Economic evaluation of 4 bovine leukemia virus control strategies for Alberta dairy farms

Alessa Kuczewski,^{1*} Henk Hogeveen,² Karin Orsel,³ Robert Wolf,⁴ Jada Thompson,⁵ Eldon Spackman,⁶ and Frank van der Meer¹

¹Department of Ecosystem and Public Health, University of Calgary, Calgary, AB, Canada T2N 4N1

²Business Economics Group, Wageningen University, Wageningen 6706 KN, the Netherlands

³Department of Production Animal Health, University of Calgary, Calgary, AB, Canada T2N 4N1

⁴Amt der Steiermärkischen Landesregierung, Graz 8010, Austria

⁵Department of Agricultural and Resource Economics, University of Tennessee, Knoxville 37996

⁶Department of Community Health Sciences, University of Calgary, Calgary, AB, Canada T2N 4Z6

ABSTRACT

Bovine leukemia virus (BLV) is a production-limiting disease common in North American dairy herds. To make evidence-based recommendations to Canadian dairy producers and their consultants regarding cost and financial benefits of BLV on-farm control, an economic model that takes the supply-managed milk quota system into account is necessary. Alberta-specific input variables were used for the presented analysis. A decision tree model program was used to evaluate economic aspects of decreasing a 40% BLV within-herd prevalence on dairy farms by implementing various control strategies over 10 yr. Investigated strategies were (1) all management strategies, including 3 options for colostrum management; (2) some management strategies; (3) test and cull; and (4) test and segregate. Each of these strategies was compared with a no control on-farm approach. The prevalence for this no-control approach was assumed to stay constant over time. Each control strategy incurred specific yearly cost and yielded yearly decreases in prevalence, thereby affecting yearly partial net revenue. Infection with BLV was assumed to decrease milk production, decrease cow longevity, and increase condemnation of carcasses at slaughter from cattle with enzootic bovine leukosis, thereby decreasing net revenue. Cows infected with BLV generated a yearly mean partial net revenue of Can\$7,641, whereas noninfected cows generated Can\$8,276. Mean cost for the control strategies ranged from Can\$193 to Can\$847 per animal over 10 yr in a 146-animal herd. Net benefits of controlling BLV on farm, as compared with not controlling BLV, per cow in a 146-animal herd over a 10-yr period for each strategy

was: Can\$1,315 for all management strategies (freezer); Can\$1,243 for all management strategies (pasteurizer); Can\$785 for all management strategies (powdered colostrum); Can\$1,028 for some management strategies; Can\$1,592 for test and cull; and Can\$1,594 for test and segregate. Consequently, on-farm BLV control was financially beneficial. Even though negative net benefits were possible and expected for some iterations, our sensitivity analysis highlighted the overall robustness of our model. In summary, this model provided evidence that Canadian dairy farmers should be encouraged to control BLV on their farm.

Key words: bovine leukemia virus, leukosis, economic evaluation, dairy economics

INTRODUCTION

Bovine leukemia virus (BLV) is a retrovirus that infects lymphocytes in cattle (Radostits et al., 2007) and inserts its genomic material into the host's genome, thereby causing lifelong infections. This virus is the causative agent of enzootic bovine leukosis (Radostits et al., 2007), characterized by development of tumors in a small subset of BLV-infected cattle. In the absence of a vaccine or treatment, prevention of infection is currently the only way to control spread of the virus (Rodríguez et al., 2011). Bovine leukemia virus is common in North American dairy cattle (Bartlett et al., 2014; Nekouei et al., 2015), with the herd prevalence in Alberta dairy herds reported to be ~90% (Scott et al., 2006). With only limited efforts to control BLV, the current herd prevalence is assumed to be at least this high. By causing tumors and negatively affecting infected cattle's immune system, BLV has adverse effects on animal welfare (Bartlett et al., 2014; Frie and Coussens, 2015) and economics of dairy farms due to premature death of dairy cows (Rhodes et al., 2003) and condemnation of carcasses after slaughter (Agricul-

Received July 6, 2018.

Accepted October 10, 2018.

*Corresponding author: alessa.kuczewski@ucalgary.ca

ture and Agri-Food Canada, 2017c). In addition, BLV infection can decrease milk production (Erskine et al., 2012a; Ott et al., 2003; Sargeant et al., 1997) and cow longevity (Brenner et al., 1989; Bartlett et al., 2013). These deleterious effects of BLV infection on the main economic determinants of a dairy farm highlight the importance of this virus infection, not only for dairy farms but also for the dairy industry as a whole (Pelzer, 1997; Trainin and Brenner, 2005). A high BLV prevalence, combined with its negative effects, make implementation of on-farm control programs desirable (Bartlett et al., 2014).

Bovine leukemia virus control programs generally use interventions to reduce virus transmission, thereby preventing new infections. Ultimately, test-positive cattle can be replaced with test-negative ones, thereby decreasing the within-herd prevalence. This can be achieved by implementing best management practices that prevent new infections, through segregating or culling infected cattle or a combination of these methods (Rodríguez et al., 2011; Bartlett et al., 2014). Regardless, on-farm disease control investments will be weighed against (economic) advantages of eradication in a farmer's decision process (Ritter et al., 2017). Economic evaluations highlighting economic consequences of a BLV infection have been published, but vary in the economic losses taken into account (Chi et al., 2002; Ott et al., 2003; Rhodes et al., 2003). Unlike the free-market system for dairy production in the United States and many other countries, the Canadian dairy industry is a supply chain-managed system with production quotas. Dairy farmers in a free market system often keep the number of cows on their farms constant due to space constraints, resulting in a relatively constant milk production. However, under these conditions milk production could potentially be increased by breeding efforts, disease control, and feed adjustments, for example; this would result in a direct increase in revenue as well as in a decrease in cost. This is not applicable to supply chain-managed systems, as the amount of milk that is produced has to stay constant, whereas the number of cows to reach a production goal can be decreased, thereby decreasing cost. The net revenue is thus only indirectly affected. For this reason, an economic model relevant for the Canadian dairy industry has to take the supply chain-managed system into account. Additionally, only 1 evaluation considered cost for a test and management-based control program (Rhodes et al., 2003). A thorough comparison of different control program variations and their economics is not yet available.

The objective of our study was to estimate economic impacts of BLV infection and its control. We modeled partial cost and net revenue for 4 variations of

a BLV control program, using a decision tree model program to simulate effects of various on-farm BLV control strategies on the within-herd BLV prevalence and, thereby, on the farm's partial net revenue. Furthermore, all control programs were compared with no on-farm control to estimate the net benefit of the BLV control strategies.

MATERIALS AND METHODS

Our economic evaluation examined partial cost and net revenues related to an on-farm BLV control program. The evaluation was based on Canadian guidelines for economic evaluation of health technologies (Canadian Agency for Drugs and Technologies in Health, 2017). A model was created with TreeAge Pro 2017 (TreeAge Software, Inc., Williamstown, MA). Calculation outputs were further analyzed in Excel (365 ProPlus, Microsoft Corp., Redmond, WA). The perspective adopted was that of an average Alberta dairy farmer. Input data were obtained from publications and reports produced by Alberta Milk (Edmonton, Alberta, Canada), CanWest DHI (Guelph, Ontario, Canada), and the Government of Canada. Whenever possible, Alberta-specific input data were used. During the analyzed period, the within-herd prevalence of BLV was modeled to change yearly due to the chosen control strategy and to stay constant for no implemented control. Based on this prevalence, partial cost and net revenues were calculated at the end of each year.

Modeling

The model was constructed to allow for comparison of each strategy's outcome after strategies were implemented. A detailed list of model variables and inputs is provided in Table 1. The initial decision node branched off to 4 control programs, as well as to a no-control program option. Within each strategy, a Markov model with 10 stages (each stage representing 1 yr) was applied to mimic a 10-yr course of on-farm BLV control. The model was analyzed with Monte Carlo simulation (microsimulations), running 5,000 trials. Results were summarized as mean per individual animal in a 146-adult cow herd (average size of Alberta dairy herds). The range of variation for these results can be found in Table A1 of the Appendix. Average partial cost and net revenues for each strategy were examined. The initial within-herd prevalence was the same for all strategies. Every cycle, the within-herd prevalence was influenced by 2 events: (1) depending on the control strategy, the within-herd prevalence was reduced accordingly; and (2) an infected animal could be purchased and introduced into the herd as a replace-

ment animal. The probability for the latter event to happen was calculated as the probability of introducing an infected animal = fraction of open herds $\times$ number of cows introduced per year $\times$ herd prevalence in Alberta $\times$ within-herd prevalence. The probability not to introduce an infected animal was $1 - (\text{probability of introducing an infected animal})$. If an infected animal was introduced, the change in prevalence equaled (prevalence decrease according to strategy) $+ (1/\text{herd size})$. However, if no infected animal was introduced, the prevalence was reduced by the strategy's assigned yearly reduction in prevalence (Table 2). This change in prevalence was tracked over time and kept within limits of 0 to 100% to enable a continuous reduction in prevalence. The resulting within-herd prevalence at the end of each cycle was the basis for calculating each strategy's partial cost and net revenue for that cycle. In addition, the model included the assumption that 1 management strategy was adhered to throughout the 10-yr period, thereby enabling comparison of each strategy's outcome.

Considered Strategies for BLV Control and the Respective Partial Cost

Various options are available to control BLV transmission. We considered the most commonly recommended strategies (Rodríguez et al., 2011; Bartlett et al., 2014), namely (1) testing and implementing best management practices, split up according to 3 different options for colostrum management (freezing or pasteurizing colostrum, or using powdered colostrum replacer); (2) testing and implementing a subset of best management strategies; (3) testing and culling; and (4) testing and segregating.

For all strategies, sensitivity and specificity of all diagnostic tests were assumed 100% (Monti et al., 2005; Walsh, 2013; Nekouei et al., 2016). As a testing protocol for all strategies, we tested all animals in the adult herd in the first year of the model, whereas only negative animals and replacement animals were retested in the following years. Test-positive animals were considered positive for the rest of their lives, as they cannot clear infection (Radostits et al., 2007).

Cost for each strategy, including expenses for testing, as well as investments made for implemented measures, are detailed below.

The strategy, all management strategies considered all commonly recommended best management practices that aim at preventing transmission of BLV between animals. All management strategies included fly control, disinfection of equipment, the purchase and use of an electric dehorner, single-use of needles, and single use of examination sleeves for AI as well as transrectal

pregnancy diagnosis (palpation or ultrasonography). Using a new examination sleeve before a rectal examination on each cow resulted in the veterinarian taking longer to conduct regular reproductive examinations. As veterinarians are commonly paid on an hourly basis for these visits, an additional 30 s (examination sleeve removal and replacement) per cow were added. Moreover, colostrum management was an important part of this strategy. Three common variations are used for prevention of BLV transmission: (1) freezing colostrum [all management strategies (freezer); Kanno et al., 2014] whereby the purchase of a freezer is required; (2) pasteurizing colostrum [all management strategies (pasteurizer)], requiring the purchase of a pasteurizer; or (3) feeding powdered colostrum replacer instead of fresh colostrum [all management strategies (powdered colostrum); Godden, 2008]. The cost for the purchased freezer or pasteurizer were assumed invested in the first year of the analyzed period. Because implementing control measures might cause prolongation of daily routines, a daily increase of labor for 30 min was assumed.

The strategy some management strategies represented a subset of all management strategies and was therefore assumed less effective, although less labor-intensive and expensive than all other options. The considered best management practices were the same as for all management strategies, excluding increased fly control and colostrum management.

The next possibility was the test-and-cull strategy. In this strategy, emphasis was placed on slaughtering test-positive cattle as part of the regular turnover of the herd. To prevent virus transmission and new infections, best management practices [see all management strategies (freezer)] were assumed implemented. In addition, culling a BLV-positive cow over a BLV-negative cow could potentially result in culling the better producing animal. Therefore, an opportunity cost was added.

The test-and-segregate strategy implied that test-positive animals were housed separately from test-negative animals, combined with measures of the all management strategies (freezer) option, thereby limiting the probability of spreading virus within the herd. This strategy considered cost for structural changes in the barn to facilitate segregating positive from negative animals. This cost was also assumed invested in the first year and added to the all management strategies (freezer) expenses.

All partial cost were discounted by a rate of 1.5% (Canadian Agency for Drugs and Technologies in Health, 2017) to account for the time value of money. The last possibility was no implementation of any of the above-mentioned best management practices aimed at preventing transmission of the virus (no control). This was not assigned any cost.

Table 1. Model variables and inputs

Parameter	Reference	Comments	Model Input	Low	High
Additional equipment for test and segregate	Farm supply store, May 2017	4 additional gates; shovel, broom: 3 each over 10 yr; 1 additional	2,000	1,000	4,000
Additional labor due to all management strategies	Government of Alberta, 2015	0.25 h/d	1,838.69	1,559.46	2,145.28
Additional labor due to some management strategies	Government of Alberta, 2015	0.1 h/d	735.475	623.78	858.115
Average carcass weight (kg)	Agriculture and Agri-Food Canada, 2016	No. of cows/no. of farms in Alberta	339	304	384
Average herd size in Alberta	2017a,b; CanWest DHI, 2017		146	92	264
Average value for 1 calf	Heikkilä and Van Biert, 2010, 2012; Van Biert, 2016	50% chance of heifer or bull calf; (heifer calf value + bull calf value)/2	390.46		
Breeding cost per animal per year	Van Biert, 2016				
Cost for manure removal per cow per year	Boyle, 2015; Manitoba Agriculture, Food and Rural Development, 2009, 2015		89.91	73.83	90
Cost for raising replacement heifers	Lee, 2015; Ontario Ministry of Agriculture, Food and Rural Affairs, 2010		120.45	16.67	135.51
Discount rate	Canadian Agency for Drugs and Technologies in Health, 2017		2,252	1,650	3,000
Disinfectant to clean instruments	Farm supply store, May 2017		0.015	0	0.03
Electric dehormer	Farm supply store, May 2017	99% isopropyl alcohol, 2 bottles per yr	50.4	0	100.8
Fly control	Farm supply store, May 2017	2 electric dehorners over 10 years	168 × 2	168	504
Freezer	Compliance store, May 2017	Pour-on treatment, twice per animal per year	502.24	100	900
Gloves	Farm supply store, May 2017	3 freezers (Can\$500 each) over 10 yr	1,000	0	1,500
Herd health	Canadian Veterinary Medical Association and Alberta Veterinary Medical Association, 2017	3 gloves per cow per year	68.94	45.96	91.92
Herd prevalence in Alberta	Scott et al., 2006	Cost for pregnancy diagnosis by veterinarian; 1 examination per cow per year, additional 30 s per cow to change examination glove	2.23	0	4.45
Hazard ratio	Bartlett et al., 2013	Bovine leukemia virus-infected animals are more likely to leave the herd than uninfected animals	0.87	0.1	1
Labor cost per cow per year	Heikkilä and Van Biert, 2010, 2015; Van Biert, 2016		1,102.39	982.88	1,150.01
Maintenance feed	Manitoba Agriculture, Food and Rural Development, 2015; Van Biert, 2016		302.37	264.36	3,198.6
Milk price (Can\$/L)	Alberta Milk, 2016, 2017				
Milk production per cow per year	CanWest DHI, 2017		0.8138	0.6997	0.8446
Needles	Farm supply store, May 2017	3 needles per cow per year	10,339	9,847	10,662
Opportunity cost	Expert opinion	Can\$100 per bovine leukemia virus-positive cow slaughtered over a different cow	131.40	87.6	175.2
Pasteurizer	Golden Calf Company (Bloomer, WI; personal communication with customer support); Milk Taxi (Holm & Laue GmbH & Co. KG, Westerrönnfeld, Germany; personal communication with Chinook Dairy Service Ltd., Chilliwack, BC)	1 pasteurizer over 10 yr	100	0	200
Powdered colostrum	Farm supply store, May 2017	2.5 bags per calf	1,150	741.8	1,850
			52.48	20.99	62.97

Continued

Table 1 (Continued). Model variables and inputs

Parameter	Reference	Comments	Model Input	Low	High
Purchase rate	Dubé et al., 2011; Van Biert, 2016	Open herds × no. of cows purchased per year	0.79	0	2
Reduced milk production due to bovine leukemia virus infection	Brenner et al., 1989; D'Angelino et al., 1998; Emanuelson et al., 1992; Ott et al., 2003; Tiwari et al., 2007		0.03	0	0.11
Replacement rate	CanWest DHI, 2017		38.9	0.25	0.452
Risk of a slaughtered animal to suffer from lymphosarcoma	Schwartz and Levy, 1994; CanWest DHI, 2017	Risk of developing lymphosarcoma when infected with bovine leukemia virus × percentage of cows older than 3 d lactation × within-herd prevalence	Values dependent on the respective within-herd prevalence		
Slaughter value (Can\$/kg)	Statistics Canada, 2017		2.08	1.3	3.14
Testing	CanWest DHI (Guelph, ON, Canada; personal communication with customer support)		8	0	15
Veterinary cost per cow per year	Heikkilä and Van Biert, 2010; Manitoba Agriculture, Food and Rural Development, 2015; Van Biert, 2016		166.97	137.11	175.29
Within-herd prevalence	Table 2		0.4	0	1

Table 2. Effectiveness or reduction in bovine leukemia virus within-herd prevalence per year for each strategy

Strategy	Reference	Change in prevalence	Low	High
All management strategies	Expert opinion	25%	0	50%
Some management strategies	Expert opinion	15%	0	50%
Test and cull	CanWest DHI, 2017; Government of Canada, 2017	$[(\text{within-herd prevalence} \times \text{herd size}) - (\text{voluntary culling rate} \times \text{herd size})] / \text{herd size}$	NA ¹	NA
Test and segregate	Bartlett et al., 2013; CanWest DHI, 2017	$[(\text{within-herd prevalence} \times \text{herd size}) - (\text{replacement rate} \times \text{herd size})] / \text{herd size}$	NA	NA
No control	Assumption: no change over time	0	NA	NA

¹Value depends on result of displayed formula.

Yearly Reduction in Within-Herd Prevalence for Each Strategy (Effectiveness)

We found no recent numbers regarding average within-herd prevalence of BLV in Alberta. Therefore, initial within-herd prevalence for all strategies was assumed to be 40%. We were able to confirm this estimate by analyzing a convenience sample made available by CanWest DHI (Guelph, ON, Canada). The median within-herd prevalence of BLV in this data set was approximately 39% (Table 3).

The reduction in within-herd prevalence depended on the control strategy considered. Values were based on literature when possible and on expert opinion if no literature was available.

The within-herd prevalence was assumed to decrease by 25% annually for all management strategies. We assumed that some management strategies would be less effective than all management strategies. The annual decrease in within-herd prevalence was therefore assumed to be 15%. Generally, disease control efforts are more effective in the early stages, whereas the effectiveness tends to decrease with the within-herd prevalence; therefore, we deemed a nonlinear decrease in prevalence appropriate.

For the test-and-cull strategy, a yearly decrease in prevalence as part of the regular turnover of the herd was assumed (CanWest DHI, 2017; Government of Canada, 2017). On average, 39.6% of a dairy herd is replaced every year (CanWest DHI, 2017). This turnover-rate consists of voluntary and involuntary culling of animals (Ansari-Lari et al., 2012); however, only the voluntary culling rate could be influenced by the producer's personal decisions. The voluntary culling rate accounted for 24.5% of the total turnover-rate (Government of Canada, 2017). Therefore, if a producer decided to make BLV the only reason for voluntary culling, a maximum of 9.7% of the herd could be replaced based on BLV infection each year (VolCullrate). Assuming that no new infections occur and that herd size and culling rates stay constant, this allowed for 14.6 animals of the herd to be culled because of BLV, every year, thereby reducing the within-herd prevalence (FinPrev).

Therefore, the number of infected animals was assumed to decrease consistently every year:

$$\begin{aligned} \text{Decrease in prevalence for test and cull} = & \\ & [(FinPrev \times \text{herd size}) \\ & - (\text{VolCullrate} \times \text{herd size})] / \text{herd size.} \end{aligned}$$

The annual reduction in prevalence for the test-and-segregate strategy was calculated as follows: Housing BLV-positive and BLV-negative animals in separate pens seemingly prevents new infections efficiently (Johnson et al., 1985). However, the within-herd prevalence would not decrease immediately, as the infected animals would not leave the herd as soon as they were identified. The replacement of BLV-positive animals with BLV-negative animals would result in a decrease in within-herd prevalence over time. The yearly turnover rate of the herd was assumed to stay constant (39.6%, CanWest DHI, 2017); however, BLV-positive animals were found to be 23% more likely than their BLV-negative herd mates to leave the herd (Bartlett et al., 2013). Therefore, increasing the yearly risk of being culled to 48.7%. These assumptions resulted in the following annual decrease in within-herd prevalence for the test-and-segregate strategy:

$$\begin{aligned} \text{Decrease in prevalence for test and segregate} = & \\ & [(\text{within-herd prevalence} \times \text{herd size}) \\ & - (\text{risk for culling} \times \text{within-herd prevalence} \\ & \times \text{herd size})] / \text{herd size.} \end{aligned}$$

For the option of not implementing any control strategy, the within-herd prevalence was assumed to remain constant at 40% over time.

We assumed that new infections in the adult herd were prevented by assuming perfect compliance with prevention protocols, as well as no fly or contact transmission. Additionally, animals that were leaving the herd were assumed to be replaced by test negative animals, except for cow purchases (see above), thereby reducing within-herd prevalence.

Table 3. Prevalence estimation based on bovine leukemia virus herd tests conducted by CanWest DHI (Guelph, ON, Canada; results for 90% of herd tested)

Item	Province					
	All	Alberta	1	2	3	4
No.	263	37	165	28	11	22
No. positive	236	31	148	26	10	21
Herd prevalence	0.90	0.84	0.90	0.93	0.91	0.95
Median within-herd prevalence	49.0	39.5	50.0	52.4	68.4	31.5
Range within-herd prevalence	1.69–100	6.67–91.11	2.0–88.1	1.69–90.63	44.64–88.04	1.82–100

Partial Net Revenues

Fixed expenditures (e.g., building maintenance) were not included in the calculations; therefore, partial net revenues were calculated for all strategies. These were calculated as mean per animal in a 146-animal herd for a 10-yr period. Calculated partial net revenues were the sum of partial net revenues of uninfected cattle (revenue UI) and partial net revenues of infected cattle (revenue I). The probability of being infected or uninfected was represented by the prevalence and incorporated into the estimate as

$$(1 - \text{prevalence}) \times \text{revenue UI} \\ + \text{prevalence} \times \text{revenue I.}$$

Revenues for uninfected cattle were assumed to be generated by milk and slaughter revenue, but reduced by raising replacement animals:

$$\text{Revenue UI} = (\text{milk production} \times \text{milk price}) \\ + [\text{replacement rate} \times \text{carcass weight} \\ \times \text{slaughter value} \times (\text{HR} - 1)] \\ - [\text{replacement rate} \times \text{heifer cost} \times (\text{HR} - 1)],$$

where milk production represented the average per cow per year, milk price the value per liter, replacement rate the percentage of a herd replaced annually, carcass weight the average carcass weight of a cow, slaughter value the price per kilogram, and heifer cost the cost of raising replacement heifers. The hazard ratio (**HR**) is the higher probability to be culled of infected animals relative to uninfected animals, and $(\text{HR} - 1)$ is the probability of uninfected animals to be culled, which is less likely than infected animals.

Partial net revenue for infected animals was also assumed to be represented by milk and slaughter revenues and reduced by cost related to raising replacement animals. Additionally, partial net revenue was assumed to be decreased by reduced milk production (Brenner et al., 1989; Emanuelson et al., 1992; Ott et al., 2003) and reduced longevity (Bartlett et al., 2013) of infected animals, as well as by development of enzootic bovine leukosis (Schwartz and Levy, 1994; CanWest DHI, 2017) and subsequent condemnation of affected carcasses. However, because Canada's dairy industry is based on a milk quota system, the revenue of selling milk was assumed to stay constant over time and not directly affected by BLV within-herd prevalence. Nevertheless, a farm's net revenue was decreased, due to indirect cost, because of BLV-related reductions in milk production. This was due to the cost of additional feed, housing,

and maintaining more cattle to generate the same amount of milk as in an uninfected herd. Additionally, because infected cattle were assumed to be replaced by uninfected cattle, the replacement animal only had to produce 97% (3% less milk production of infected animals, see below) of the amount of milk a healthy, uninfected cow would generate in order to produce the same amount of milk as an infected cow. Therefore, partial net revenue generated by infected animals was calculated as

$$\text{Revenue I} = (\text{milk production} \times \text{milk price}) \\ + (\text{replacement rate} \times \text{carcass weight} \\ \times \text{slaughter value} \times \text{HR}) - (\text{replacement rate} \\ \times \text{carcass weight} \times \text{slaughter value} \times \text{lymphosarcoma}) \\ - (1 - \text{milk loss}) \times (\text{replacement rate} \times \text{heifer cost} \\ \times \text{HR}) - [\text{milk loss} \times (\text{dry feed} \\ + \text{breeding} + \text{veterinary cost} + \text{labor} \\ + \text{manure removal} + \text{calf value})],$$

where dry feed represents the feed necessary for maintenance of a dry cow, breeding is the average cost for breeding a cow per year, veterinary cost is the average annual cost related to veterinary expenses per animal, labor is the average annual labor necessary per animal, manure removal is the annual average cost for disposing of one animal's manure, and calf value is the value of a calf that could be born and sold if the number of animals would not decrease. As the prevalence of BLV changes in each stage, revenue changes accordingly. All revenues were discounted by a rate of 1.5% (Canadian Agency for Drugs and Technologies in Health, 2017).

The difference between the different control strategies and the no control strategy was calculated as

$$\text{Net benefit} = \text{partial net revenue (control strategy)} \\ - \text{cost (control strategy)} \\ - \text{partial net revenue (no control)}.$$

This represents the net benefit producers implementing BLV control would accumulate as opposed to producers who would not control BLV on their farm. Moreover, for the various control strategies, net benefit per year per cow was calculated.

Within-Herd Prevalence and Partial Net Revenue

Herd-based yearly partial net revenues were examined according to different levels of the within-herd preva-

Table 4. Results of simulation, comparing 4 on-farm bovine leukemia virus control strategies (all results are presented in Can\$)

Item	Strategy				
	No control	All management strategies (freezer)	All management strategies (pasteurizer)	All management strategies (powdered colostrum)	Some management strategies
Mean cost per animal ¹ over 10 yr	0	317	389	847	193
Mean partial net revenue ² per animal ¹ over 10 yr	82,248	83,563	83,491	83,033	83,276
Average net benefit ³ per year per animal ¹	—	131.5	124.3	78.5	102.8
Partial net revenue ² per animal ¹ over 10 yr: scenario (infected cattle can be introduced every year)	82,248	83,539	83,467	83,009	83,246
Partial net revenue ² per animal ¹ over 10 yr: scenario (no infected cattle are introduced)	82,248	83,593	83,521	83,063	83,314

¹Per animal in a 146-animal herd, 40% initial within-herd prevalence.²Partial net revenue = partial net revenue (strategy) – cost (strategy).³Net benefit = partial net revenue (strategy) – cost (strategy) – partial net revenue (no control).

lence. Instead of examining revenue per head within a herd, the partial net revenue for the entire herd for 1 yr was calculated as herd-based partial net revenue = number of infected animals × revenue I + number of uninfected animals × revenue UI.

Variability and Uncertainty

A one-way sensitivity analysis was performed for all input variables as provided in Table 1. Combined with the comparison of the net benefit for each control strategy, this facilitated identification of variables with the main sources of uncertainty and the largest effect on the economically preferred choice.

Scenario Analysis

To show the effect of having an open herd compared with a closed herd, 2 scenario analysis were conducted. First, a closed herd scenario, where no animals are purchased and therefore no infected animals are introduced into the herd. Second, an open herd scenario, where animals are purchased and introduced into the herd every year.

RESULTS

Cost

Mean cost in the first year for each control strategy per animal in a 146-animal herd, excluding cost of testing but including investments for hardware (e.g., dehorner, pasteurizer, barn alterations), were Can\$29 for all management strategies (freezer), Can\$101 for all management strategies (pasteurizer), Can\$75 for all management strategies (colostrum), Can\$11 for some management strategies, Can\$39 for test and cull, and Can\$55 for test and segregate. Mean cost for the following years for each control strategy per animal in a 146-animal herd, excluding cost of testing, were Can\$20 for all management strategies (freezer), Can\$20 for all management strategies (pasteurizer), Can\$73 for all management strategies (colostrum), Can\$9 for some management strategies, Can\$30 for test and cull, and Can\$33 for test and segregate. The cost for testing was added annually. Mean costs per animal over a 10-yr period including testing in a 146-animal herd are shown in Table 4. The range of variation is shown in Table A1 of the Appendix.

Partial Net Revenue

Based on described formulas, annual mean partial net revenue of an infected cow was Can\$7,641, whereas

Table 5. Annual partial net revenue based on within-within herd prevalence of bovine leukemia virus infection in Can\$ per 146-animal herd

Prevalence	1 – Prevalence	Number of animals infected	Number of animals uninfected	Partial net revenue ¹ infected animals	Partial net revenue uninfected animals	Total partial net revenue
1	0	146	0	1,115,647	0	1,115,647
0.9	0.1	131.4	14.6	1,004,082	120,823	1,124,905
0.8	0.2	116.8	29.2	892,517	241,647	1,134,164
0.7	0.3	102.2	43.8	780,953	362,470	1,143,423
0.6	0.4	87.6	58.4	669,388	483,294	1,152,682
0.5	0.5	73	73	557,823	604,117	1,161,940
0.4	0.6	58.4	87.6	446,259	724,941	1,171,199
0.3	0.7	43.8	102.2	334,694	845,764	1,180,458
0.2	0.8	29.2	116.8	223,129	966,588	1,189,717
0.1	0.9	14.6	131.4	111,565	1,087,411	1,198,975
0	1	0	146	0	1,208,234	1,208,234

¹Partial net revenue = revenue generated by infected/uninfected animals, respectively, per year.

mean partial net revenue of an uninfected cow was Can\$8,276. Partial net revenue for each strategy over a 10-yr period per animal in a 146-animal herd is provided in Table 4. The range of variation is shown in Table A1 of the Appendix

Herd-Based Partial Net Revenue

The herd-based partial net revenue per year was found to be between Can\$1,115,647 for a 100% within-herd prevalence and Can\$1,208,234 for a 0% within-herd prevalence for a herd with 146 animals. A list of levels of the within-herd prevalence from 0 to 100% in 10% increments with matching herd based partial net revenue is provided in Table 5.

Net Benefit

Mean net benefit per cow in a 146-animal herd over a 10-yr period compared with no control for each strategy

was Can\$1,315 for all management strategies (freezer), Can\$1,243 for all management strategies (pasteurizer), Can\$785 for all management strategies (powdered colostrum), Can\$1,028 for some management strategies, Can\$1,592 for test and cull, and Can\$1,594 for test and segregate (Table 4).

Variability and Uncertainty

The test-and-segregate strategy was the preferred strategy for most variables in the one-way sensitivity analysis. Test and cull was the most common alternative. Increasing the yearly change in prevalence for one strategy at a time allowed us to change the preferred strategy to the respective control strategy. Similarly, an initial within-herd prevalence of 0% made all strategies less efficient than no implementation of control strategies on farm. An initial within-herd prevalence of 10% resulted in a positive net revenue for all strategies, except for all management strategies (pasteurizer) and all

Figure 1. Tornado diagram of sensitivity analysis for variables with the highest effect on net revenues (net revenue-cost) of the test-and-segregate strategy. “Years” was excluded due to high range of results (Can\$16,191 to Can\$117,421 for low and high variable inputs for the test-and-segregate strategy): the effect of this variable would have decreased visibility of the range of other variables.

management strategies (colostrum). All management strategies (pasteurizer) was shown to be economically beneficial for a within-herd prevalence of 20%, whereas all management strategies (colostrum) resulted in a positive net benefit for a within-herd prevalence of 30%.

Through sensitivity analysis, the following variables had the biggest effect on mean net revenue (in order of importance): years of implementation of on-farm control (Can\$16,191 to Can\$117,421 for low and high variable inputs for the test-and-segregate strategy, respectively); milk price (Can\$71,783 to Can\$87,097); average milk production per cow per year (Can\$79,749 to Can\$86,529); HR (Can\$89,188 to Can\$82,861); cost to raise replacement heifers (Can\$84,495 to Can\$83,031); slaughter value (Can\$83,557 to Can\$84,232); initial within-herd prevalence (Can\$84,108 to Can\$83,441); replacement rate (Can\$84,267 to Can\$83,649); herd size (Can\$83,659 to Can\$83,982), and cost for testing (Can\$83,951 to Can\$83,747; Figure 1).

Variables representing years of implementation of on-farm control, initial within-herd prevalence, as well as variables representing the main drivers for the annual reduction in within-herd prevalence (e.g., HR for test and segregate) for each strategy were additionally able to generate a negative net benefit, when entering assigned low values (Table 1).

Scenario Analysis

According to results of the scenario analysis, partial net revenue after 10 yr per animal in a 146-animal herd averaged Can\$41 (range = 22–68) higher when no infected animals were introduced as opposed to introducing animals (1.39 animals per year; Van Biert, 2016) with a 54% chance of being infected (90% herd prevalence, with average 40% within-herd prevalence) into the herd every year (Table 4).

DISCUSSION

The present model resulted in similar findings as other economic analysis in that BLV-infected cattle yielded lower partial net revenue than uninfected cattle (Chi et al., 2002; Ott et al., 2003; Rhodes et al., 2003). All of these reports and others (Pelzer, 1997; Trainin and Brenner, 2005) concluded that BLV caused economic losses. However, we found wide variation in factors that were taken into account and, consequently, in monetary loss attributed to BLV. Chi et al. (2002) only considered treatment and mortality losses due to BLV. In addition, Ott et al. (2003) considered mainly milk losses due to BLV infection. Rhodes et al. (2003) considered subclinical and clinical losses of BLV and

examined, in detail, the cost of BLV infection. However, those authors only considered a free market milk price and did not take a quota system into account. Our analysis did not examine subclinical and clinical losses of BLV in as much detail (cost of treatment and possible fetal wastage were not considered). However, to our knowledge, the model presented herein is the only model specifically incorporating a quota system. This is important, as not only Alberta but also Canada as a whole relies on a supply managed system.

In our economic model, implementation of any one of several on-farm BLV control strategies resulted in a positive net benefit, making BLV control economically beneficial. Although one other study (Rhodes et al., 2003) reached the same conclusion for a test and manage control program and a within-herd prevalence of at least 12.5%, similar analyses for other control strategies are missing.

Based on comparisons of various strategies considered in the present model, test and segregate was the most beneficial. This was expected and can be explained by the highest rate of yearly reduction in prevalence, resulting in the highest net benefit, compared with other strategies. According to available literature (Johnson et al., 1985; Suh et al., 2005), test-and-segregate control programs are highly efficient in preventing new infections, therefore resulting in a rapid increase in income. Although this strategy requires structural and organizational changes for dairy operations that might be difficult to implement, it offers an effective way of preventing new infections when uninfected replacement animals are difficult to realize. Even though these changes could be implemented in a reversible manner, segregation strategies for other diseases (e.g., mastitis) were found it to be rather unpopular due to the necessity of additional labor and altered routines (Huijps et al., 2009).

In contrast to economically beneficial on-farm BLV control, negative net benefits were possible for some input variations in the sensitivity analysis. The same variables were also identified among the 10 variables with the biggest effect on the model. However, none of the iterations causing negative net benefits were unexpected. Low input values (1–3 yr, depending on the considered strategy) for the number of years of implementation of on-farm control resulted in a negative net benefit. Years was also identified as the variable with the biggest effect on the model. The more stages of the model (years of implementation) were run, the more revenue accumulated, with an increasing effect on the result. Additionally, to control BLV efficiently, a long-term commitment is necessary (Brunner et al., 1997); consequently, a timespan of 10 yr was considered

in this analysis. Interestingly, according to this model, BLV control became economically beneficial after a relatively short period. The reduction in prevalence of 15% per year for the some management strategies resulted in a positive net benefit when continued over at least 2 yr (data not shown). Similarly, for a control program to be beneficial, the controlled disease has to be present on farm. Therefore, a very low or no within-herd prevalence of BLV resulted in a negative net benefit, whereas a higher prevalence and therefore more negative effects of the disease increased benefits of controlling the disease, confirming results of Rhodes et al. (2003). Consequently, within-herd prevalence ranked number 7 in the sensitivity analysis for the test-and-segregate strategy. Nevertheless, this might underestimate the true situation. Best management practices commonly recommended for BLV control will decrease the within-herd prevalence of BLV; however, they can be beneficial in additional ways. Pasteurizing colostrum, for example, can also improve calf health by reducing risks for calf scours and other diseases, thereby reducing calf morbidity including the necessity of treatment and mortality, resulting in additional economic benefits not considered in this model (Godden et al., 2012; Wolf et al., 2014). Finally, low input values for the effectiveness of each strategy also generated negative net benefit. This was unsurprising, as BLV control has to be efficient in reducing within-herd disease prevalence to increase net revenue. Other variables identified to have an effect on overall outcomes of this analysis were also readily explained. Milk price as well as the average yearly milk production per cow (ranked 2 and 3, respectively, in sensitivity analysis for the test-and-segregate strategy) are fundamental determinants of income of a dairy farm and therefore expected to affect results. These variables undergo fluctuation in the dairy industry and the inputs represent variability among years and herds. This is also true for slaughter value (rank 6 in the sensitivity analysis for test and segregate). Similarly, high cow longevity means more revenue, because fewer replacement animals are necessary and surplus cattle can be sold. The uncertainty around HR for premature culling and the variability around the replacement rate therefore affect the net revenue of this analysis (ranks 4 and 8 in sensitivity analysis for the test-and-segregate strategy), because they influence the number of replacements needed and, therefore, the cost of raising them. The identification of the variable for cost to raise replacement heifers mirrors variability in cost to raise these animals (rank 5 in the sensitivity analysis for test and segregate). However, independent of input values for these variables, BLV control remained economically beneficial.

Test and cull most commonly resulted in a higher net revenue than test and segregate in the sensitivity analysis. Test and segregate was the most efficient strategy in our model; however, it was more costly than test and cull. This combination allowed the test-and-cull strategy to result in the highest net revenue for some variables in the sensitivity analysis.

Nevertheless, one limitation of our analysis was the small amount of available data for input variables, which means that some model inputs were only estimates and therefore had higher uncertainty. However, we used average values for Alberta, wherever possible, and the sensitivity analysis incorporated the range of realistic alternative values, making the analysis very applicable. Well-documented studies concerning implementation of best management practices and their influence on the within-herd prevalence of BLV were not readily available; therefore, only estimates could be used. It is impossible to reflect reality with a model such as ours. The actual decrease in prevalence on a certain farm is likely to differ from what is presented here, as it is highly dependent on the individual farm's circumstances. However, values solely based on within-herd prevalence, without the assumption of a constant decrease in prevalence over time (Table 5), suggested that any decrease in BLV within-herd prevalence would result in an increased annual net revenue for the farmer. Similarly, the sensitivity analysis for the annual decrease in prevalence for the all control strategies (freezer) and all control strategies (pasteurizer) strategies showed that a decrease in prevalence of at least 5% every year would result in a positive net benefit in the considered time span.

The within-herd prevalence was assumed to stay constant over time when no control measures were implemented. This might underestimate the true situation, as the within-herd prevalence would probably rise over time in a newly infected herd. This assumption likely led to a conservative estimate, and the benefit of controlling BLV over not controlling might be higher than portrayed here. Nonetheless, based on sensitivity analysis, the model was highly robust and a valuable source of information for economic considerations of a BLV control program. The assumption of perfect diagnostic tests introduces some additional uncertainty. Although sensitivity and specificity of BLV ELISA are high, they are not perfect (Walsh, 2013; Nekouei et al., 2016; Kuczewski et al., 2018). Consequently, some cattle might be identified as test negative even though they are infected; this could delay reductions in within-herd BLV prevalence. In contrast, false-positive results are also possible, which could result, depending on the strategy, in culling of an uninfected cow and the un-

necessary premature slaughter of an animal and ensuing losses. However, chances of culling a BLV-negative animal are very low (~1%, based on 40% within-herd prevalence in a 146-animal herd and an ELISA test with 95% specificity and sensitivity). Similarly, if compliance is lacking and not all best management strategies are followed consistently, the decrease in BLV within-herd prevalence might be delayed. The results of different studies were not clear on the importance of biting flies in the transmission of BLV between animals (Weber et al., 1988; Erskine et al., 2012c). However, the issue of potential transmission of BLV through biting flies was addressed by incorporating increased fly control in our model.

The cost for testing infected animals could be increased or decreased by using various testing strategies. Using serum samples enables testing calves and heifers before lactation. Alternatively, testing of a subset of animals allows for estimation of within-herd prevalence while reducing cost for antibody testing (Erskine et al., 2012b).

Even though BLV infection likely has a negative effect on the infected animals' immune system, and thereby health (Frie and Coussens, 2015), this effect was only considered partially in this analysis by taking production effects and higher risk for culling into account. In reality, these costs would be increased by treatment and other disease-specific costs. Consequently, the present results probably underestimated the true benefit of controlling BLV on farm. Assuming that BLV-infected animals are more likely to have lower milk production and less likely to successfully eliminate pathogens (Ott et al., 2003; Vanleeuwen et al., 2010; Erskine et al., 2012a), eradicating BLV will make voluntary culling space available. This culling space could be used to increase overall performance of the herd by reducing the BLV within-herd prevalence more quickly as well as by replacing animals with a lower milk production with animals with a higher genetic potential for milk production, resulting in fewer animals needed to meet quota requirements. Consequently, herd size could be decreased, resulting in fewer expenses for animal maintenance. Alternatively, overall milk production or quota could be increased. The decrease in herd size would result in an additional yearly benefit of Can\$2,172.55 per animal.

Even though the present analysis uses Alberta-specific data as an example, outcomes could be used as a guideline for Canada and other supply-managed systems in general. Whereas some characteristics vary between provinces (e.g., herd size, housing system), the entire Canadian dairy industry relies on a quota system. Additionally, taking the results of the sensitivity analysis into account, a smaller herd size resulted in

smaller, but overall positive net benefits. The housing for dairy cattle differs in that tiestalls are more common in eastern Canada than in Alberta. This might have an influence on interanimal contact, and therefore on the risk of BLV transmission between animals, depending on how different farms are managed (e.g., pasture time and housing of dry cows). However, most risk factors for BLV transmission are independent of the housing system, and quantifying the difference in risk of transmission is therefore difficult to realize and likely does not have a big effect on transmission risk.

To get a better understanding of the disease and to populate economic models with more detailed information, future research should examine development of BLV prevalence when no control is pursued, as well as when specific management changes (e.g., one-time use of needles) are implemented. Additionally, implementation of on-farm control programs could be closely monitored, to learn about the true economic effects of BLV and its control.

CONCLUSIONS

Based on the model we developed and presented here, implementation of any of the 4 proposed on-farm control strategies (all management strategies, some management strategies, test and cull, and test and segregate) resulted in a positive net benefit for the average dairy farm with 146 cows and a 40% within-herd prevalence of BLV, independent of the strategy chosen. In addition, the model also highlighted considerable economic losses due to BLV infection. These results should encourage implementation of BLV control programs and eradication of BLV on dairy farms.

ACKNOWLEDGMENTS

The authors acknowledge the assistance of Fiona Clement (Department of Community Health Sciences, University of Calgary, Calgary, AB, Canada) in the initial phase of the model creation and are grateful for her input and the assistance of John Kastelic (Department of Production Animal Health, University of Calgary) in editing the manuscript. The authors also thank Diego Nobrega (Department of Production Animal Health, University of Calgary) for his help with the analysis of the DHI data. This study was funded by Alberta Milk (Edmonton, AB, Canada) and the Alberta Livestock and Meat Agency (Edmonton, AB, Canada).

REFERENCES

- Agriculture and Agri-Food Canada. 2016. Average cattle carcass weights for federal slaughter (in lbs.). Accessed May 24, 2017.

- <http://aimis-simia.agr.gc.ca/rp/index-eng.cfm?menupos=1.02.06&action=pR&r=107&LANG=EN&pdctc=>.
- Agriculture and Agri-Food Canada. 2017a. Number of dairy cows by province. Accessed May 24, 2017. <http://aimis-simia-cdic-ccil.agr.gc.ca/rp/index-eng.cfm?action=pR&r=219&pdctc=>.
- Agriculture and Agri-Food Canada. 2017b. Number of farms with shipment of milk on August 1st Accessed May 24, 2017 <http://aimis-simia-cdic-ccil.agr.gc.ca/rp/index-eng.cfm?action=pR&r=220&pdctc=>.
- Agriculture and Agri-Food Canada. 2017c. Red meat condemnation report by species for federally inspected plants. Accessed May 24, 2017 <http://aimis-simia.agr.gc.ca/rp/index-eng.cfm?menupos=1.02.08&ACTION=pR&r=134&LANG=EN&PDCTC=>.
- Alberta Milk. 2016. Historical average milk prices - \$/hL. Accessed May 24, 2017. <https://secure.albertamilk.com/secure/abm/milkprices/averagemilkpriceshistorical.aspx>.
- Milk, A. 2017. Average milk prices. *Milking Times*, May 2017:6. Accessed May 24, 2017. <https://albertamilk.com/news/category/milkingtimes/>.
- Ansari-Lari, M., M. Mohebbi-Fani, and A. Rowshan-Ghasrodashti. 2012. Causes of culling in dairy cows and its relation to age at culling and interval from calving in Shiraz, Southern Iran. *Vet. Res. Forum* 3:233–237.
- Bartlett, P. C., B. Norby, T. M. Byrem, A. Parmelee, J. T. Ledergerber, and R. J. Erskine. 2013. Bovine leukemia virus and cow longevity in Michigan dairy herds. *J. Dairy Sci.* 96:1591–1597. <https://doi.org/10.3168/jds.2012-5930>.
- Bartlett, P. C., L. M. Sordillo, T. M. Byrem, B. Norby, D. L. Grooms, C. L. Swenson, J. Zalucha, and R. J. Erskine. 2014. Options for the control of bovine leukemia virus in dairy cattle. *J. Am. Vet. Med. Assoc.* 244:914–922. <https://doi.org/10.2460/javma.244.8.914>.
- Boylan, K. 2015. How much does manure management cost you? *Progressive Dairyman*. Accessed May 2017. <http://www.progressivedairy.com/topics/manure/how-much-does-manure-management-cost-you>.
- Brenner, J. M., Van-Haam, D. Savir, and Z. Trainin. 1989. The implication of BLV infection in the productivity, reproductive capacity and survival rate of a dairy cow. *Vet. Immunol. Immunopathol.* 22:299–305. [https://doi.org/10.1016/0165-2427\(89\)90017-2](https://doi.org/10.1016/0165-2427(89)90017-2).
- Brunner, M. A., D. H. Lein, and E. J. Dubovi. 1997. Experiences with the New York State bovine leukosis virus eradication and certification program. *Vet. Clin. North Am. Food Anim. Pract.* 13:143–150. [https://doi.org/10.1016/S0749-0720\(15\)30369-8](https://doi.org/10.1016/S0749-0720(15)30369-8).
- Canadian Agency for Drugs and Technologies in Health. 2017. Guidelines for the Economic Evaluation of health technologies: Canada. 4th ed. Accessed Sep. 25, 2018. <https://www.cadth.ca/about-cadth/how-we-do-it/methods-and-guidelines/guidelines-for-the-economic-evaluation-of-health-technologies-canada>.
- Canadian Veterinary Medical Association and Alberta Veterinary Medical Association. 2017. Suggested fee guide for large animal procedures. Accessed May 2017. <https://www.canadianveterinarians.net/practice-economics/alberta-reports>.
- CanWest DHI. 2017. Western Progress Report 2016. Accessed May 2017, <http://canwestdhi.com/publications.htm>.
- Chi, J., J. A. VanLeeuwen, A. Weersink, and G. P. Keefe. 2002. Direct production losses and treatment costs from bovine viral diarrhoea virus, bovine leukosis virus, *Mycobacterium avium* subspecies *paratuberculosis*, and *Neospora caninum*. *Prev. Vet. Med.* 55:137–153. [https://doi.org/10.1016/S0167-5877\(02\)00094-6](https://doi.org/10.1016/S0167-5877(02)00094-6).
- D'Angelino, J. L., M. Garcia, and E. H. Birgel. 1998. Productive and reproductive performance in cattle infected with bovine leukosis virus. *J. Dairy Res.* 65:693–695. <https://doi.org/10.1017/S0022029998003124>.
- Dubé, C., C. Ribble, D. Kelton, and B. McNab. 2011. Estimating potential epidemic size following introduction of a long-incubation disease in scale-free connected networks of milking-cow movements in Ontario, Canada. *Prev. Vet. Med.* 99:102–111. <https://doi.org/10.1016/j.prevetmed.2011.01.013>.
- Emanuelson, U., K. Scherling, and H. Pettersson. 1992. Relationships between herd bovine leukemia virus infection status and reproduction, disease incidence, and productivity in Swedish dairy herds. *Prev. Vet. Med.* 12:121–131. [https://doi.org/10.1016/0167-5877\(92\)90075-Q](https://doi.org/10.1016/0167-5877(92)90075-Q).
- Erskine, R. J., P. C. Bartlett, T. M. Byrem, C. L. Render, C. Febvay, and J. T. Houseman. 2012a. Association between bovine leukemia virus, production, and population age in Michigan dairy herds. *J. Dairy Sci.* 95:727–734. <https://doi.org/10.3168/jds.2011-4760>.
- Erskine, R. J., P. C. Bartlett, T. M. Byrem, C. L. Render, C. Febvay, and J. T. Houseman. 2012b. Using a herd profile to determine age-specific prevalence of bovine leukemia virus in Michigan dairy herds. *Vet. Med. Int.* 2012:350374. <https://doi.org/10.1155/2012/350374>.
- Erskine, R. J., P. C. Bartlett, T. M. Byrem, C. L. Render, C. Febvay, and J. T. Houseman. 2012c. Herd-level determinants of bovine leukemia virus prevalence in dairy farms. *J. Dairy Res.* 79:445–450. <https://doi.org/10.1017/S0022029912000520>.
- Frie, M. C., and P. M. Coussens. 2015. Bovine leukemia virus: A major silent threat to proper immune responses in cattle. *Vet. Immunol. Immunopathol.* 163:103–114. <https://doi.org/10.1016/j.vetimm.2014.11.014>.
- Godden, S. 2008. Colostrum management for dairy calves. *Vet. Clin. North Am. Food Anim. Pract.* 24:19–39. <https://doi.org/10.1016/j.cvfa.2007.10.005>.
- Godden, S. M., D. J. Smolenski, M. Donahue, J. M. Oakes, R. Bey, S. Wells, S. Sreevatsan, J. Stabel, and J. Fetrow. 2012. Heat-treated colostrum and reduced morbidity in preweaned dairy calves: results of a randomized trial and examination of mechanisms of effectiveness. *J. Dairy Sci.* 95:4029–4040. <https://doi.org/10.3168/jds.2011-5275>.
- Government of Alberta. 2015. OCCinfo: Occupations and Educational Programs: Wages and Salaries, Accessed May 24, 2017. <https://occinfo.alis.alberta.ca/occinfopreview/info/browse-wages/wage-profile.html?id=8431>.
- Government of Canada. 2017. Culling and replacement rates in dairy herds in Canada. Accessed May 24, 2017. http://www.dairyinfo.gc.ca/pdf/genetics-cull_e.pdf.
- Heikkilä, R., and P. Van Biert. 2010. Dairy cost study, the economics of milk production in Alberta 2009. Vol. 69. Alberta Government, Alberta Agriculture and Forestry, Economics and Competitiveness Branch, Economics Section. Accessed May 2017. [https://www1.agric.gov.ab.ca/\\$department/deptdocs.nsf/all/econ14116](https://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/econ14116).
- Heikkilä, R., and P. Van Biert. 2012. Dairy cost study, the economics of milk production in Alberta 2011. Vol. 71. Alberta Government, Alberta Agriculture and Forestry, Economics and Competitiveness Branch, Economics Section. Accessed May 2017. [https://www1.agric.gov.ab.ca/\\$department/deptdocs.nsf/all/econ14116](https://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/econ14116).
- Heikkilä, R., and P. Van Biert. 2015. Dairy cost study, the economics of milk production in Alberta 2014. Vol. 74. Alberta Government, Alberta Agriculture and Forestry, Economics and Competitiveness Branch, Economics Section. Accessed May 2017. [https://www1.agric.gov.ab.ca/\\$department/deptdocs.nsf/all/econ14116](https://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/econ14116).
- Huijps, K., H. Hogeveen, T. J. G. M. Lam, and R. B. M. Huirne. 2009. Preferences of cost factors for mastitis management among Dutch dairy farmers using adaptive conjoint analysis. *Prev. Vet. Med.* 92:351–359. <https://doi.org/10.1016/j.prevetmed.2009.08.024>.
- Johnson, R., C. D. Gibson, and J. B. Kaneene. 1985. Bovine leukemia virus—A herd-based control strategy. *Prev. Vet. Med.* 3:339–349. [https://doi.org/10.1016/0167-5877\(85\)90011-X](https://doi.org/10.1016/0167-5877(85)90011-X).
- Kanno, T., R. Ishihara, S. Hatama, Y. Oue, H. Edamatsu, Y. Konno, S. Tachibana, and K. Murakami. 2014. Effect of freezing treatment on colostrum to prevent the transmission of bovine leukemia virus. *J. Vet. Med. Sci.* 76:255–257. <https://doi.org/10.1292/jvms.13-0253>.
- Kuczewski, A., K. Orsel, H. W. Barkema, D. F. Kelton, W. A. Hutchins, and F. van der Meer. 2018. Short communication: Evaluation of 5 different ELISA for the detection of bovine leukemia virus antibodies. *J. Dairy Sci.* 101:2433–2437. <https://doi.org/10.3168/jds.2017-13626>.
- Lee, K. 2015. There is a cost to raising heifers. *Progressive Dairyman: Canada*. Accessed May 2017. <http://www.progressivedairyman.ca/topics/calves-heifers/there-is-a-cost-to-raising-heifers>.

- Agriculture, M. Food and Rural Development. 2015. Guidelines for estimating dairy cow production costs 2015. Accessed May 2017. https://www.gov.mb.ca/agriculture/business-and-economics/financial-management/pubs/cop_dairy_cow.pdf.
- Agriculture, M. Food and Rural Development. 2009. Guidelines for estimating organic cow-calf production costs. Accessed May 2017. https://www.gov.mb.ca/agriculture/business-and-economics/financial-management/pubs/cop_beef_organiccowcalf.pdf.
- Monti, G. E., K. Frankena, B. Engel, W. Buist, H. D. Tarabla, and M. C. de Jong. 2005. Evaluation of a new antibody-based enzyme-linked immunosorbent assay for the detection of bovine leukemia virus infection in dairy cattle. *J. Vet. Diagn. Invest.* 17:451–457. <https://doi.org/10.1177/104063870501700507>.
- Nekouei, O., J. Durocher, and G. Keefe. 2016. Diagnostic performance of an indirect enzyme-linked immunosorbent assay (ELISA) to detect bovine leukemia virus antibodies in bulk-tank milk samples. *Can. Vet. J.* 57:778–780. [https://doi.org/10.1016/1045-1056\(90\)90064-7](https://doi.org/10.1016/1045-1056(90)90064-7).
- Nekouei, O., J. VanLeeuwen, J. Sanchez, D. Kelton, A. Tiwari, and G. Keefe. 2015. Herd-level risk factors for infection with bovine leukemia virus in Canadian dairy herds. *Prev. Vet. Med.* 119:105–113. <https://doi.org/10.1016/j.prevetmed.2015.02.025>.
- Ontario Ministry of Agriculture, Food and Rural Affairs. 2010. The Cost of raising replacement dairy heifers. Accessed May 24, 2017. <http://www.omafr.gov.on.ca/english/livestock/dairy/facts/11-055.htm>.
- Ott, S. L., R. Johnson, and S. J. Wells. 2003. Association between bovine-leukosis virus seroprevalence and herd-level productivity on US dairy farms. *Prev. Vet. Med.* 61:249–262. <https://doi.org/10.1016/j.prevetmed.2003.08.003>.
- Pelzer, K. D. 1997. Economics of bovine leukemia virus infection. *Vet. Clin. North Am. Food Anim. Pract.* 13:129–141. [https://doi.org/10.1016/S0749-0720\(15\)30368-6](https://doi.org/10.1016/S0749-0720(15)30368-6).
- Radostits, O. M., C. C. Gay, K. W. Hinchcliff, and P. D. Constable. 2007. Enzootic bovine leukosis (bovine lymphosarcoma). Pages 1209–1221 in *Veterinary Medicine—A Book of the Diseases of Cattle, Horses, Sheep, Pigs and Goats*. 10th ed. Saunders Elsevier, Philadelphia, PA.
- Rhodes, J. K., K. D. Pelzer, and Y. J. Johnson. 2003. Economic implications of bovine leukemia virus infection in mid-Atlantic dairy herds. *J. Am. Vet. Med. Assoc.* 223:346–352. <https://doi.org/10.2460/javma.2003.223.346>.
- Ritter, C., J. Jansen, S. Roche, D. F. Kelton, C. L. Adams, K. Orsel, R. J. Erskine, G. Benedictus, T. J. G. M. Lam, and H. W. Barkema. 2017. Invited review: Determinants of farmers' adoption of management-based strategies for infectious disease prevention and control. *J. Dairy Sci.* 100:3329–3347. <https://doi.org/10.3168/jds.2016-11977>.
- Rodríguez, S. M., A. Florins, N. Gillet, A. de Brogniez, M. T. Sanchez-Alcaraz, M. Boxus, F. Boulanger, G. Gutierrez, K. Trono, I. Alvarez, L. Vagnoni, and L. Willems. 2011. Preventive and therapeutic strategies for bovine leukemia virus: Lessons for HTLV. *Viruses* 3:1210–1248. <https://doi.org/10.3390/v3071210>.
- Sargeant, J. M., D. F. Kelton, S. W. Martin, and E. D. Mann. 1997. Associations between farm management practices, productivity, and bovine leukemia virus infection in Ontario dairy herds. *Prev. Vet. Med.* 31:211–221. [https://doi.org/10.1016/S0167-5877\(96\)01140-3](https://doi.org/10.1016/S0167-5877(96)01140-3).
- Schwartz, I., and D. Levy. 1994. Pathobiology of bovine leukemia virus. *Vet. Res.* 25:521–536.
- Scott, H. M., O. Sorensen, J. T. Y. Wu, E. Y. W. Chow, K. Manninen, and J. A. VanLeeuwen. 2006. Seroprevalence of *Mycobacterium avium* subspecies *paratuberculosis*, *Neospora caninum*, bovine leukemia virus, and bovine viral diarrhoea virus infection among dairy cattle and herds in Alberta and agroecological risk factors associated with seropositivity. *Can. Vet. J.* 47:981–991.
- Statistics Canada. 2017. Table 002–0043 Farm product prices, crops and livestock, monthly. Accessed May 24, 2017. <http://www5.statcan.gc.ca/cansim/a26?lang=eng&retrLang=eng&id=0020043&paSer=&pattern=&stByVal=1&p1=1&p2=-1&tabMode=dataTable&csid=>
- Suh, G. H., J. C. Lee, C. Y. Lee, T. Y. Hur, D. S. Son, B. S. Ahn, N. C. Kim, and C. G. Lee. 2005. Establishment of a bovine leukemia virus-free dairy herd in Korea. *J. Vet. Sci.* 6:227–230.
- Tiwari, A., J. A. VanLeeuwen, I. R. Dohoo, G. P. Keefe, J. P. Haddad, R. Tremblay, H. M. Scott, and T. Whiting. 2007. Production effects of pathogens causing bovine leukosis, bovine viral diarrhoea, paratuberculosis, and neosporosis. *J. Dairy Sci.* 90:659–669. [https://doi.org/10.3168/jds.S0022-0302\(07\)71548-5](https://doi.org/10.3168/jds.S0022-0302(07)71548-5).
- Trainin, Z., and J. Brenner. 2005. The direct and indirect economic impacts of bovine leukemia virus infection on dairy cattle. *Isr. J. Vet. Med.* 60:94–105.
- Van Biert, P. 2016. Dairy Cost Study: The economics of milk production in Alberta 2015. Vol. 75. Alberta Government, Alberta Agriculture and Forestry, Economics and Competitiveness Branch, Economics Section. [https://www1.agric.gov.ab.ca/\\$department/deptdocs.nsf/all/econ14116](https://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/econ14116).
- Vanleeuwen, J. A., J. P. Haddad, I. R. Dohoo, G. P. Keefe, A. Tiwari, and H. M. Scott. 2010. Risk factors associated with *Neospora caninum* seropositivity in randomly sampled Canadian dairy cows and herds. *Prev. Vet. Med.* 93:129–138. <https://doi.org/10.1016/j.prevetmed.2009.11.013>.
- Walsh, R. B. R. B. 2013. Evaluation of enzyme-linked immunosorbent assays performed on milk and serum samples for detection of neosporosis and leukosis in lactating dairy cows. *Can. Vet. J.* 54:347–352.
- Weber, A. F., R. D. Moon, D. K. Sorensen, D. W. Bates, J. C. Meiske, C. A. Brown, N. L. Rohland, E. C. Hooker, and W. O. Strand. 1988. Evaluation of the stable fly (*Stomoxys calcitrans*) as a vector of enzootic bovine leukosis. *Am. J. Vet. Res.* 49:1543–1549.
- Wolf, R., F. Clement, H. W. Barkema, and K. Orsel. 2014. Economic evaluation of participation in a voluntary Johne's disease prevention and control program from a farmer's perspective—The Alberta Johne's Disease Initiative. *J. Dairy Sci.* 97:2822–2834. <https://doi.org/10.3168/jds.2013-7454>.