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Economic risk analysis model for Bovine Viral Diarrhea Virus biosecurity in cow-calf herds

Rebecca L. Smith[1*], Michael W. Sanderson[2], Rodney Jones[3**], Yapo N'Guessan[3***], David Renter[2], Robert Larson[1], Brad J. White[1]

[1]Department of Clinical Sciences, Kansas State University, Manhattan, KS 66502

[2]Department of Diagnostic Medicine and Pathobiology, Kansas State University, Manhattan, KS 66502

[3]Department of Agricultural Economics, Kansas State University, Manhattan, KS 66502

corresponding author: Mike Sanderson, 785-532-4264, fax 785-532-4851, sandersn@vet.k-state.edu

[*]currently with Department of Population Medicine and Diagnostic Sciences, Cornell University College of Veterinary Medicine, Ithaca, NY 14850

[**] Currently with Department of Agricultural Economics, Oklahoma State University, Stillwater, OK 74074

[***] Former PhD research assistant

Abstract

A stochastic model was designed to calculate the cost-effectiveness of biosecurity strategies for Bovine Viral Diarrhea Virus (BVDV) in cow-calf herds. Possible sources of BVDV introduction considered were imported animals, including the calves of pregnant imports, and fenceline contact with infected herds, including stocker cattle raised in adjacent pastures. Spread of BVDV through the herd was modeled with a stochastic SIR model. Financial consequences of BVDV, including lost income, treatment costs, and the cost of biosecurity strategies, were calculated for 10 years, based on the risks of a herd with a user-defined import profile. Results indicate that importing pregnant animals and stockers increased the financial risk of BVDV. Strategic testing in combination with vaccination most decreased the risk of high-cost outbreaks in most herds. The choice of a biosecurity strategy was specific to the risks of a particular herd.

1 Introduction

Bovine viral diarrhea virus (BVDV) costs the beef industry through decreased production and increased expenses (Wittum et al., 1994; Gunn et al., 1998; Bennett et al., 1999; Larson et al., 2002). It is a common disease in the US cattle herd (Houe et al., 1995; Paisley et al., 1996; Chase et al., 2003).

Fetal infection between 40 and 125 days gestation can lead to a persistently infected animal (PI) (Stokstad and Loken, 2002), which will shed virus for life through oculonasal discharges (Confer et al., 2005). Persistently infected animals are generally considered to be the primary source of BVDV introduction to a herd (Houe, 1999; Niskanen et al., 2002).

Animals with transient infections (TIs), caused by exposure to BVDV while not in the risk period to become PI, experience a range of negative effects. In adults, these are mostly reproductive disorders, such as abortion (Fredriksen et al., 1998), decreased conception risk (Houe and Meyling, 1991; McGowan et al., 1993a; McGowan et al., 1993b; Larsson et al., 1994; Wittum et al., 2001), early embryonic death (EED) (McGowan et al., 1993a; McGowan et al., 1993b), and congenital defects (Munoz-Zanzi et al., 2003; Ellsworth et al., 2006). In calves, common symptoms include immunosuppression leading to increased morbidity and mortality (Castrucci et al., 1992; Bjorkman et al., 2000; Kozasaa et al., 2005).

Biosecurity against BVDV introduction includes testing imported animals, vaccinating against BVDV, testing-and-culling programs of the resident herd, and avoiding potentially infectious contact with infected herds, especially PI animals. Testing strategies on imported animals aim to reduce the number of PIs introduced to a herd and may be cost effective (Stott et al., 2003). Vaccination is meant to decrease the spread of the virus once it is introduced to the herd; specifically, it is intended to prevent the birth of new PIs. Test-and-cull programs, often focusing on calves, are used to decrease the number of PIs present in an infected herd. This is commonly done before the breeding season to decrease the number of sources of infection present during the risk period (days 45-180 of gestation) for producing more PIs. In addition to these strategies, avoiding contact with other cattle herds at fencelines and in communal pastures may also prevent herd infection (Valle et al., 1999).

A multitude of stochastic models have been developed to study the effects of BVDV control programs on dairy herds (Innocent et al., 1997a; Innocent et al., 1997b; Cherry et al., 1998; Viet et al., 2004a; Viet et al., 2004b; Viet et al., 2005; Viet et al., 2006; Ezanno et al., 2007). Management differences between dairy and beef operations, however, make those models less helpful in decision making for cow-calf producers. In particular, the limited breeding season of beef herds limits the risk period for the creation of PI animals. This limited breeding season also increases the risk to the herd during this time period, as a greater proportion of dams will be in the risk period at one time compared to a dairy, when breeding is usually spread over the course of a year. Also, testing strategies in dairy herds often include monitoring of the bulk milk tank, which is not possible in beef herds. In addition, the spread of the virus is affected by the lower animal density of pastured beef herds, compared to intensively managed dairies, and by the continued contact between calves and adults until weaning in beef herds.

One previous model has been developed for BVDV in a cow-calf herd (Cleveland, 2003). This model was designed to examine the effect of test-and-cull strategies in an endemically infected cow-calf herd. While this model is quite useful for the closed, infected herd aiming to control the infection, it does not address the effectiveness of biosecurity strategies in herds not currently infected. It also does not provide estimates of cost-effectiveness, which are necessary for producers to make informed biosecurity decisions. One partial budget analysis examined the efficacy of testing for BVDV in incoming feedlot calves (Larson et al., 2005), but management factors again make the results less applicable to cow-calf operations. No models that are available in the literature address the overall impact of all BVDV control strategies within cow-calf herds, although Nickell et al. (2011) do consider the value of different whole-herd testing strategies. We have previously developed risk analysis models for the introduction (Smith et al., 2009) and within-herd spread (Smith et al., 2010) of BVDV for cow-calf herds. The purpose of this study was to develop a stochastic risk-analysis model, using the existing models for the introduction and spread of BVDV in cow-calf herds, to determine the cost-efficacy of control and the total cost of BVDV in US cow-calf herds.

2 Materials and Methods

This paper describes the integration of three Monte Carlo simulation models: a model for the annual introduction risk for BVDV to a cow-calf herd and the impact of biosecurity strategies (Smith et al., 2009), a model for the effects of BVDV over 10 years after introduction to a naïve cow-calf herd and the impact of control strategies on those effects (Smith et al., 2010), and a model for the economic costs of BVDV effects, biosecurity, and control.

The first two models have been described previously. Briefly, the introduction model was a Monte Carlo model in which the probability of introducing BVDV to a herd in any year was calculated based on two risk categories, imports and fenceline contact (Smith et al. 2009). The number of PIs imported to the herd was based on the number of animals imported in a given age category and/or pregnancy status, the PI prevalence in that age group, including fetal prevalence for calves of pregnant imports, and the testing strategy to prevent PI importation. Infection through fenceline contact was modeled based on the presence of BVDV in the adjacent herd and the probability of infectious contact with that herd, leading to a dichotomous variable for infection from fenceline contact. The adjacent herd in this model consists of imported stockers (young animals grazed on available pasture for later sale to feedlots or finishers). These introductions (importation of PIs and fenceline infection) were calculated independently for each of 10 years based on the import profile and management of the herd.

The model for the spread and effects of BVDV (Smith et al 2010) was driven by the introduction of a single PI calf imported in year 1. Infection in the herd was tracked using a modified Reed-Frost (SIR) model based on the number of animals in the herd, the number of PIs in the herd, and the number of susceptible animals. This discrete-time model uses 3-week periods, in which conception was also modeled, allowing calculation of infections during the risk period for fetal persistent infection.

The model reported here integrates both the probability of PIs from outside introduction and from endemic infections. In each year, the number of PIs produced during the previous year's breeding season was added to the herd in the 3-week period of the calving season corresponding to their date of conception. PI calves may be removed from the herd each year by a pre-breeding test-and-cull strategy. When infection occurred by fenceline contact, the presence of a single PI crossing into the herd was added to the Reed-Frost calculation for a single 3-week time period to represent cross-fence contact.

The number of PI mortalities was calculated for each 3-week period, allowing the PIs to be removed from the herd at death. The number of PI morbidities, however, was based on the number of PIs present on an annual basis, as morbidity in PI cattle does not impact the risk to spreading infections in the herd. All other effects of BVDV were also modeled on an annual basis, based on the number of infections in each risk group within the herd. The number of abortions was based on the number of pregnant females exposed to infection during the appropriate time period, while the numbers of TI morbidities and mortalities were based on the number of infected calves on an annual basis. The number of EEDs and congenital defects were calculated based on the number of infections during their respective risk periods, as were the number of PIs to be born. EEDs occurring before the end of the breeding season, at which time the dams were allowed to rebreed, were distinguished from EEDs occurring after the breeding season has ended and rebreeding was no longer possible.

Vaccination was modeled on an annual basis, removing a proportion of the breeding females (determined by the vaccine efficacy) from the susceptible category for a single year.

Vaccinated or otherwise immune animals were assumed to give birth to immune calves, which were assumed to remain immune until weaning.

The economic model for the total 10-year cost of BVDV in cow-calf herds was based on a partial budget, integrating management costs and lost income. Parameters used to estimate performance in this model are described in Table 1. Annual inputs from the introduction risk and herd spread models were used to calculate the cost of BVDV for that year. Economic impacts (cost) were based on both treatment cost (based on the number of calf morbidities) and lost income due to decreased performance. Total lost income was calculated as the price per kilogram times the difference between estimated performance in diseased and non-diseased animals. Price per kilogram was modeled on a draw of historical prices for the month of September from a 10-year period (2003-2012). The decreased weaning weight was the sum of the decrease in weaning weight due to BVDV in morbid calves and the total weight of calves lost to BVDV mortality. Decreased weaning weights were also calculated for calves based on the number of EEDs occurring in cows that successfully rebred before the end of the breeding season, as these would result in younger (and consequently lighter) calves at weaning. Calf mortality was the sum of the number of abortions, EEDs in cows that failed to rebreed, congenital defects, TI mortalities, and PI mortalities. The possible weaning weight of those lost calves was based on a binomial calculation for the numbers of heifers and steers that were lost and on the weaning weight distribution for each gender.

The stochastic model was developed with @Risk 6.1 (Palisade Corp, Ithaca, NY), an add-in for Excel® 2010 (Microsoft Corp, Redmond, WA).

2.1 Validation

Validation of the model disease outputs was performed in Smith et al. (2010) using two published outbreaks involving 4 cow-calf herds in which the source of the virus could be inferred (Taylor et al. 1994;VanCampen et al., 2000). No published economic outcome is available to directly validate the economic outcomes of the model.

Taylor et al. (1994) reported data for 3 years following the recognition of the outbreak. It was modeled as a 200 cow herd with 1 PI fetus introduced in year 1. Calf morbidity, mortality and endemic PI's produced were reported and compared to model output. VanCampen et al. (2000) reported data for 1 year on 3 herds of 250 cows, 340 cows and 285 cows. Each herd was modeled with the introduction of 1 PI calf in year 1. Calf mortality and number of abortions were reported and compared to model output.

For each outbreak validation, the simulation was run for 3000 iterations and the median and 95% prediction interval for each of the categories observed were calculated. Model output and 95% prediction intervals were compared to the observed values.

2.2 Model Application

A range of possible herd profiles is described in Table 2, and a variety of biosecurity strategies is listed in Table 3. The model was run for 3000 iterations with a fixed random number seed for each of the possible herds listed with each of the listed biosecurity strategies appropriate to that herd. Calculated costs included the cost of disease and the cost of prevention and treatment for each simulation. The median and 95% prediction intervals for total 10-year cost were collected from the model. Stochastic dominance graphs were generated for each herd with all biosecurity strategies.

Investigation of the probability of exceeding a target value for the 10-year cost of BVDV in the herd, accounting for both the cost of disease and the cost of prevention, was performed using target analysis as a means of quantifying economic risk for each herd scenario. This involved determining the proportion of iterations in which the total 10-year cost was at least the target value, indicating the probability of the herd spending at least as much as the target on BVDV over a 10-year period. The optimal (dominant) control strategy would have the lowest probability of exceeding the specified target cost; if probabilities of exceeding the target cost for more than one strategy were not significantly different, those strategies would be considered co-dominant. The target values were set as $40,000 for a 400-head herd, $7,500 for a 100-head herd, and $2,500 for a 50-head herd. These values were selected to represent the average return to labor and management for each respective cow-calf herd size for ten years (USDA:ERS, 2012), taking into account economies of scale and size. These values represent a severe loss to the enterprise that could jeopardize business continuity and that nearly all enterprises would want to minimize. All scenario distributions for the probability of exceeding the target value met the criteria for a normal approximation (np and n(1-p) >5) so 95% confidence intervals around the probability of exceeding the target were calculated based on the normal approximation for the binomial distribution. Probabilities were considered significantly different if the 95% confidence intervals did not overlap.

2.3 Sensitivity analysis

A global sensitivity analysis was performed on the model to determine the importance of the parameter distributions listed in Table 1. Sensitivity analyses on the introduction and the spread models have been previously reported (Smith et al. 2009, Smith et al. 2010). The sensitivity analysis results for the integrated economic model reported here were produced with 5 biosecurity scenarios for a 400-head herd importing 60 pregnant heifers, 4 bulls, and 100 stockers. The biosecurity and control scenarios were M (using no biosecurity or control program), N (vaccinating all adult animals), T (testing all imported animals, including stockers and calves of pregnant heifers), Y (testing all imported animals, including calves of pregnant heifers but excluding stockers, and vaccinating all adult animals), and Z (testing all imported animals, including stockers and calves of pregnant heifers, and vaccinating all adult animals). These scenarios represent a mixed selection of the scenarios presented in the model results, including the scenario with the lowest mean cost (Y) and the scenario with the lowest probability of exceeding the target (Z).

A local sensitivity analysis was also performed on the 5 scenarios for each parameter whose correlation coefficient was statistically significant in the global sensitivity analysis for at least one scenario. For each scenario, the mean 10-year cost of BVDV was determined with each of the parameters of interest fixed individually at the 5th and 95th percentiles, as listed, for 3000 iterations of the model with a fixed number seed. This allowed the sensitivity analysis to determine the impact of each distribution within approximately 90% of its expected range. Differences between the low and high values for cost were calculated and reported as proportions of the mean cost of the scenario in the base model.

3 Results

3.1 Validation

Validation of disease outputs are reported in Smith et al. (2010).

3.2 Model Application

Three thousand was a sufficient number of iterations for mean, standard deviation, and percentiles of all outputs in all simulations to converge within 5%. In none of the simulations were there significant differences between the mean costs of any biosecurity strategy, based on comparison of 95% confidence intervals (data not shown). First-order stochastic dominance was not observed for any strategy, regardless of herd size. Two examples of cumulative probability graphs demonstrating the variation in costs are provided in Figure 1.

The results of the target analysis are presented in Table 4; dominant or co-dominant strategies based on non-overlapping 95% PI's are in bold type for each column. The median and 95% prediction intervals of 10 year costs are presented in Table 5 for all herd and strategy combinations.

3.3 Sensitivity Analysis

The correlation coefficients from a global sensitivity analysis for all input parameters are shown in Table 6 for all scenarios analyzed. For a herd with no control or biosecurity (M) or a herd relying only on vaccination (N), the most significant parameters were the abortion risk, calf sale prices, and the TI mortality risk; an increase in any of these parameters increased the mean 10-year cost of BVDV. The herd relying only on vaccination also experienced lower costs when vaccine efficacy was increased. In any herd relying on testing, the cost of the test was the most significant parameter. When vaccination was added to testing, the cost of vaccination was also significant. The proportional difference in mean cost from a local sensitivity analysis is shown in Table 7 for all parameters found to be significant in the global sensitivity analysis. This is the difference in mean cost when the parameter is fixed at its upper value from when the parameter is fixed at its lower value, divided by the mean cost when all parameters are allowed to vary; a positive value indicates that increasing the parameter's value will increase the mean cost of BVDV, while a negative value indicates that increasing the parameter's value will decrease the mean cost of BVDV.

4 Discussion

The model presented here predicts the economic risks associated with specific management decisions, including the importation of different classes of cattle and different biosecurity and control strategies related to BVDV. While the model does not predict, in a deterministic sense, the most cost-effective strategy for BVDV, it does give herd-specific risk calculations that can assist in decision making, allowing the individual producer to include their individual degree of risk aversion into the decision making process. The outcome utilized was based on the probability of exceeding a target value of cost, accounting for both the costs of disease and prevention. This allows decision making based on the cost of disease and the cost and effectiveness of mitigation.

Validation of a stochastic disease model with field data is an accepted method (Cleveland, 2003; Viet et al., 2004a). However, most field data were either available from endemically infected herds, for which this model was not designed, or from outbreaks in which the source of virus is uncertain. Validation of this model has been previously reported (Smith et al., 2010) using two published outbreak reports.   The model was able to predict the observations available for each herd within the stochastic framework that was not substantially different from the observed value. The economic results reported here are a direct extension of the production parameters validated in the previous report.

The predictions of the model regarding cost showed no significant differences between biosecurity strategies in mean cost of BVDV over 10 years in 100 and 50 head herds or in 400 head herds importing pregnant heifers, and no first-order stochastic dominance in descending probability cost distributions regardless of the scenario modeled. This was due to the low prevalence of PIs resulting in introduction of a PI being a rare event. With a rare outcome, the mean cost of the disease is skewed to the left (lower end), obscuring differences in control programs. This was the primary motivation for building a stochastic model for BVDV, so these results were expected.

As means were similar and first-order dominance did not occur, decisions may need to be made based on alternative risk calculations. The results presented here, based on the probability of exceeding a target value, are one alternative method of risk-based decision making. Target analysis is an intuitive method for decision making in cow-calf production enterprises, providing a single probability estimate of downside risk for decision making.

It can be seen in Table 4 that herd size and import profile were important determinants in the risk of exceeding the target cost. Based on non-overlapping 95% prediction intervals herds importing pregnant heifers had a significantly higher probability of exceeding the target cost than herds importing non-pregnant heifers if no biosecurity strategy was employed (strategy M). Testing adult imports only (strategy O) decreased risk compared to doing nothing (strategy M) only in herds importing non-pregnant heifers, and was never co-dominant. Pregnant heifers may be PI and carrying a PI calf, but alternatively they may be non-PI but were transiently infected during the risk period and carrying a PI calf. This highlights two important considerations: 1) importing a pregnant heifer brings in two animals at risk for PI status, and 2) even in import testing strategies, it is impossible to test fetal status and the fetus is in a higher risk category for being PI. A testing strategy that only tests the replacement heifers would miss the PI calf of a non-PI heifer and allow introduction of BVDV to the herd. Conversely, testing the calves of pregnant imports after birth and before the breeding season will allow detection of the calf and identification of the dam for further testing. In this model, representing best practices, the dams of positive calves were always tested and the calves of positive dams were automatically removed. Calves and fetal imports were at proportionately greater risk to the herd than their dams due to the higher PI prevalence in younger animals.

Regardless of the other import decisions, importing stockers increased the risk of exceeding the target cost. This assumes there was fenceline contact between the breeding herd and the stockers during a time frame when PI animals could be created. In U.S. beef production systems, stockers may be imported at relatively high numbers to take advantage of additional grazing or as a market risk management option. The number of stockers modeled here represents approximately 1 truckload of stockers and was meant to be representative of the lower end of potential import volume. Some combination of vaccinating and testing (strategies U-Z), was always dominant if stockers and non-pregnant heifers were imported. If imported heifers were pregnant, the preferred combination of vaccinating and testing always included testing imported calves and calves of pregnant imports (strategies Y or Z) in medium and large herds. In the 400-head herd importing stockers and pregnant heifers, dominance was observed for strategy Z, which adds stocker testing to strategy Y. Testing stockers decreased the probability of a high-cost outbreak, though not the median cost of BVDV (Table 5), in large herds by decreasing the risk of importing PI stockers (Smith et al. 2009). However, the cost of testing stockers (strategy R) was greater than the target value for 50-head herds and the cost of combining stocker testing with the other testing strategies (strategies T and Z) was greater than the target value for 100-head herds. Because the base cost of testing stockers is so high, it was only included in the lowest-risk options for 400-head herds. If management and facilities allow, the most cost effective management of the risk due to stockers may be to assure that there was no contact between the imported stockers and the breeding herd, which would be comparable to the herds in these results that did not import stockers.

In the absence of stockers, vaccination of breeding animals as a single biosecurity practice (strategy N) only slightly decreased the risk of exceeding economic targets. Instead, testing-based strategies, with vaccination, became co-dominant. If pregnant heifers were imported, large and medium-sized herds required testing of imported calves in combination with other strategies because more animals were imported than in small herds, increasing the risk of introducing a PI animal. Based on the results of this model, it would be advisable for herds in which the majority of risk is based on importation of animals to the breeding herd, rather than stockers, to prioritize appropriate testing strategies. Herds that have contact with other herds at fencelines or in communal pastures have introduction risk that cannot be controlled by testing, requiring a vaccination strategy.

In the 50- and 100-head herds, strategies combining vaccination or large amounts of testing (strategies T and Z) cost more than the target value specified. While these strategies may decrease the risk of introducing and spreading BVDV in the herd, they do not appear to be cost-effective in the long term. This finding agrees with Nickell et al. (2011), which found that whole-herd testing strategies had negative value if herd prevalence was low. A more judicious use of targeted testing and vaccination, was preferable from an economic standpoint. This decision will be driven by the individual producer's risk aversion.

The results presented in Table 4, although useful, were limited to a single target value. While this is useful for decision making if the target value is known, different producers may have different levels of acceptable risk. Therefore, different producers will likely prefer to make decisions based on alternative target values. Figure 1 shows that different target values will provide different results. It should be noted that the lowest variation in cost was always in the scenario with the most interventions (Table 5), but that this scenario only had the lowest median cost in large herds importing either pregnant heifers or stockers (A3P,A3N and A4P). This shows that a high number of interventions would be successful in controlling an outbreak should it occur, but that the base cost may be too high to be economically justifiable for all but the largest herds. However, the risk-averse producer may prefer to select a control program with a large base cost, within reason, in exchange for more regularity in costs in the long term.

The results presented here are specific to the herd profiles used to obtain them and indicate that the most cost effective biosecurity plan should be designed for the specific risks of the herd. We elected to include herd size, heifer imports and stocker number of imports as fixed values because they represent herd level decisions related to resource availability and management preference rather than random variables. Herd size is a relatively fixed value over time for most herds, heifer replacement rates are correlated to herd size and stocker imports are a management strategy that is constrained by resource availability. The groups and management decisions included were meant to represent the range of size and management practice in US Cow-calf herds to provide a broad estimate of effects. While generalizations may be made, it is preferable to model specific herd practices on an individual basis. However, the results presented here suggest that, for herds with modest import rates, strategic testing of imports was the most cost-effective way to exclude BVDV and control losses. For herds with some level of uncontrolled risk, such as exposure to stockers or neighboring herds, vaccination of the breeding herd may be a cost-effective addition to strategic testing strategies.

The global sensitivity analysis of the integrated model (Table 6) provided some intriguing results. In herds with little to no control or biosecurity, the cost of BVDV was directly and strongly related to the number of lost calves (abortions and mortality) and the price those calves would have brought. In herds with large amounts of testing, however, the cost of testing was the most influential distribution, and the cost of vaccination was influential when animals were vaccinated. When testing strategies were used, a $2.16 increase in the cost of a test (increasing the test cost from its 5th percentile to its 95th percentile) resulted in a 43% increase in the mean cost of a herd testing all imported animals, while the same increase resulted in 40% cost increase in a herd that added vaccination of all adult animals to the control program and a 36% cost increase in a herd testing all imports except stockers that also relied on vaccination. The impact of increasing the cost of vaccine by $0.67 (increase from 5th to 95th percentile) was smaller, but that was due to the fact that more animals were tested than were vaccinated with the biosecurity strategy used, as increases in control costs were the only difference observed (data not shown). These findings would indicate that the cost of the test and the vaccine could have a substantial impact on the choice of biosecurity strategy.

The local sensitivity analysis shows that, in the absence of testing, the effect of changing the vaccine efficacy alone was far greater than the effect of changing the vaccine price alone, such that a vaccine with a higher efficacy and a higher price would still be cost-effective. In combination with testing, however, vaccine efficacy had little effect such that increasing the cost of the vaccine in order to increase the vaccine efficacy would not be cost-effective. The vaccine efficacy distribution also incorporated substantial natural variability. Published estimates of vaccine efficacy in preventing PIs vary considerably. Some of this variability may be due to differences between vaccines, but some may also be due to differences in the specifics of the trials related to cattle factors and viral challenge factors. In a production setting, additional variability exists due to vaccine handling and management of cattle that may affect their ability to mount an effective immune response. This model attempts, with a wide distribution, to capture some of the variation seen with different vaccines, their performance against different strains of BVDV, and the management factors that affect their efficacy.

The biological variable shown to be most influential was the abortion risk, as abortions were among the most costly of outcomes and, like vaccine efficacy (as discussed above), the abortion risk can also vary widely between strains. The TI mortality risk was also rather influential in the absence of control. Surveyed experts believed that TI mortality risks were generally modest, based on their personal experience in cow-calf herds experiencing outbreaks, but high mortality risks in calves have been observed. This phenomenon may be due to variability seen in BVDV strains and herd susceptibility, so these distributions were appropriately wide and, therefore, influential in the model. The TI mortality distribution was more influential when no control strategy was used (strategy M) in a large herd with a greater potential number of calves affected; this herd would experience more TIs over 10 years simply due to the number of animals at risk, which would explain the greater influence of the TI mortality risk. If animals were tested, the effect of biological variables was substantially decreased, as testing would decrease the risk of introducing an infected animal to the herd.

This model predicts that a combination of vaccination and testing is most likely to prevent large outbreak costs due to BVDV in cow-calf herds, but that viruses with a high abortion risk and tests with a high unit cost could greatly increase the mean cost. These results should be useful to cow-calf herds interested in comparing the potential economic consequences with the risk of BVDV outbreaks under alternative common management protocols.

This model assesses the impact of planned strategies implemented over a long range planning horizon. We believe this approach has value particularly for the herd production practices modeled where cattle are imported each year and supports that these planned strategies can be economic in decreasing costs over the 10 year planning horizon. Alternate surveillance strategies could be used such as passive surveillance of production and disease or targeted testing. Passive surveillance strategies monitoring, for example pregnancy rates or increased calf morbidity or mortality would be difficult to implement in the model without including other causes of these herd problems to account for the rate of false positive signals (for BVD). Test based surveillance and triggers for more extensive testing and interventions could be considered and implemented in future models and may be more cost effective particularly in lower risk herds with fewer animals imported.

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Table 1: Distributions used in economic analysis of biosecurity strategies for bovine viral diarrhea virus in a cow-calf herd

Parameter Description	Distribution	Reference(s)
Young calf and fetal prevalence	Normal(0.59%,0.08%), Truncate(0,1)	(Caldow et al., 1993; Wittum et al., 2001; Cleveland, 2003)
Youngstock prevalence (stockers, bulls)	Normal(0.47%, 0.11%) Truncate (0, 1)	(Howard et al., 1990; Taylor et al., 1995; Fulton et al., 2000; Givens et al., 2003; Cleveland, 2003; Loneragen et al., 2005; Gnad et al., 2005)
Heifer prevalence	If source herd was positive (from a binomial based on herd prevalence), youngstock prevalence/herd prevalence	Expert survey*
Cow prevalence	Normal (0.07%, 0.04%) Truncate (0, 1)	(Smith et al., 2007)

Herd prevalence	Normal (10.16%, 2.7%) Truncate (0, 1)	(Wittum et al., 1997; Wittum et al., 2001)
Probability of fenceline infection	Pert (6%,47%,83%)	Expert survey[*]
R_0[@]-PI[^] animal present	Pert (5,7,12)	Personal opinion
R_0[@]-no PI[^] animal present	Pert (1.2,3,5)	Personal opinion
Test sensitivity	Pert (89.6%,97.9%,99.5%)	(Frey et al., 1991; Mignon et al., 1992; Haines et al., 1992; Ellis et al., 1995; Sandvik and Krogsrud, 1995; Brinkhof et al., 1996; Deregt and Prins, 1998; Graham et al., 1998; Schreiber et al., 1999; Saliki et al., 2000; Plavsic and Prodafikas, 2001; Grooms and Keilen, 2002; Deregt et al., 2002; Ozkul et al., 2002; Kim and Dubovi, 2003; Cornish et al., 2005; Walz et al., 2005; Kuhne et al.,

		2005; Kennedy et al., 2006)
Vaccine Efficacy	Pert (0.42,0.845,1)	(Brownlie et al., 1995; Cortese et al., 1998; Patel et al., 2002; Zimmer et al., 2002; Dean et al., 2003; Kovacs et al., 2003; Fairbanks et al., 2004; Brock et al., 2006; Ficken et al., 2006a; Ficken et al., 2006b)
Abortion Risk	Pert (1.7%,10%,25%)	Expert survey*
TI$ Mortality Risk (the proportion of all TI$ calves that will die in one year due to BVDV)	Pert (1%,11%,32%)	Expert survey*
TI$ Morbidity Risk (the proportion of TI$ calves that will become morbid due to BVDV)	Pert (2%,24%,69%)	Expert survey*

weight lost by morbidity (kg)	Normal (15.9, 3.5) Truncate (0,)	(Wittum et al., 1994)
PI[^] mortality (the proportion of all PI[^] calves that will die in one year due to BVDV)	Pert (11%,44%,74%)	Expert survey[*]
PI[^] Morbidity Risk (the proportion of PI[^] calves that will become morbid due to BVDV)	Pert (23%,44%,64%)	Expert survey[*]
Probability of a PI[^] fetus due to infection during the risk period (vertical transmission risk)	Normal (82%, 8.2%) Truncate (0, 1)	(Stokstad and Loken, 2002)
Probability of an EED[!] due to infection during the risk period	Normal (16%,8%) Truncate (0,1))	(McGowan et al., 1993a; McGowan et al., 1993b)
Probability of a deformed calf due to infection during	Pert (3.2%,13.6%,30%)	Expert survey[*]

the risk period		
Duration of immunity from transient infection	50% for 1 year, 50% for 2 years	Personal opinion
Weaning weight kg (steers)	Normal (272,4.5) for 60 day breeding seasons Normal (263,4.5) for 100 day breeding seasons	Expert consensus based on available production data sources (Kansas Farm Management Association Enterprise data, and regional Standardized Performance Analysis data)
Weaning weight kg (heifers)	Normal (268,4.5) for 60 day breeding seasons Normal (259,4.5) for 100 day breeding seasons	
Price of 227-272 kg heifers ($/45 kg)	Normal (146.50, 14.67) with correlation of 0.9 between all prices in all years	
Price of 227-272 kg steers ($/45 kg)	Normal (164.03, 16.96) with correlation of 0.9 between all prices in all years	http://www.agmanager.info/livestock/marketing/database/default.asp - Monthly Feeder Cattle and Western Kansas Slaughter Cattle
Price of 272-318 kg heifers ($/45 kg)	Normal (137.77, 12.93) with correlation of 0.9 between all	

	prices in all years	Prices Accessed August 13, 2013
Price of 272-318 kg steers ($/45 kg)	Normal (149.75, 14.35) with correlation of 0.9 between all prices in all years	
Cost of test (/head)	Pert (2.5,4,6)	Survey[#]
Cost of vaccination (/head)	Uniform (0.75,1.5)	Survey[&]
Cost of labor ($/hour)	Pert (7.25,9,12)	Expert opinion
Treatment costs (/calf)	Pert (4,10,15)	Expert survey[&]

[*] A written survey of 5 veterinarians with field and research experience with BVDV.

[+] An oral survey of 5 veterinarians with field research with BVDV.

[#] A survey of regional diagnostic laboratories and private laboratories.

[&] A survey of online distributor prices.

[^] PI - persistent infection

[$] TI - Transient infection

[@] R_0 – Basic reproductive number of new cases arising from an infectious case in a susceptible population

[!] EED - Early Embryonic Death

Table 2: Herd profiles used in analysis of a model for bovine viral diarrhea virus in a cow-calf herd. Import numbers represent annual imports; stockers are imported to adjacent fields, where they represent a fenceline contact risk.

Herd	**number of breeding females**	**number and type of heifers imported**	**number of bulls imported**	**number of calves imported**	**number of stockers imported**
A3P	400	60 pregnant	4	0	100
A3N	400	60 non-pregnant	4	0	100
A4P	400	60 pregnant	4	0	0
A4N	400	60 non-pregnant	4	0	0
B3P	100	15 pregnant	1	0	100
B3N	100	15 non-pregnant	1	0	100
B4P	100	15 pregnant	1	0	0
B4N	100	15 non-pregnant	1	0	0
C3P	50	8 pregnant	1 every other year	0	100

C3N	50	8 non-pregnant	1 every other year	0	100
C4P	50	8 pregnant	1 every other year	0	0
C4N	50	8 non-pregnant	1 every other year	0	0

Table 3: Biosecurity and control strategies used in analysis of a model for bovine viral diarrhea virus in a cow-calf herd; in strategies involving testing of at least one category, all animals in the category were tested

Strategy	**Vaccination of breeding animals**	**Test Imported Adults**[*]	**Test Imported Calves and Calves of Pregnant Imports**	**Test all calves before breeding**	**Test Imported Stockers**
M					
N	**X**				
O		**X**			
P			**X**		
Q				**X**	
R					**X**
S		**X**	**X**	**X**	
T		**X**	**X**	**X**	**X**
U	**X**	**X**			
V	**X**		**X**		

W	**X**			**X**	
X	**X**				**X**
Y	**X**	**X**	**X**	**X**	
Z	**X**	**X**	**X**	**X**	**X**

[*] adults refers to breeding animals: heifers, cows, and bulls

Table 4: Risk analysis model-predicted probability (and 95% confidence interval) of exceeding target costs due to bovine viral diarrhea virus over 10 years in cow-calf herds. Herd profiles are defined in Table 2 and strategies are defined in Table 3. The target cost was $40,000 for all A herds, $7,500 for all B herds, and $2,500 for all C herds.

Strategy	**Herd profile**											
	A3P	**A3N**	**A4P**	**A4N**	**B3P**	**B3N**	**B4P**	**B4N**	**C3P**	**C3N**	**C4P**	**C4N**
M	99% (98-100%)	82% (80-84%)	98% (98-99%)	73% (71-75%)	88% (87-89%)	72% (70-74%)	81% (80-82%)	57% (55-59%)	76% (74-78)	62% (60-64%)	61% (59-63%)	40% (38-42%)
N	97% (96-98%)	71% (69-73%)	96% (95-97%)	67% (65-69%)	76% (74-78%)	54% (52-56%)	72% (70-74%)	47% (45-49%)	59% (57-61%	41% (39-43%)	50% (48-52%)	29% (27-31%)
O	99% (98-	50% (48-	98% (98-	27% (25-	87% (86-	51% (49-	80% (79-	25% (23-	76% (74-	55% (53-	60% (58-	26% (24-

	100%)	52%)	99%)	29%)	88%)	53%)	81%)	27%)	78%)	57%)	62%)	28%)
P	63% (61-65%)	N/A	47% (45-49%)	N/A	55% (53-57%)	N/A	31% (29-33%)	N/A	57% (55-59%)	N/A	30% (28-32%)	N/A
Q	77% (75-79%)	74% (72-76%)	75% (73-77%)	71% (69-73%)	65% (63-67%)	59% (57-61%)	55% (53-57%)	50% (48-52%)	74% (72-76%)	66% (64-68%)	57% (55-59%)	42% (40-44%)
R	99% (98-99%)	75% (73-77%)	N/A	N/A	82% (81-83%)	59% (57-61%)	N/A	N/A	100%	100%	N/A	N/A
S	17% (15-19%)	24% (22-	7% (6-8%)	15% (13-	30% (28-	31% (29-	13% (12-	14% (13-	74%[c] (72-	73% (71-	51% (49-	50% (48-

		26%)		17%)	32%)	33%)	14%)	15%)	76%)	75%)	53%)	52%)
T	9% (8-10%)	16% (14-18%)	N/A	N/A	100%	100%	N/A	N/A	100%	100%	N/A	N/A
U	96% (95-97%)	24% (22-26%)	95% (94-96%)	15% (13-17%)	74% (72-76%)	24% (22-26%)	69% (67-71%)	**11% (10-12%)**	59% [b] (57-61%)	**30% (28-32%)**	49% (47-51%)	**13% (12-14%)**
V	42% (40-44%)	N/A	35% (33-37%)	N/A	29% (27-31%)	N/A	18% (17-19%)	N/A	**33% (31-35%)**	N/A	**17% (16-18%)**	N/A
W	72% (70-74%)	70% (68-	71% (69-	69% (67-	57% (55-	51% (49-	51% (49-	47% (45-	97% (96-	97% (96-	96% (95-	95% (94-

		72%)	73%)	71%)	59%)	53%)	53%)	49%)	98%)	98%)	97%)	96%)
X	97% (96-97%)	68% (66-70%)	N/A	N/A	78% (77-79%)	52% (50-54%)	N/A	N/A	100%	100%	N/A	N/A
Y	7% (6-8%)	15% (14-16%)	**3%** **(2-4%)**	**11%** **(10-12%)**	**17%** **(16-18%)**	**18%** **(16-19%)**	**7%** **(6-8%)**	**9%** **(8-10%)**	100%	100%	100%	100%
Z	**4%** **(3-5%)**	**12%** **(11-13%)**	N/A	N/A	100%	100%	N/A	N/A	100%	100%	N/A	N/A

Strategies within columns with overlapping 95% CI are not significantly different

Herd Profiles within rows and herd size group with overlapping 95% CI are not significantly different

Numbers in bold are the lowest risk option for that column.

Table 5: Risk analysis model-predicted median (95% prediction interval) costs (reported as $1,000) due to bovine viral diarrhea virus over 10 years in cow-calf herds. Herd profiles are defined in Table 2 and strategies are defined in Table 3.

Strategy	**Herd profile**											
	A3P	**A3N**	**A4P**	**A4N**	**B3P**	**B3N**	**B4P**	**B4N**	**C3P**	**C3N**	**C4P**	**C4N**
M	209 (83-310)	134 (0-270)	207 (72-309)	118 (0-266)	28 (0-61)	21 (0-54)	26 (0-60)	15 (0-50)	9 (0-24)	6 (0-20)	7 (0-22)	0 (0-17)
N	136 (31-221)	76 (5-188)	135 (24-220)	71 (4-185)	16 (1-40)	10 (1-33)	15 (1-39)	5 (1-31)	4 (1-13)	**1** **(1-11)**	3 (1-13)	**1** **(1-10)**
O	210 (81-313)	40 (3-241)	207 (69-312)	**3** **(2-223)**	28 (1-61)	9 (1-42)	26 (1-60)	**1** **(1-34)**	9 (1-24)	4 (1-18)	6 (0-22)	0 (0-14)

P	95 (2-261)	N/A	26 (2-250)	N/A	11 (1-45)	N/A	**1** **(1-36)**	N/A	4 (1-19)	N/A	0 (0-15)	N/A
Q	101 (18-221)	99 (16-222)	99 (17-220)	97 (15-219)	14 (4-45)	13 (4-44)	10 (4-43)	7 (4-43)	4 (2-16)	3 (2-16)	3 (2-16)	2 (2-15)
R	211 (78-314)	123 (4-271)	N/A	N/A	30 (4-64)	20 (4-55)	N/A	N/A	11 (4-27)	5 (4-21)	N/A	N/A
S	**21** **(18-79)**	21 (18-126)	20 (18-61)	20 (18-120)	6 (4-20)	6 (4-24)	5 (4-15)	5 (4-21)	3 (2-10)	3 (2-11)	3 (2-8)	2 (2-9)
T	24 (22-67)	24 (21-124)	N/A	N/A	9 (8-20)	9 (8-26)	N/A	N/A	7 (6-12)	7 (6-13)	N/A	N/A

U	132 (26-223)	**8** **(7-149)**	130 (20-222)	8 (7-139)	15 (2-38)	**2** **(2-22)**	14 (2-37)	2 (2-18)	4 (1-14)	**1** **(1-8)**	2 (1-12)	**1** **(1-7)**
V	22 (7-170)	N/A	**8** **(7-165)**	N/A	**2** **(2-25)**	N/A	2 (2-22)	N/A	**1** **(1-9)**	N/A	**1** **(1-8)**	N/A
W	66 (21-150)	64 (20-148)	65 (20-150)	63 (20-147)	9 (5-30)	8 (5-29)	8 (5-29)	6 (5-28)	3 (2-11)	3 (2-11)	3 (2-10)	3 (2-10)
X	139 (29-224)	75 (9-190)	N/A	N/A	19 (5-43)	10 (5-36)	N/A	N/A	7 (5-17)	5 (5-14)	N/A	N/A
Y	24 (22-51)	24 (22-78)	*24* *(22-44)*	*24* *(22-77)*	6 (6-13)	6 (6-16)	*6* *(5-11)*	*6* *(5-15)*	3 (3-7)	5 (3-7)	***3*** ***(3-6)***	*3* *(3-6)*
Z	*28*	*28*	N/A	N/A	*10*	*10*	N/A	N/A	*7*	*7*	N/A	N/A

	(26-50)	*(25-81)*			*(9-15)*	*(9-19)*			*(7-10)*	*(7-11)*		

Numbers in bold were the lowest median cost for that column.

Numbers in italics were the lowest variability for that column.

Table 6: Correlation coefficient from a global sensitivity analysis of the 10-year cost of BVDV in a 400-head cow-calf herd importing 60 pregnant heifers, 4 bulls, and 100 stockers annually in 5 control scenarios. Values in bold were significantly correlated with the mean 10 year cost of BVDV.

Input Parameter	**Correlation coefficient**				
	M[1]	**N**[2]	**T**[3]	**Y**[4]	**Z**[5]
Abortion Risk	**0.58**	**0.51**	0.00	0.01	0.01
Price of 227-272 kg steers	**0.30**	**0.25**	0.00	-0.02	-0.01
Price of 227-272 kg heifers	**0.30**	**0.25**	0.00	-0.02	-0.01
Price of 272-318 kg steers	**0.29**	**0.24**	0.01	-0.01	0.01
Price of 272-318 kg heifers	**0.29**	**0.24**	0.01	-0.01	0.01
TI[$] **Mortality Risk**	**0.25**	**0.17**	0.06	0.06	0.03
PI[^] **Mortality Risk**	0.08	0.05	0.00	0.01	0.01
Calf prevalence	0.06	0.07	0.02	0.03	0.02
R_0[@] **for PI**[^] **animals**	-0.06	0.02	-0.01	-0.02	-0.02
PI[^] **Fetal Mortality Risk**	0.05	0.03	0.01	-0.01	0.00

TI[$] Morbidity Risk	0.04	0.03	0.03	0.02	0.02
Herd prevalence	0.04	0.05	0.06	0.02	0.03
Treatment costs/morbid calf ($)	0.04	0.05	0.03	0.01	0.01
Weight lost by Morbidity (kg)	0.04	0.02	0.02	0.01	0.02
Prevalence in cows	0.02	0.01	0.03	0.03	0.03
Vaccine Efficacy	0.01	**-0.21**	0.02	-0.05	-0.05
Probability of infection from fenceline contact	-0.01	-0.02	0.10	0.11	0.07
Fetal Malformation Risk	-0.01	-0.01	0.00	0.00	0.01
R_0[@] for TI[$] animals	-0.01	0.01	0.03	0.09	0.04
Unit cost of vaccination ($)	-0.01	0.01	0.03	**0.23**	**0.23**
Test Sensitivity	0.01	0.01	-0.05	-0.02	-0.04
Risk of Early Embryonic Death	0.01	0.00	0.01	0.02	0.01
Unit cost of test ($)	0.01	-0.02	**0.78**	**0.72**	**0.86**
Labor costs ($/hour)	0.00	-0.01	0.02	0.03	0.03
Stocker prevalence	0.00	0.00	0.00	0.03	-0.01

[1] No biosecurity or control programs for BVDV

[2] Annual vaccination of all adult animals

[3] Testing all imports (including stockers) and calves of imports and testing all calves before breeding

[4] Testing imports to the breeding herd (excluding stockers) and calves of imports and testing all calves before breeding, with annual vaccination of all adult animals

[5] Testing all imports (including stockers) and calves of imports and testing all calves before breeding, with annual vaccination of all adult animals

[^] PI - Persistent infection

[$] TI - Transient infection

[@] R_0 – Basic reproductive number of new cases arising from an infectious case in a susceptible population

Table 7: Results of a local sensitivity analysis showing the proportional change in the mean 10-year cost of BVDV in a 400-head cow-calf herd importing 60 pregnant heifers, 4 bulls, and 100 stockers annually in 5 control scenarios. Proportional changes were calculated taking the difference in mean costs for the scenario with the input parameter of interest fixed at the 95th and 5th percentiles and dividing by the mean cost for the scenario with all parameters allowed to vary within their distributions.

Input Parameter	**Range Used**	**Proportional Change**				
		M[1]	**N[2]**	**T[3]**	**Y[4]**	**Z[5]**
Abortion Risk (/year)	0.0448-0.1866	0.70	0.73	0.15	0.13	0.05
Price of 227-272 kg steers (/45kg)	$99.30-$155.10	0.41	0.39	0.07	0.05	0.02
Price of 227-272 kg heifers (/45kg)	$92.20-$140.50					
Price of 272-318 kg steers (/45kg)	$95.70-$142.90					
Price of 272-318 kg heifers (/45kg)	$91.90-134.40					
TI[$] Mortality Risk (/year)	0.0425-0.229	0.31	0.26	0.04	0.03	0.01
Vaccine Efficacy	0.612-0.952	N/A	-0.33	N/A	-0.05	-0.04

Unit cost of test ($)	$3.04-$5.20	N/A	N/A	0.43	0.36	0.40
Unit cost of vaccine ($)	$0.79-$1.46	N/A	0.02	N/A	0.10	0.09

[1] No biosecurity or control programs for BVDV, mean cost = $205,429

[2] Annual vaccination of all adult animals, mean cost = $133,445

[3] Testing all imports (including stockers) and calves of imports and testing all calves before breeding, mean cost = $27,632

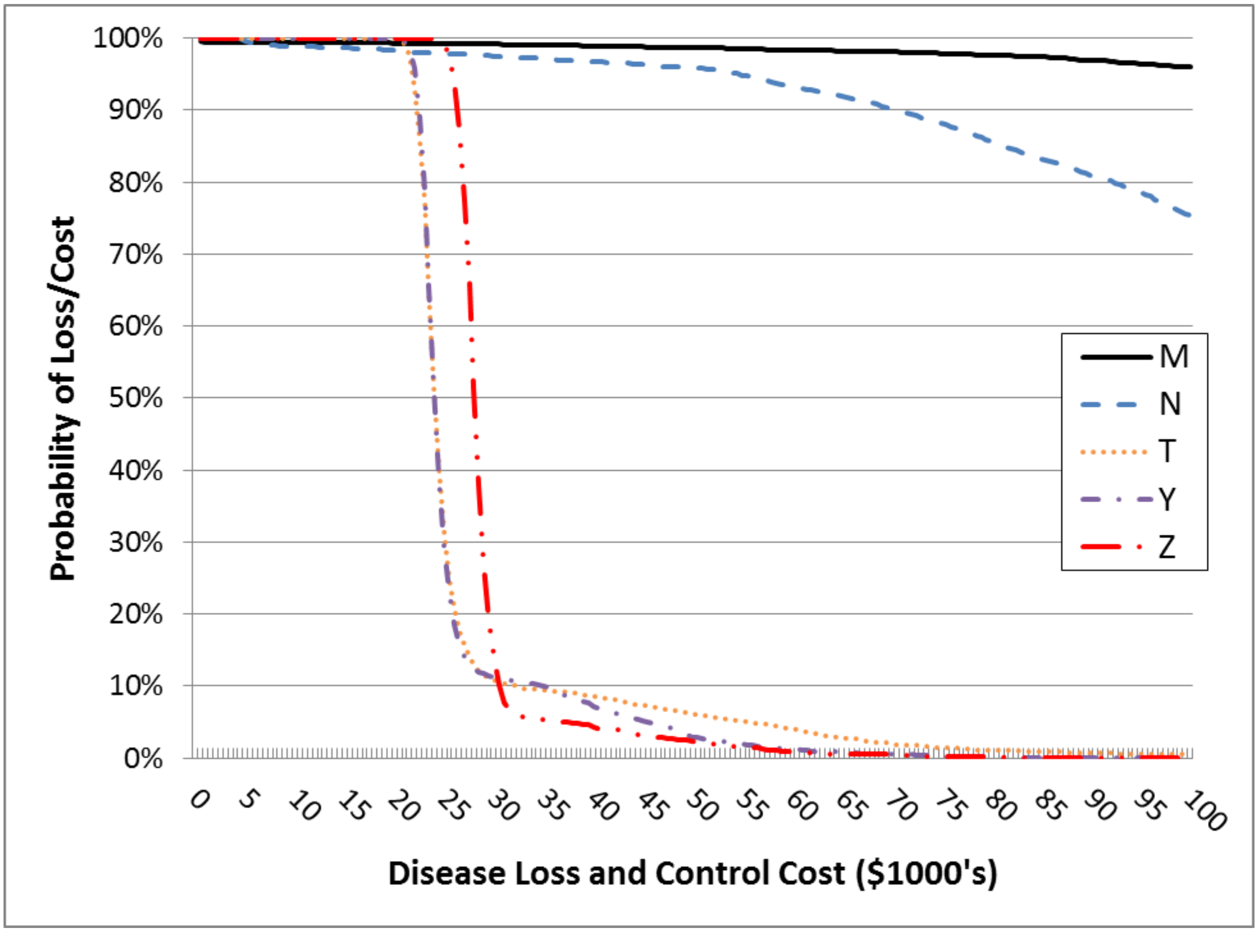
[4] Testing imports to the breeding herd (excluding stockers) and calves of imports and testing all calves before breeding, with annual vaccination of all adult animals, mean cost = $26,499

[5] Testing all imports (including stockers) and calves of imports and testing all calves before breeding, with annual vaccination of all adult animals, mean cost = $29,254

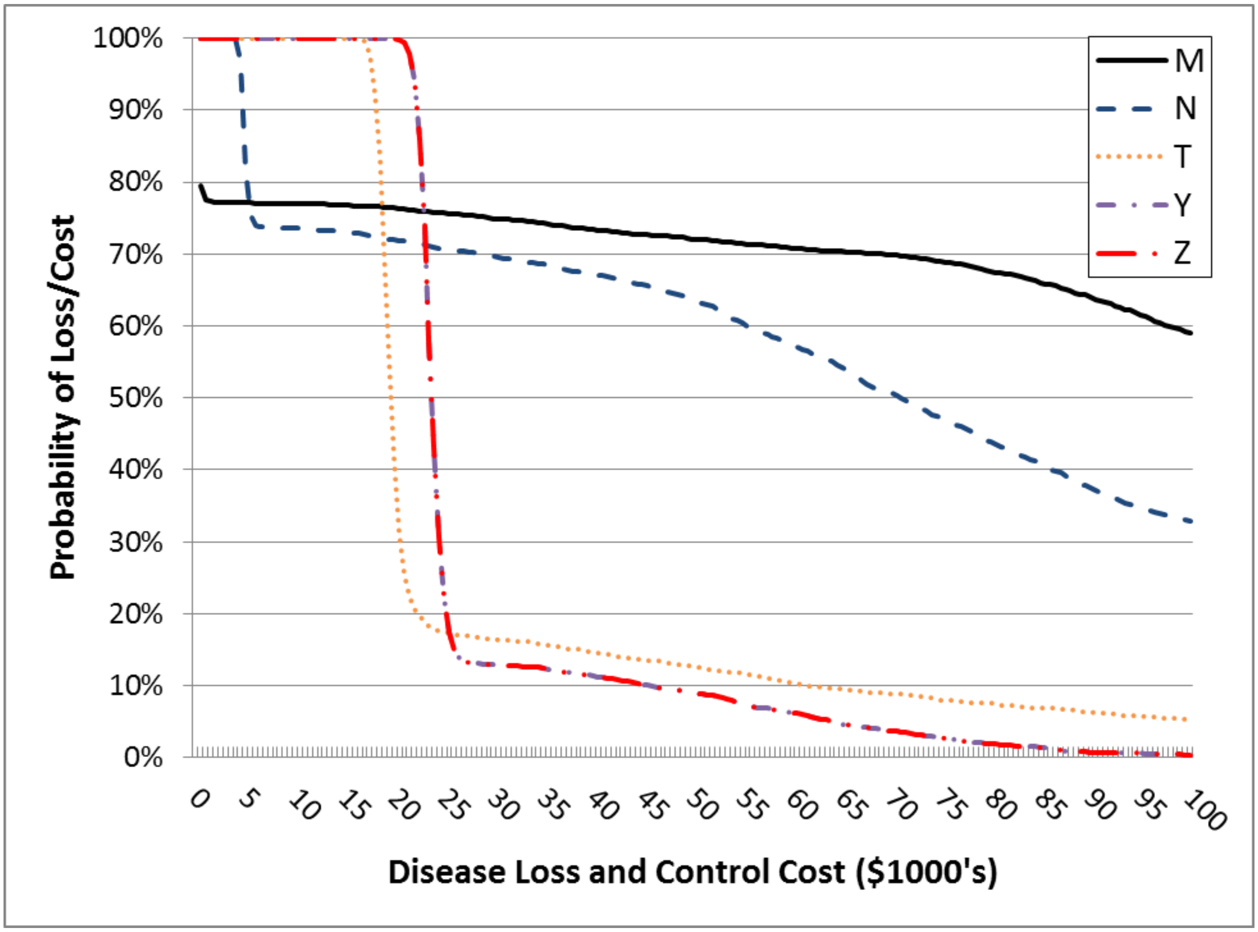
[$] TI - Transient infection

Figure 1 Descending Cumulative Probability curves for 10-year disease loss and control costs for 5 different control strategies used in the sensitivity analysis (each represented by a different line color and style). a) 400 head herd importing 60 pregnant heifers and 100 stockers; b) 400 head herd importing 60 non-pregnant heifers and no stockers

a



b


100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Probability of Loss/Cost
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
100
Disease Loss and Control Cost ($1000's)
M
N
T
Y
Z