevalence, and the cost of the control input. Following Mclnerney (1996), if regular inputs are fixed at $R = \hat{R}$, then the problem may be written in terms of cost minimization:

$$\text{Min}_C = pf(\hat{R})\delta(D_o[1 - \zeta(C)]) + wC, \tag{8}$$

where $pf(\hat{R})\delta(D_o[1 - \zeta(C)])$ represents disease loss and wC represents expenditure on disease control. Optimal expenditure on disease control occurs where the marginal cost of control, w, is

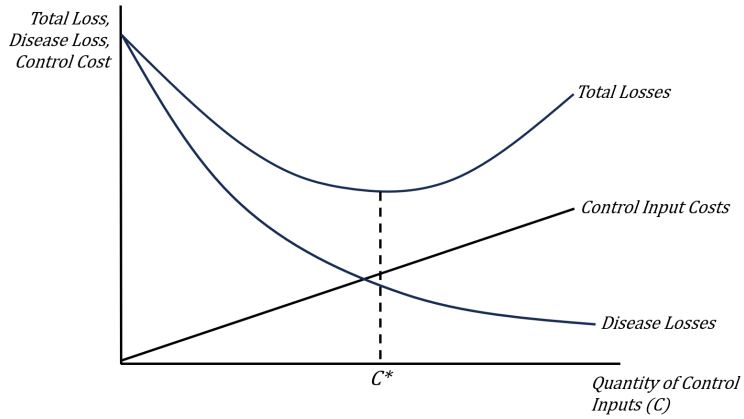

Figure 2. Contribution of Disease Losses and Control Input Costs to the Total Losses of a Disease

Notes: Adapted from Hennessy and Marsh (2021).

equal to marginal disease losses, $pD_o f(\hat{R})\delta'(D)\zeta'(C)$. Figure 2 illustrates an interior solution. Increasing disease control inputs used up to C^* decreases the total losses because the marginal reduction in disease losses exceeds the marginal cost of disease control inputs. Past C^*, the marginal cost of disease control inputs exceeds the marginal reduction in disease losses. Hence, employing C^* quantity of disease control inputs minimizes the total cost of a disease.

Empirical Model

Three Monte Carlo stochastic simulation models were combined to estimate the total cost of eight BVDV control strategies over a 1-year horizon. A 1-year horizon was chosen because multiple epidemiological studies have shown that herds of susceptible cattle that come into contact with a PI animal seroconvert within 6 months of exposure (Wentink et al., 1991; Moerman et al., 1993; Houe, 1999). Total cost of BVDV was defined as the sum of control costs and expected BVDV losses. Expected BVDV losses were defined as the product of the risk of a BVDV outbreak and losses associated with a BVDV outbreak. The model was applied to herd sizes of 50, 100, and 500 head. From these results, the required PI-free premium needed for more intensive control strategies to become the most cost effective was estimated. The simulation was conducted for 1,000 iterations to obtain an "average case" scenario over a distribution of variables. All the simulations were conducted in R Studio (Boston, MA) using a fixed random seed.

Table 1 reports model baselines for calving percentage, weaning weight, and replacement rate. The model assumed that each herd was naïve to BVDV and that PIs were the only source of viral exposure. Each herd shared fence-line contact with one neighboring herd and faced no risk of BVDV exposure from wildlife. Revenue was generated through selling calves at weaning, and all control strategies were mutually exclusive from one another. Because our intention is to provide a general framework from which to build upon for herds in specific regions, nationally representative data sources were used for the analysis.

The eight BVDV control strategies considered involved various combinations of three BVDV control components: maintaining a closed herd, vaccination, and testing for PI cattle, as described in Table 2. Because PI introduction commonly occurs through the importation of replacement animals, we defined closed herd status as all replacements being raised on farm, and open herd status was defined as all replacements being imported. Vaccination is used to protect animals against transient BVDV infection. For strategies that included vaccination, we assumed that the herd was vaccinated annually and that calves were vaccinated twice before sale. Testing involves virus isolation from

Table 1. Input Distributions for Control Costs, Risk of BVDV Outbreak, and Losses of BVDV Outbreak

Variable	Definition	Distribution	Source
cp	Calving percentage (%)	Pert(84.4, 89.5, 95.6)	USDA (2020)
r	Replacement rate (%)	15%	Thomas (2021)
w_c	Weaning weight (cwt)	Tnorm(4.5, 0.3, 4, 5)	USDA (2020; 2021; 2022)
P_f	Cost of raising replacement heifer over 2 years ($/head)	Tnorm(1,728, 118, 1490, 1965)	FarmProgress (2016), USDA (2022)
P_i	Cost of purchasing replacement heifer ($/head)	Tnorm(1,363, 124, 1115, 1611)	Prevatt (2020), USDA (2022)
p_t	Cost of BVDV-PI test ($/head)	Poisson(1000, 7.25)	OADDL (2021), KSVDL (2022), TVMDL (2022)
p_v	Cost of vaccine ($/dose)	Pert(2.00, 3.58, 4.20)	Dr. Koziol, DVM, Riley et al. (2019), ValleyVet (2022)
HP	Prevalence of herds having at least one PI animal (%)	Pert(4%, 9%, 12%)	Wittum et al. (2001), USDA (2010b)
p	Within-herd prevalence of PI animals in positive herds (%)	U(0.01%, 5.00%)	Wittum et al. (2001), USDA (2010b)
HP	Number of herds replacements are imported from (n)	U(1,8)	Dr. Koziol, DVM
T_{ef}	Reduction in risk of exposure from testing (%)	Pert(0, 42%, 66%)	Smith et al. (2009)
V_{ef}	Vaccine efficacy (%)	Pert(40%, 88%, 99%)	Fairbanks et al. (2004), Ficken, Ellsworth, and Tucker (2006)
d	Within-herd prevalence of BVDV (%)	Bin(1,000, 45.14%)	Scharnböck et al. (2018)
cp_{rd}	Reduction in calving percentage (%)	Gamma(1000, 2%, 0.5%)	Taylor, Janzen, and Van Donkersgoed (1997), Waldner and Kennedy (2008)
w_{rd}	Reduction in weaning weight (lbs)	Gamma(1000, 28.6, 1)	Taylor, Janzen, and Van Donkersgoed (1997), Waldner and Kennedy (2008)
m_c	Increased preweaning mortality (%)	Gamma(1000, 1%, 0.5%)	Taylor, Janzen, and Van Donkersgoed (1997), Waldner and Kennedy (2008)
pc_{cow}	Premature culling rate of infected cows (%)	Gamma(1000, 1.8%, 0.5%)	Bennett, Christiansen, and Clifton-Hadley (1999), Chi et al. (2002a)
p_c	Calf price ($/cwt)	Tnorm (174.78, 45.47, 83.82, 265.74)	USDA (2022)
p_r	Replacement cost ($/hd)	Tnorm(1,363, 124, 1,115, 1,611)	Prevatt (2020), USDA (2022)
p_s	Cull cow value ($/cwt)	Tnorm (75.59, 20.46, 34.65, 144.91)	USDA (2022)
c_w	Cull cow weight (cwt)	Tnorm(13.39, 0.47, 12.00, 14.00)	USDA (2022)
c_v	Veterinary cost ($/case)	Pert(50, 60, 70)	Chi et al. (2002a), Dr. Koziol, DVM
c_m	Medication cost ($/case)	Pert(10, 15, 20)	Chi et al. (2002a), Dr. Koziol, DVM
c_l	Extra labor cost ($/case)	Pert(3, 5, 7)	Chi et al. (2002a), Dr. Koziol, DVM

Notes: Parentheses represent numbers describing each distribution. Tnorm(mean, standard deviation, lower bound, upper bound), Poisson(number of trials, lambda) Pert(minimum, most likely, maximum), U(minimum, maximum), Bin(number of trials, probability of success), Gamma(number of trails, shape, rate). Within-herd prevalence is defined as proportion of antibody positive animals in herd.

Table 2. Definition of BVDV Control Strategies Used for Simulations

Control Strategy	Herd Status	Vaccination	Testing
A	Closed	Yes	Yes
B	Closed	Yes	No
C	Closed	No	Yes
D	Closed	No	No
E	Open	Yes	Yes
F	Open	Yes	No
G	Open	No	Yes
H	Open	No	No

serum, blood, or tissue to identify PI animals. Examples of PI tests include antigen-capturing ELISA, immunohistochemistry, and polymerase chain reaction. For strategies that included testing, we assumed that all new replacements and calves were tested for PI. Combinations of these control components formed eight BVDV control strategies, presented in Table 1.

Data Sources

All cattle price data were accessed through the USDA Agricultural Marketing Service (2022) using the custom report feature. Ten-year historical data from June 2012 through June 2022 were used for the analysis. Data from all locations were retained to generate nationally representative data distributions.

Calf price mean and standard deviation were estimated from steer and heifer price data for cattle of 400–500 lb, medium and large frame sizes, muscle scores 1 and 2. Data for only 400–500 lb cattle were used to control for the negative correlation between calf price and weight. Weaning weight was matched with price data to be truncated within 400–500 lb. A normal distribution of prices and weaning weights was assumed, and the data were truncated within 2 standard deviations from the mean to control for outliers.

Cull cow prices were obtained from the breaker, boner, and lean categories with weights of 1,200–1,400 lb. A normal distribution was assumed, and data were truncated within 2 standard deviations of the mean. Cull cow weights were matched with price data and truncated within 1,200–1,400 lb.

The cost of raising a replacement heifer on a farm was the sum of the forgone revenue associated with marketing the heifer at weaning plus the 2-year costs of raising her to a fall pregnancy check. The forgone revenue was estimated by multiplying heifer price (as described above) by weaning weight. The 2-year costs of maintaining the heifer were estimated following the budget approach developed by South Dakota State University Extension and reported in FarmProgress (2016). To account for the known variation in feed, labor, and veterinary costs, these costs were allowed to vary by 25% from the mean. The cost of purchasing a replacement heifer is estimated to be roughly 1.5 times the average price of a 550-lb feeder steer (Prevatt, 2020); therefore, the 10-year historical price of a 550-lb feeder steer was multiplied by 1.5 to obtain the estimated cost of purchasing a replacement heifer. For the cost of raising versus purchasing a replacement heifer, the data were truncated within 2 standard deviations from the mean. It is important to note that the cost of raising versus purchasing a replacement heifer will vary significantly depending on regional differences, economic factors, weather conditions, and forage availability. Hence, the decision to raise versus purchase replacement heifers depends not only on BVDV risk but also on economic factors, forage availability, and operational objectives. Costs of testing, vaccination, veterinary care, medication, and extra labor costs were acquired from clinical diagnostic laboratories (OADDL, KSVDL, TVDML), journal articles, or coauthor Koziol's professional experience as a food animal veterinarian.

Baseline distributions (i.e., non-BVDV associated) for management, health, and performance parameters were obtained from the US Department of Agriculture (2020). Epidemiological data on the prevalence of herds containing at least one PI animal and the within-herd prevalence of PI animals were obtained from the USDA report on the prevalence and control of BVDV on US cow–calf operations in 2007–2008 (US Department of Agriculture, 2010b) and from Wittum et al. (2001). Data for within-herd prevalence of transient infections of BVDV were obtained from a meta-analysis of BVDV prevalence in cattle populations reported in Scharnböck et al. (2018). Data pertaining to the efficacy of testing, vaccination, and production impacts of BVDV infection were acquired from various peer-reviewed journal articles (Fairbanks et al., 2004; Ficken, Ellsworth, and Tucker, 2006; Smith et al., 2009).

Cost of BVDV Control

The first simulation estimated the costs of each BVDV control strategy. The cost of maintaining a closed herd, C_c, was calculated as

$$C_c = r \times n\left(\frac{\left(P_f - P_i\right)}{2}\right), \tag{9}$$

where r is the replacement rate, n is herd size, P_f is the 2-year cost of raising a replacement heifer, and P_i is the cost of importing a replacement heifer. The cost of raising a replacement heifer was the sum of the forgone revenue associated with marketing the heifer at weaning plus the 2-year costs of raising the animal. The forgone revenue was estimated by multiplying heifer price (as described above) by weaning weight. The 2-year costs of maintaining the heifer were estimated following the budget approach developed by South Dakota State University Extension, which includes feed costs, veterinary costs, marketing and shipping, breeding feeds, and indirect costs. These values are divided by 2 determine annual costs. The price of purchasing a replacement heifer was estimated following the approach recommended by University of Florida Extension and assumed that the cost of a replacement heifer is roughly 1.5 times the average price of a 550-lb feeder steer (Prevatt, 2020). The 10-year historical price of a 500-lb feeder steer was multiplied by 1.5 to obtain the estimated cost. The cost of vaccination, V_c, was calculated as

$$V_c = p_v \times n(2 \times cp + 1), \tag{10}$$

where p_v is the per head cost of vaccination and cp is the calving percentage. The scalar of 2 is included because calves are vaccinated twice prior to sale. The herd-level cost of PI testing, T_c, was calculated as

$$T_c = p_t \times n(r + cp), \tag{11}$$

where P_t is the per head cost of testing. The distribution of inputs for simulating the cost of control strategies is provided in Table 1. No adjustment to costs was made to account for the ability to negotiate bulk transactions by larger firms.

BVDV Outbreak Risk

The second simulation estimated the risk of a BVDV outbreak for each control strategy. The model for BVDV risk was adapted from Morley (1993), who defined the risk of an outbreak as the product of the probability of exposure to at least one PI animal and the probability of infection given exposure. For each control strategy, the risk of a BVDV outbreak, R, was defined as

$$R = \left\{P(E) - \begin{bmatrix} 0 \text{ if } T = 0 \\ T_{\text{ef}} \text{ if } T = 1 \end{bmatrix}\right\} \times \begin{bmatrix} 1 \text{ if } V = 0 \\ 1 - V_{\text{ef}} \text{ if } V = 1 \end{bmatrix}, \tag{12}$$

where $P(E)$ is the probability of exposure to at least one PI animal; T_{ef} is the proportional reduction in the probability of exposure due to testing, T; and V_{ef} is the proportional reduction of probability of infection due to vaccination, V, or vaccine efficacy.

We assumed that PI exposure could occur only from the importation of a PI animal or from fence-line contact with neighboring herds infected with BVDV. Closed herds face risk from fence-line contact, while open herds face risk from fence-line contact and importation. The probability of exposure was modeled using the multilevel binomial probabilistic model from Murray (2004) because it can account for potential clustering of PI animals from an infected herd. The probability of exposure to at least one PI animal was defined as

$$P(E) = 1 - \left[1 - HP\left(1 - (1-p)^{i}\right)\right]^{h} \tag{13}$$

where HP is the prevalence of herds with at least one PI animal, p is the prevalence of PI animals within herds that have at least one PI animal, i is the number of animals being imported, and h is the number of herds from which animals are being imported. For fence-line contact, we assumed a firm faced potential exposure from one neighboring herd of the same size. No additional management behavior (e.g., established trust and reputation, type and quality of cattle purchased) is considered in the model. Table 1 reports the distribution of inputs for simulating the risk of BVDV outbreak.

BVDV Outbreak Losses

The third simulation estimated the losses associated with a BVDV outbreak. The model followed the framework presented by Bennett, Christiansen, and Clifton-Hadley (1999) and employed by Chi et al. (2002a), where the losses are the sum of production losses and treatment expenditures. Production losses were further subcategorized as reproductive, preweaning morbidity, preweaning mortality, and premature culling losses. Reproductive losses, L_r, were calculated as

$$L_r = n \times d \times cp_{rd} \times p_c \times w_c, \tag{14}$$

where n is herd size; d is the prevalence of antibody-positive animals in the herd;[1] cp_{rd} is the reduction in calving percentage due to abortion, reduced conception rates, and congenital defects; p_c is the calf price measured in dollars per hundredweight, and w_c is calf weaning weight measured in hundredweight. Preweaning morbidity losses, L_b, were calculated as

$$L_b = n \times cp \times d \times w_{rd} \times p_c, \tag{15}$$

where w_{rd} is the reduction in the weaning weight of infected calves. Preweaning mortality losses, L_m, were calculated as

$$L_m = n \times cp \times d \times m_c \times p_c \times w_c, \tag{16}$$

where m_c is the percentage increase in preweaning mortality due to exposure to a PI animal. Premature culling losses, L_p, were calculated as

$$L_p = n \times d \times pc_{cow} \times (p_r - (p_s \times c_w)), \tag{17}$$

where pc_{cow} is the percentage increase in premature culling, p_r is the cost of purchasing a replacement heifer, and p_s is the price of a cull cow measured in dollars per hundredweight, and c_w is cull cow weight measured in hundredweight.

[1] Antibody-positive animals represent animals that are transiently infected with BVDV, which is the outcome of exposure of PI animals.

Treatment costs were the sum of veterinary, medication, and extra labor costs. The cost of veterinary care, C_v, was calculated as

$$C_v = n \times d \times cp_{rd} \times c_v, \tag{18}$$

where c_v is the cost of veterinary care per case. Veterinary costs were only incurred for clinical cases, which we defined as reproductive complications. Medication, C_m, and extra labor costs, C_l, were calculated as

$$C_m = n \times d \times 2 \times cp_{rd} \times c_m, \tag{19}$$

$$C_l = n \times d \times 2 \times cp_{rd} \times c_l, \tag{20}$$

where c_m is the cost of medication per case and c_l is the cost of extra labor per case. Following (Chi et al., 2002a), medication and labor were applied to clinical and subclinical cases and there were assumed to be twice as many subclinical cases as clinical cases. Table 1 provides the distribution of inputs for simulating the losses of a BVDV outbreak.

Sensitivity Analysis

The sensitivity of model output to the risk of BVDV outbreak was examined for all herd sizes. The impact of altering BVDV risk was determined by adding 10% and 20% of the average outbreak risk estimated from the simulation model. The changes in total cost for all control strategies under the three herd sizes were evaluated on a per head basis. Differences in risk and costs among control strategies within herd-size strata were assessed using the Wilcoxon rank-sum test.

Incentives for Enhancing BVDV Control

After identifying the most cost-effective strategy for each herd size, the required PI-free premium needed for a testing plus vaccination strategy (strategy E) to become the most cost-effective control option was estimated for infected and uninfected herds. The testing plus vaccination strategy was chosen as the enhanced control strategy because vaccination protects a herd from transient infection and testing and removing PI animals reduces their flow into the supply chain. Maintaining a closed herd was excluded from the enhanced control strategy because the decision to maintain a closed herd does not depend solely on disease risk but also market conditions, forage availability, and genetic objectives. Hence, for simplicity, the testing plus vaccination strategy was chosen because employing these disease control inputs is more directly influenced by BVDV risk.

For uninfected herds, the required PI-free premium per head was estimated as the difference in the control costs of the most cost-effective strategy and the testing plus vaccination strategy divided by the number of calves marketed. For infected herds, the PI-free premium per head was estimated as the difference in the control costs of the most effective strategy and the testing plus vaccination strategy and the forgone revenue of marketing PI animals divided by the total number of non-PI calves marketed. For infected herds, it was assumed that 2% of the calf crop was PI, following estimates of within-herd prevalence of PI animals of infected herds from (US Department of Agriculture, 2010b).

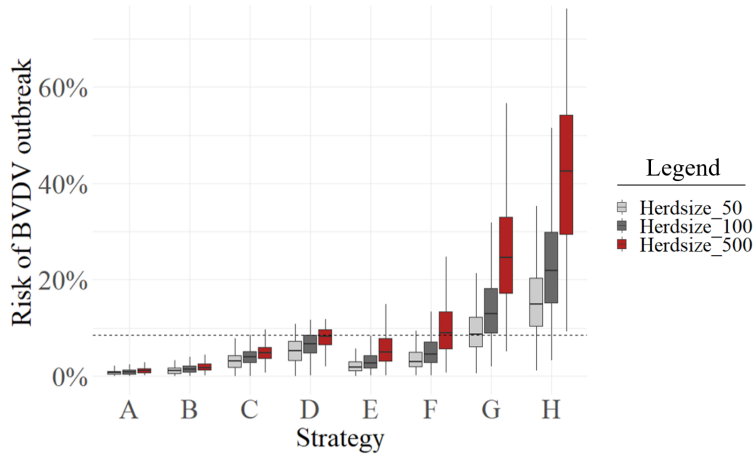

Figure 3. Risk of BVDV Outbreak under Each Control Strategy for Herd Sizes 50, 100, and 500

Notes: Box plots represent minimum and maximum (whiskers), first and third quartiles (box), and median (line within the box). Strategies A–D are closed herd, A and E are vaccination and testing, B and F are vaccination only, C and G are testing only, and D and H are no additional control strategies.

Results

Figure 3 shows the effect of control strategies on BVDV outbreak risk. Within each herd-size stratum, the risk of an outbreak for each BVDV control strategy was statistically different from the others ($p < 0.01$). The simulation model predicted that the average BVDV risks for herd sizes of 50, 100, and 500 head were 5.22%, 7.41%, and 12.88%, respectively. The dashed line across Figure 3 represents the overall average risk for all herd sizes considered, estimated to be 8.51%.

Strategies A–F resulted in mean BVDV risk values at or below the national average. Maintaining a closed herd was particularly effective at reducing risk. For all herd sizes considered, strategies that included closed herd status (A–D) resulted in an average risk of 3.32%. For open herd strategies that included vaccination (E and F), the simulated average risk for all herd sizes considered was estimated to be 5.21%. Strategies G and H results in an average risk that was greater than the national average for each herd size.

The simulation model resulted in substantial differences in the variability of BVDV risk. Strategies that included closed herd status (A–D) resulted in less variability of risk outcome relative to open herds. For open herds, not only did G and H result in the highest average risk, but they also resulted in the greatest uncertainty in risk outcome. The results also indicate a positive relationship between herd size and BVDV risk due to the potential for greater spread of disease among the larger herd. This relationship is particularly evident for open herds strategies. The mean BVDV risks associated with the open herd strategy were 7.79%, 11.47%, and 21.80% for herd sizes of 50, 100, and 500 head, respectively.

Figure 4 illustrates the control costs, expected losses, and total BVDV cost for each strategy under the three herd sizes considered. The top panel depicts the control costs of each strategy. The average control costs for all herd sizes and strategies considered was $22/head. Within each herd-size stratum, the control costs associated with each strategy were statistically different from one another ($p < 0.01$). As expected, strategies that included more disease management inputs had higher control costs relative to the average. On average, maintaining a closed herd was considered the most expensive disease control input due to the expenditure on capital and labor required to raise replacement heifers internally and the forgone revenue of marketing the heifer at weaning. Consequently, closed herd strategies resulted in above-average control costs across strategies.

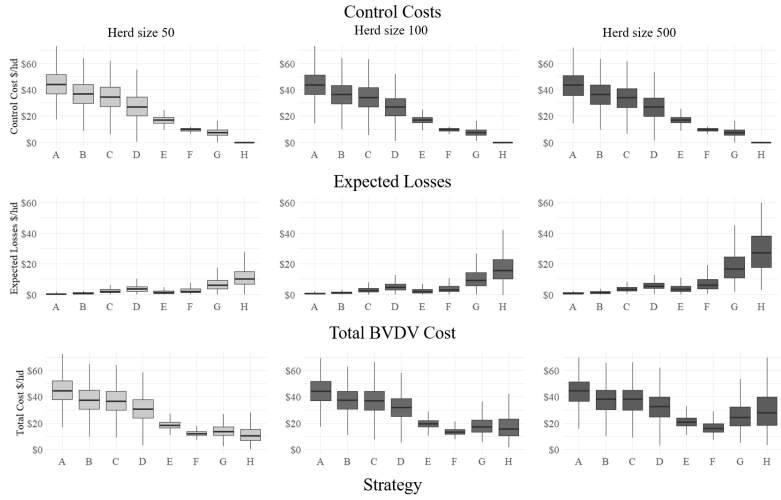

Figure 4. Control Costs, Expected Losses, and Total Cost of BVDV Control Strategies for Herd Sizes 50, 100, and 500

Notes: Box plots represent minimum and maximum (whiskers), first and third quartiles (box), and median (line within the box). Strategies A–D are closed herd, A and E are vaccination and testing, B and F are vaccination only, C and G are testing only, and D and H are no additional control strategies.

However, this result will vary significantly depending on region, economic factors, and forage availability. Because of this variability, closed herd strategies fac greater variation in control costs due to variation in year-to-year operational costs. In contrast, open herd strategies experienced relatively less variation in control costs because vaccination and testing constituted a smaller proportion of total expenditure on control costs. Additionally, they experienced less variation in total BVDV costs. Summary statistics of the control costs for each herd size are provided in Appendix Table A1.

The center panel of Figure 4 depicts the expected losses of each strategy. Average expected losses across all control strategies were \$3.87, \$5.71, and \$9.20 per head, for herd sizes of 50, 100, and 500, respectively. Within each herd-size stratum, the expected losses for each control strategy were statistically different from one another ($p < 0.01$). For all herd sizes considered, strategies A–F resulted in expected losses at or below the mean for a given herd size. Further, strategies that included more disease management inputs reduced the variability in expected losses. Under open herd strategies, larger herds faced a higher probability of BVDV outbreak. Correspondingly, larger herds had greater expected losses due to BVDV. For example, for herd sizes of 50 and 500, strategy H yielded expected losses of \$11.76 and \$31.04 per head, respectively. Production losses and treatment expenditures constituted 93% and 7% of expected BVDV losses, respectively. Within production, reproductive losses were the largest contributor (39.7%), followed by morbidity (39.1%), preweaning mortality (12.3%), and premature culling (8.9%). Within treatment expenditures, veterinary costs was the largest contributor (61%), followed by medication costs (30%), and extra labor costs (9%). Additional information about the losses associated with a BVDV outbreak is provided in Appendix Table A1.

The bottom panel of Figure 4 illustrates the total BVDV cost for each control strategy by herd size. For a herd of 50, all total BVDV costs were statistically different from one another ($p < 0.01$) except for strategies B and C ($p = 0.24$). For a herd of 50, strategies that required little to no BVDV management resulted in the lowest total BVDV cost. Strategies F, G, and H resulted in the lowest costs, at \$12.45, \$14.62, and \$11.76 per head, respectively. There are trade-offs among the three options. Strategy H resulted in the average lowest total cost but had greater outcome variability. Strategies F and G resulted in slightly higher total costs but reduced outcome uncertainty. The added

Table 3. Sensitivity Analysis Comparison of the Total Economic Impact When the Probability of BVDV Outbreak Is Increased by 10% and 20% ($ /head)

	Control Strategies							
Change in Outbreak Risk	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**
Herd size: 50								
10%	$0.05	$0.07	$0.24	$0.38	$0.17	$0.27	$0.72	$1.18
20%	$0.11	$0.18	$0.48	$0.76	$0.33	$0.54	$1.43	$2.35
Herd size: 100								
10%	$0.07	$0.11	$0.31	$0.50	$0.25	$0.41	$1.11	$1.81
20%	$0.14	$0.23	$0.61	$1.00	$0.51	$0.83	$2.21	$3.61
Herd size: 500								
10%	$0.08	$0.14	$0.36	$0.59	$0.43	$0.74	$1.91	$3.10
20%	$0.17	$0.28	$0.72	$1.18	$0.87	$1.47	$3.81	$6.21

control costs associated with closed herd strategies were not offset by reduced expected BVDV losses. Consequently, these strategies were predicted to be less cost-effective.

Similarly, for a herd of 100, less management-intensive options resulted in lower total BVDV costs. All total BVDV were statistically different from one another ($p < 0.01$), except for strategies B and C ($p = 0.48$). Like the results from a herd size of 50, strategies F, G, and H resulted in the lowest total BVDV costs, at $13.307, $18.33, and $18.06 per head, respectively. Among these alternatives, the model predicted vaccination (strategy F) to have the lowest total cost and the least outcome variability. Compared to open herd strategies, closed herd strategies increased the average total cost of BVDV by $23.34/head. Because larger herds face greater risk of exposure, their expected losses are greater. Consequently, incurring a larger amount of control costs to mitigate the substantially large expected losses makes some expenditure on BVDV control more cost effective.

For a herd of 500, the heightened risk of BVDV outbreak resulted in moderately intensive control strategies being the most cost effective. All strategies were statistically different from one another ($p < 0.01$), with the exception of strategies B and C ($p = 0.17$). Strategies E, F, and G resulted in the lowest expected total BVDV costs of $21.08, $16.49, and $26.64 per head, respectively. In addition to resulting in the lowest total cost, the results suggest that strategy F has the lowest variability in outcome. The considerable BVDV risk faced by large herds relative to smaller herds resulted in strategy H having a higher expected total BVDV cost and greater variability.

Table 3 reports the results of the sensitivity analysis. The ranking of strategies by cost-effectiveness from the simulation output was not altered given changes in the risk of BVDV. Strategies for determining which total BVDV cost is primarily associated with expected BVDV losses were more sensitive to changes in BVDV risk. For example, for a herd size of 50, a 20% increase in the risk of a BVDV outbreak increases the total cost of strategy H by $2.35/head versus strategy E by $0.33/head. The largest changes in total cost due to changes in risk occur in a herd of 500 head. Under this scenario, a 20% increase in BVDV risk is predicted to increase total BVDV cost by between $0.17/head and $6.21/head, depending on the control strategy.

Figure 5 illustrates the cumulative density functions of the PI-free premiums required for the testing plus vaccination strategy (Strategy E) to be the most cost-effective control option. PI-free premiums were considered for infected and uninfected herds of 50, 100, and 500 head.

The most cost-effective strategy for a herd size of 50 was the no control option (H). For testing plus vaccination to become the most cost-effective strategy for an uninfected herd, the PI-free premium must cover the costs of testing and vaccination for the entire herd. For an infected herd, the PI-free premium must cover the cost of testing, vaccination, and the forgone revenue associated with marketing PI calves, assuming 2% of calves are PI. For herd sizes of 100 and 500, strategy F (vaccination) was the most cost-effective. For testing plus vaccination to become the most cost-

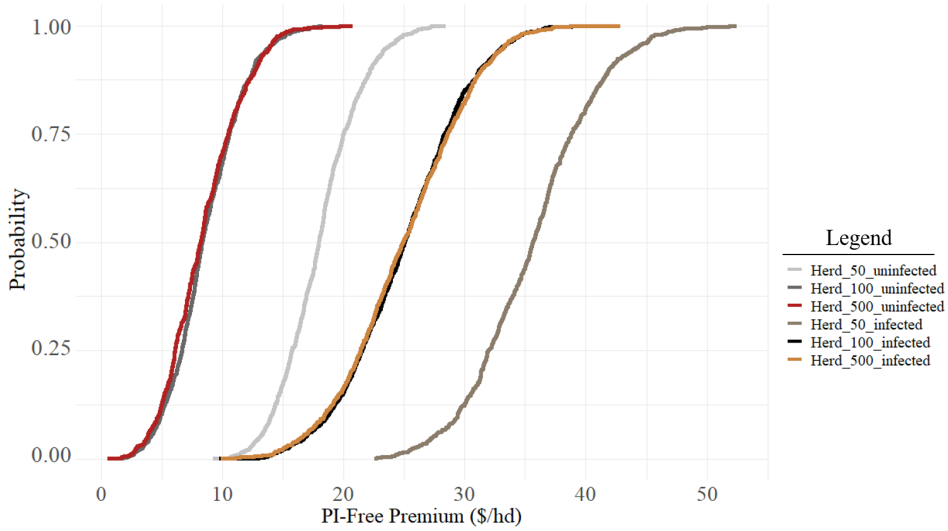

Figure 5. Cumulative Density Function of PI-Free Premiums Needed for Testing Plus Vaccination to Be the Most Cost-Effective Strategy for Infected and Uninfected Herds

effective strategy for an uninfected herd, the PI-free premium must cover the costs of testing. For an infected herd, the PI-free premium must cover the costs of testing and the forgone revenue associated with marketing PI calves.

For uninfected herds, the average required PI-free premiums to induce the testing plus vaccination strategy to be the most cost-effective strategy were $18.10, $8.64, and $8.41 per head for herd sizes of 50, 100, and 500, respectively. The variation in these values largely depends on the cost of testing and vaccination for a producer. For infected herds, the average required PI-free premiums to make testing plus vaccination the most cost-effective strategy were $35.95, $25.32, and $25.28 per head for herd sizes of 50, 100, and 500, respectively. In addition to the variability due to control costs, the required PI-free premiums for infected herds can significantly vary depending on the within-herd prevalence of PI animals. For example, if the within-herd prevalence of PI calves were 10%, the required PI-free premium for a herd size of 50 would be $110.75/head.

Discussion

BVDV and PI animals cause economic losses in the beef industry. This paper develops a stochastic simulation model to assess the total costs of BVDV control strategies for US cow–calf producers based on herd size. Additionally, it assesses the required PI-free premium to incentivize greater BVDV management for infected and uninfected herds. Despite multiple economic studies suggesting that industry-wide adoption of BVDV control would yield positive net benefits, the adoption of BVDV management has been low, particularly for small herds. Our findings suggest that the low prevalence of PI cattle—along with diminishing marginal returns to BVDV control inputs—results in less intensive BVDV control strategies becoming more cost-effective for cattle producers. Further, our results suggest that current PI-free premiums may not be sufficient to incentivize the combination of testing and vaccination for uninfected or infected herds, particularly for herds of less than 50 head.

An important finding—which supports our first hypothesis—is that minimizing expected BVDV losses never minimized the total economic impact of BVDV on a herd. Two underlying bioeconomic processes drive this finding. The first is the effect of untreated disease incidence on the marginal value of a disease control input. The second is the two-step method of control and damage function used to describe the marginal value of a disease control input.

According to our conceptual model and as reported by Fox and Weersink (1995), the marginal value of a disease control input depends on the price of output, the untreated disease incidence, the disease-free level of output, the severity of output reduction due to disease, and the effectiveness of control inputs in reducing disease prevalence. Because most herds are PI free, the untreated disease incidence is 0 or close to 0. Hence, for PI-free herds, the marginal value of BVDV control inputs is low due to the negligible levels of untreated disease incidence. In other words, because most herds are not infected with BVDV, engaging in BVDV management has little value for the producer.

As reported in Lichtenberg and Zilberman (1986), the two-step mechanism of evaluating the effect of a disease control input on the production function underscores the importance of the damage function when determining the marginal value of disease control inputs. At high levels of disease incidence, the marginal value of a disease control input will be sizable. This is because, at high levels of prevalence, the proportional reduction in disease prevalence due to each additional unit of disease control input applied is substantial. This will correspond to large reductions in disease incidence within the damage function, leading to large increases in realized output. Hence, the marginal value of a disease control input is relatively large when high levels of disease are present. When disease prevalence is low, the marginal effect of a disease control input on the proportional reduction in disease incidence is relatively small. Correspondingly, the proportional reduction in the damage function may be negligible, and the marginal value of a disease control input decreases. Therefore, as we increase the quantity of disease control inputs used, the prevalence of a disease decreases and the marginal value of a disease control input diminishes.

To demonstrate, for a herd size of 50, our results suggest that increasing from no control to vaccination solely (strategy H to F), reduces the average level of risk by 12.59%, whereas increasing control from maintaining a closed herd and vaccination to maintaining a closed herd, testing, and vaccination (B to A) reduces the average level of risk by only 0.49%. Correspondingly, the value (in terms of reducing expected losses from BVDV) of moving from strategy H to strategy F is \$9.96/head, whereas moving from B to A is only \$0.36/head. Similar results have been noted in the dairy sector when evaluating the cost effectiveness of including introduction checks, vaccination, and producer sourcing for dairy heifers in Canada (Chi et al., 2002b). The combination of low levels of untreated PI-BVDV incidence and diminishing marginal returns to disease control inputs suggest that it is rational for a producer to not engage in PI animal eradication. This conclusion has critical implications for the stocker and feedyard sectors. Because cow–calf producers are unlikely to enhance BVDV management given the current set of incentives, the financial losses attributed to PI cattle will persist.

For cow–calf producers, the model suggests that the majority of expected losses from BVDV were due to reproductive complications. This finding agrees with previous research using the same model in the dairy sector (Chi et al., 2002a; Houe, 2003). However, our model predicts that a larger portion of losses are attributable to reduced performance (increasing preweaning morbidity) rather than production losses from reduced milk yield, as found in previous studies. Additionally, our estimates of BVDV production losses fall within the range of a recent meta-analysis: Pinior et al. (2019) estimated that mean annual production losses due to BVDV infection fall within a range of €42.14–€67.19 (\$49.72–\$79.28) per head depending on viral circulation intensity. Our model predicts mean annual production losses due to BVDV infection of \$73.58/head. However, our model predicts greater variation in expected losses due to BVDV infection, largely dependent on the reproductive and biological impacts of a BVDV infection. Assuming that 9% of cow–calf herds have at least 1 PI animal and that cattle are naïve to BVDV, the estimated US cow–calf sector production losses due to BVDV would range between \$29 million and \$65 million annually.

Within the cow–calf population, our results suggest that larger herds are more likely to be exposed to a PI animal. This is particularly true for herds that import replacement heifers. For example, for open herd strategies, our study found that the average levels of BVDV outbreak risk are 7.79%, 11.47%, and 21.80% for herd sizes of 50, 100, and 500, respectively. Our findings suggest that because larger herds face greater risk and thereby greater expected losses,

adopting some level of BVDV management becomes more cost effective. These findings support our second hypothesis. Correspondingly, we would expect larger herds to adopt more rigorous BVDV management protocols (e.g., regular vaccination for calves and the cow herd). This claim is reinforced when model outputs are compared to BVDV management practices seen in cow–calf production. For example, the US Department of Agriculture (2021) reported that 52.6%, 68.3%, and 84.8% of operations with herds of 1–49, 50–100, and 200+, respectively, vaccinated cattle against BVDV.

For the beef industry, our results suggest that PI animals are unlikely to be eradicated given the current incentive structure. While vaccination protects herds against infection, it does not generally eliminate PI animals.[2] Consequently, disease caused by PI animals is likely to continue. Our model suggested that for a herd size of 50, it was cost effective to not engage in BVDV control. Given that roughly 40% of US beef cow inventory resides in herds of 50 cows or fewer (US Department of Agriculture, 2010a), these small herds are likely sources of PI cattle that enter the supply chain. While our model predicts that it is cost effective to engage in vaccination for herds of more than 100 head, vaccination is not completely efficacious at preventing BVDV infection. Hence, PI animals can still be generated. If the beef industry aims to reduce the prevalence and economic impact of PI animals, increasing incentives for BVDV control within the cow–calf sector will be required.

PI-free premium compensation from feeder cattle buyers to feeder cattle sellers may incentivize greater BVDV control. While PI-free premiums exist, the volume of cattle marketed under these premiums has been low. Our model predicts that current PI-free premiums may not be sufficient to incentivize enhanced BVDV management. Our model predicts that for a testing plus vaccination strategy to be the most cost effective for uninfected herds, the PI-free premiums must be, on average, \$18.10, \$8.64, and \$8.41 per head for herd sizes of 50, 100, and 500, respectively. The estimates of these premiums depend on the cost of control inputs and labor costs. The required PI-free premiums are larger for herds of less than 50 than for larger herds because our model predicts that not engaging in BVDV control will be cost effective for small herds. Hence, to incentivize switching to a vaccination plus testing strategy, premiums need to be large enough to cover the costs of employing both disease control inputs. In contrast, the model predicts that vaccination is the most cost-effective strategy for medium and large herds; therefore, PI-free premiums need to cover only the costs of testing and labor.

The required PI-free premiums for infected herds are significantly larger due to forgone revenue from marketing PI animals. For infected herds, the average required PI-free premiums for the testing plus vaccination strategy to be the most cost effective were \$35.95, \$25.32, and \$25.28 per head for herd sizes of 50, 100, and 500, respectively. These values will depend on the cost of control strategies, prevalence of PI animals, calf price, and forgone revenue of marketing PI animals. When input costs and calf prices are high, the cost of testing and the forgone revenue of marketing PI cattle increase. Hence, the required PI-free premiums required to incentivize greater BVDV control likely outpace the available PI-free premiums on the market. Consequently, during inflationary periods, it is possible that fewer cattle will be marketed as PI free.

Martinez, Boyer, and Burdine (2021) found that lots that were PI tested were associated with a \$1.19/cwt (about \$10/head) premium. While this estimate is larger than the PI-free premiums needed for medium and large uninfected herds, it is important to note that without testing, the infection status of a herd is unknown. Hence, because current PI-free premiums are not sufficient to cover the forgone revenue of marketing PI animals, producers may be disincentivized to test calves for PI status. Additionally, knowledge gaps among producers may inhibit the adoption of testing. Among small operators, 48% do not know whether removing PI calves affects the value of calves in the remaining herd (US Department of Agriculture, 2021). Consequently, providing sufficient compensation for enhanced BVDV control and improving education about the value of PI testing are warranted to encourage enhanced BVDV control.

[2] A small exception can occur when females are vaccinated against BVDV during a specified period of gestation (Zimmer et al., 2002).

As with any simulation model, the applicability of the results depends on the suitability of the model structure and input distributions. Although veterinary knowledge of BVDV is extensive, economic and epidemiological data about BVDV specific to cow–calf production is limited. Accordingly, the greatest limitation of this research was the assumptions made about the distributions of epidemiological parameters in the model. The risk of outbreak could be underestimated given that the model does not consider the risk of BVDV exposure from cervids and transiently infected cattle. Additionally, differences in producer attitudes toward risk were not considered. While generalizations can be made, the most cost-effective BVDV control strategy will depend on farm characteristics unique to each operation.

Conclusion

For most herds, vaccination is found to be the strategy that minimizes the total cost of BVDV for a cow–calf producer. The total cost of a strategy is determined by its level of BVDV risk, cost of disease control inputs, and losses due to an outbreak. The positive relationship between herd size and BVDV risk suggests that larger herds are more likely to adopt rigorous BVDV management programs. The estimated PI-free premium required to induce a testing plus vaccination strategy to be the most cost effective largely exceeds current PI-free premiums on the market. If BVDV control is *a priori*ty for the cattle industry, then greater incentives must be relayed to cow–calf producers. Future research should (i) investigate the cost of PI exposure to feedlots and (ii) assess mechanisms of reducing transaction costs associated with buying and selling cattle in a PI-free market.

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Table A1. Summary Statistics of the 1,000 Iterations of Cost of BVDV Control Strategies and BVDV Outbreak Losses

	Herd Size 50				Herd Size 100				Herd size 500			
Variable	**Mean**	**SD**	**Min.**	**Max.**	**Mean**	**SD**	**Min.**	**Max.**	**Mean**	**SD**	**Min.**	**Max.**
Control costs												
Maintaining closed herd	$1,347	$516	$-$159.2	$2,824	$2,694	$1,042	-$277	$3,400	$13,432	$5,112	-$5,095	$28,717
Herd vaccination	$476	$57	$314	$593	$916	$161	$566	$1,189	$4,568	$790	$2,838	$5,951
BVDV-PI testing	$371	$141	$0	$853	$728	$278	$0	$1,600	$3,793	$1,462	$0	$10,670
BVDV outbreak losses												
Reproductive losses	$1,389	$887	$42.17	$6,491	$3,017	$1,926	$269	$12,395	$13,981	$9,178	$595	$78,363
Morbidity losses	$1,369	$434	$425	$3,502	$2,755	$833	$966	$6,524	$13,386	$4,186	$4,412	$29,117
Mortality losses	$431	$447	$0	$3,316	$826	$834	$0.94	$4,905	$4,193	$4,263	$0.92	$41,134
Premature culling losses	$311	$511	$-$160	$3,809	$744	$1238	-$502	$15,913	$3,512	$5,308	-$1,178	$41,706
Veterinary cost	$106	$63	$3.5	$416	$228	$132	$18	$819	$1,088	$675	$52	$5,321
Medication cost	$53.189	$32	$1.59	$211	$115	$67	$11	$401	$544	$338	$27	$2,810
Extra labor cost	$17.69	$11	$0.58	$72	$38	$23	$2.28	$165	$182	$117	$9.35	$1,037
Total BVDV outbreak losses	$3,679	$1,419	$14	$9,190	$7,727	$2,986	$2	$22,736	$36,888	$14,301	$8,348	$125,173

Notes: Parentheses represent numbers describing each distribution. Tnorm(mean, standard deviation, lower bound, upper bound), Poisson(number of trials, lambda) Pert(minimum, most likely, maximum), U(minimum, maximum), Bin(number of trials, probability of success), Gamma(number of trails, shape, rate). Within-herd prevalence is defined as proportion of antibody positive animals in herd.