Economic losses due to Johne's disease (paratuberculosis) in dairy cattle

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ABSTRACT

Johne's disease (JD), or paratuberculosis, is an infectious inflammatory disorder of the intestines primarily associated with domestic and wild ruminants including dairy cattle. The disease, caused by an infection with *Mycobacterium avium* subspecies *paratuberculosis* (MAP) bacteria, burdens both animals and producers through reduced milk production, premature culling, and reduced salvage values among MAP-infected animals. The economic losses associated with these burdens have been measured before, but not across a comprehensive selection of major dairy-producing regions within a single methodological framework. This study uses a Markov chain Monte Carlo approach to estimate the annual losses per cow within MAP-infected herds and the total regional losses due to JD by simulating the spread and economic impact of the disease with region-specific economic variables. It was estimated that approximately 1% of gross milk revenue, equivalent to US\$33 per cow, is lost annually in MAP-infected dairy herds, with those losses primarily driven by reduced production and being higher in regions characterized by above-average farm-gate milk prices and production per cow. An estimated US\$198 million is lost due to JD in dairy cattle in the United States annually, US\$75 million in Germany, US\$56 million in France, US\$54 million in New Zealand, and between US\$17 million and US\$28 million in Canada, one of the smallest dairy-producing regions modeled.

Key words: paratuberculosis, economic impact, Monte Carlo simulation, Markov process

INTRODUCTION

Johne's disease (JD), or paratuberculosis, is an infectious chronic inflammatory disorder of the intestines that can affect domestic and wild ruminants including dairy cattle (Fecteau and Whitlock, 2010). The disease

is caused by an infection with *Mycobacterium avium* ssp. *paratuberculosis* (MAP), a bacterial organism that is relatively resistant to environmental, physical, and chemical stressors (Manning and Collins, 2001; Whittington et al., 2004; Donaghy et al., 2009) and that can persist for extended periods outside of its host environment, surviving up to 55 wk in a dry, fully shaded environment (Whittington et al., 2004). Although MAP infection has also been observed in omnivores and carnivores such as wild rabbits (Greig et al., 1999), foxes (Beard et al., 2001), and nonhuman primates (McClure et al., 1987; Zwick et al., 2002), JD is primarily associated with cattle and sheep. As the infection progresses in cattle through its 4 distinct stages, the clinical effects worsen in severity from diarrhea and reduced milk production to lethargy, hypoproteinemia, and severe emaciation (Tiwari et al., 2006). These clinical effects can result in substantial economic losses for dairy producers (Garcia and Shalloo, 2015), with decreased milk production (Lombard et al., 2005; McAloon et al., 2016), decreased slaughter value (Benedictus et al., 1985; Kudahl and Nielsen, 2009; Raizman et al., 2009), and premature culling (Ott et al., 1999; Shephard et al., 2016) among the primary sources. Annual losses per cow among MAP-infected dairy herds in the United States have been estimated at US\$21 (Ott et al., 1999), US\$35 (Groenendaal et al., 2002), and up to US\$79 (Pillars et al., 2009); annual losses among MAP-infected dairy herds in Canada have been estimated at CA\$49 (approximately US\$40) per cow (Tiwari et al., 2008). Raizman et al. (2009) estimated income over feed cost losses of US\$366 per MAP-shedding cow per lactation, and more recently, Bhattarai et al. (2013) estimated annual losses of US\$1,644 per 100 cows in a US herd with a true prevalence of 7%.

With the herd-level prevalence of MAP infection likely exceeding 50% in most countries with significant dairy industries (Barkema et al., 2018), there is a need to estimate the economic losses due to JD across major dairy-producing regions within a single methodological framework. This prospect is complicated by the heterogeneity of both economic characteristics across regions and methodologies across MAP prevalence studies.

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However, the former can be addressed by modeling with region-specific economic variables and the latter by modeling with a range of assumed prevalence scenarios across regions. Accordingly, this study uses Markov chain Monte Carlo methods to (1) model the spread of MAP infection within dairy herds, (2) estimate economic losses due to JD for regions with available prevalence estimates, and (3) estimate economic losses due to JD using a range of assumed prevalence scenarios across a more comprehensive group of major dairy-producing countries, states, and provinces.

MATERIALS AND METHODS

A MAP-negative Markov model was developed to establish baseline steady-state herd characteristics, followed by a MAP-positive Markov model where herd structure and the distribution of infected animals across age groups changed over time. Using a Monte Carlo simulation approach, MAP-positive herds from each region were compared with baseline MAP-negative herds from each region to generate 3 main sets of results: the general behavior of the model with assumptions of 10% initial within-herd prevalence and 50% herd-level prevalence for a generic herd with no region-specific economic variables; estimated losses due to MAP infection for a select group of dairy-producing regions with available prevalence estimates; and estimated losses for a more comprehensive group of dairy-producing regions over a range of assumed prevalence scenarios. Last, the Canadian estimates were reexamined with special consideration for the unique market conditions that arise due to supply management (e.g., fixed annual production levels and relatively high farm-gate prices).

MAP-Negative Models

A MAP-negative baseline Markov herd model was developed with purchased replacements coming from a separately modeled MAP-negative pool. The herd and replacement pools were modeled using the same constraints and structure: 15 age categories ranging from 0–3 mo to 8–9 yr of age, with each age category having its own matrix of transition probabilities, and the model spanning a 10-period horizon with each period representing 1 yr. In the MAP-negative models, animals either age or may be culled until they reach the 8–9 yr category when they must be culled. Natural replacements (aged 0 to 12 mo) and purchased replacements (aged 12 mo to 3 yr) are added to the herd each year to maintain the herd's age structure, with the former coming from within the herd and the latter coming from the replacement pool. After the initial age parameters were set, the herd and pool were modeled for fifty 1-yr

periods stabilizing with an annual cow-culling rate of 27%, a young-stock percentage (including calves less than one year) of 48%, and for a 100-cow herd, 1.36 cows and 3.07 young-stock between 1 and 2 yr of age being brought in from the external replacement pool each year. These numbers are similar to those observed in Canadian dairy herds, which have an average cow-culling rate between 26% and 33% (OMAFRA, 2020), an average young-stock percentage of 48% (STATCAN, 2020), and purchase an average of 1.37 cows and 3.09 young-stock between 1 and 2 yr of age per 100 cows per year (Van Biert, 2019).

MAP-Positive Models

Whereas the MAP-negative models had only 2 possible outcomes in each age group's transition matrix (i.e., continue aging or be culled), the MAP-positive models are more complex. Infection with MAP is characterized by a long incubation period (Jubb et al., 2004; Fecteau and Whitlock, 2010), with varying levels of susceptibility across age groups (Windsor and Whittington, 2010; Mortier et al., 2013) and shedding across stages of infection (Weber et al., 2010; Mitchell et al., 2012; Mortier et al., 2014; Wolf et al., 2015). The modeling implications of these characteristics will be expanded upon later in this section. However, in general terms, the MAP-positive models function in the following way: the animal can remain negative and continue aging, become infected and continue aging, or be culled. Once an animal is infected, it can either be culled or its infection can undergo progression, regression, or inertia (remain the same). Animals in each stage of infection are associated with a different risk of being culled, and within each stage, there are various non-shedding, lightly shedding, moderately shedding, and heavily shedding states. Infection pressure on animals in the herd f_t is determined by the number and degree of shedding animals in the herd in period t , defined as

$$\text{infection pressure} = f_t = \frac{MAP_l \times L_t + MAP_m \times M_t + MAP_h \times H_t}{\text{animals}}, \quad [1]$$

where MAP_l , MAP_m , and MAP_h equal the amount of MAP bacteria shed by lightly shedding, moderately shedding, and heavily shedding animals, respectively. L_t , M_t , and H_t equal the number of animals shedding at those levels in period t , and animals equals the total number of animals in the herd, which is fixed over the 10-period horizon.

All other potential outcomes are functions of infection pressure f_t and compete for the probability of

remaining in the herd equal to $(1 - x)$, where x is the probability of being culled. For MAP-negative animals, the probability of being culled remains the steady-state value according to their age category. For MAP-positive animals, the probability of being culled depends on the stage of their infection, with the probability increasing with the severity of infection. In their general forms across all time periods, the transition probability P for each outcome within each age-specific transition matrix can be defined as

$$P(\text{infection}) = \left(1 - e^{-\sum_{i=0}^n f_i \times w}\right) \times \frac{f}{\sum_{i=0}^n f_i} \times (1 - x), \quad [2]$$

$$P(\text{progression}) = \left(1 - e^{-\sum_{i=0}^n \left(f_i + \frac{1}{f_i}\right) \times w}\right) \times \frac{f}{\sum_{i=0}^n \left(f_i + \frac{1}{f_i}\right)} \times (1 - x), \quad [3]$$

$$P(\text{regression}) = \left(1 - e^{-\sum_{i=0}^n \left(f_i + \frac{1}{f_i}\right) \times w}\right) \times \frac{\frac{1}{f}}{\sum_{i=0}^n \left(f_i + \frac{1}{f_i}\right)} \times (1 - x), \quad [4]$$

$$P(\text{inertia}) = \left(e^{-\sum_{i=0}^n \left(f_i + \frac{1}{f_i}\right) \times w}\right) \times \frac{(1 - x)}{a}, \quad [5]$$

where n is the number of potential outcomes given an animal's age and stage of infection; $P(\text{infection})$ is the probability of an animal transitioning from a MAP-negative stage to the initial stage of infection (the probability of infection); $P(\text{progression})$ is the probability of transitioning from one stage of infection to a more severe stage (the probability of disease progression); $P(\text{regression})$ is the probability of transitioning from one stage of infection to a less severe stage (the probability of disease regression); and $P(\text{inertia})$ is the probability of transitioning to the same stage of infection (the probability of neither disease progression nor regression occurring). There is a positive relationship between infection pressure f and $P(\text{infection})$, and there is a positive relationship between infection pressure f and $P(\text{progression})$ and a negative relationship between infection pressure f and $P(\text{regression})$. This reflects the observed association between environmental MAP load and the rate of disease progression (Weber et al.,

2010; Windsor and Whittington, 2010; Bolton et al., 2011), including repeated exposure to MAP (Fecteau et al., 2010; McGregor et al., 2012; Suwandi et al., 2017; Marquetoux et al., 2018). Note that this differs from explicitly modeling initial infectious dose dependence, which would require complicated tracking of infected animals through time not readily accomplished within a Markov framework. However, the modeling approach employed here still captures the positive feedback between within-herd prevalence, infection pressure, and the rate of infection progression. Last, by definition, there is a negative relationship between the sum of all infection, progression, and regression probabilities and $P(\text{inertia})$ because the more likely the stage of infection is to change over one transition period, the less likely it is to remain unchanged. In Equation [5], a is the number of potential inertia outcomes where transitions would only occur to another state (level of shedding) within the same stage of infection (e.g., a transition from a nonshedding state of stage 3 infection to a moderately shedding state of stage 3 infection). In Equations [2] through [5], w is a weight that allows for adjustment in the rate of spread of MAP infection within the herd. For this study, w was set it at 0.075, which through trial and error was determined to result in an approximate doubling of within-herd prevalence over 10 yr. However, by adjusting this value, other within-herd prevalence scenarios could be modeled, from scenarios where prevalence remains relatively constant over 10 yr to explosive epidemics where prevalence increases dramatically.

To accurately reflect MAP's infectivity-age relationship, its long incubation period, and its clinical progression, limits on the ranges of possible outcomes were set within each age group's transition matrix as well as the potential states of shedding across stages: infected animals up to 12 mo old can only be in stage 1 of infection (the initial stage of infection where animals are infected and may shed low levels of MAP bacteria); infected animals up to 24 mo old can be in stages 1 or 2 (stage 2 being the subclinical stage where animals appear healthy but may shed low and moderate levels of bacteria); from 2 to 5 yr old they can be in stages 1, 2, or 3 (stage 3 being the clinical stage of infection where animals may exhibit clinical symptoms such as intermittent diarrhea and weight loss and may begin to shed low, moderate, and high levels of bacteria); animals 5 to 9 yr old can be in all stages of infection, with the final stage of infection, stage 4 (the terminal stage characterized by severe emaciation, often mandibular edema, and high levels of shedding), being a de facto absorptive stage that most often results in culling within one period; all stages of infection have possible nonshedding states within them except stage 4; animals

can only become infected in their first 12 mo; once an animal is MAP-positive they will remain positive for their lifetime; and progression or regression can only transition the animals to within one stage of their current stage of infection. For example, a “12–15 month” calf that is MAP-positive in stage 2 of infection can either progress to stage 3, regress to stage 1, remain in stage 2, or be culled within 1 yr. Similarly, a “5–6 year” cow in stage 3 of infection can either progress to stage 4, regress to stage 2, remain in stage 3, or be culled within 1 yr. Examples of the initial period 0 herd structure matrix, the period 0 transition matrices for animals aged 0–3 mo, 2–3 yr, and 8–9 yr, and the final period 1 herd structure matrix for the MAP-positive model, are available in Supplemental Tables S1–S5 (<https://doi.org/10.5683/SP2/60XE0R>).

Monte Carlo Simulations

Monte Carlo simulations are a type of methodology that uses random sampling from a set of input variables, each with their own distributions, to determine a range of possible outcomes. In this case 10,000 iteration simulations were run using randomized variables in a Markov model according to the mean and distribution

associated with each variable. For the MAP-specific variables in the model (Table 1), all variables were assumed to have normal distributions with standard deviations of 10% of their mean values. However, for the initial within-herd prevalence and initial regional cow-level prevalence, a set of herd conditions (disease distributions) was required for each potential initial value randomly selected in each of the 10,000 iterations. To obtain these initial conditions, MAP-positive replacements were introduced into the steady-state MAP-negative herd and fifty 1-yr periods were simulated using the MAP-positive model transition probabilities previously described. As prevalence increased over time in this 50-yr simulation, the distribution of infected animals in the herd changed, generating a range of disease distributions for every iteration within each subsequent 10-yr simulation. This model initialization allowed for within-herd and regional cow-level prevalence to be simulated with normal distributions and standard deviations equal to 20% of the mean. Although these assumed standard deviations may seem constrictive, data required to determine their true values were unavailable and the selected standard deviations capture a wide range of input values without destabilizing the simulations and their results.

Table 1. Input variables used in for the Monte Carlo simulations of the *Mycobacterium avium* ssp. *paratuberculosis*-positive Markov herd model¹

Variable	Mean value	Unit	Source
Effect of infection on production	5.90	%	McAloon et al. (2016)
Replacement pool	5,000.00	Cows	Assumed
Replacement cost (labor)	2.00	h	Assumed
Bacteria shed, light shedders ²	5.00	cfu	Whitlock et al. (2000) and Crossley et al. (2005)
Bacteria shed, moderate shedders ²	25.00	cfu	Whitlock et al. (2000) and Crossley et al. (2005)
Bacteria shed, heavy shedders ²	50.00	cfu	Whitlock et al. (2000) and Crossley et al. (2005)
Weight at 0 to 3 mo	74.24	kg	Jones and Heinrichs (2017)
Weight at 3 to 6 mo	141.82	kg	Jones and Heinrichs (2017)
Weight at 6 to 9 mo	214.70	kg	Jones and Heinrichs (2017)
Weight at 9 to 12 mo	286.52	kg	Jones and Heinrichs (2017)
Weight at 12 to 15 mo	354.86	kg	Jones and Heinrichs (2017)
Weight at 15 to 18 mo	425.32	kg	Jones and Heinrichs (2017)
Weight at 18 to 21 mo	477.63	kg	Jones and Heinrichs (2017)
Weight at 21 to 24 mo	524.05	kg	Jones and Heinrichs (2017)
Weight at maturity (2 to 9 yr)	680.39	kg	Jones and Heinrichs (2017)
Value reduction, stage 4 animals	31.0	%	Kudahl and Nielsen (2009)
Value reduction, stage 3 animals ³	29.0	%	Calculated
Value reduction, stage 2 animals ³	26.0	%	Calculated
Value reduction, stage 1 animals ³	15.0	%	Calculated
Culling risk, stage 4 animals	3.20	Ratio	Hendrick et al. (2005)
Culling risk, stage 3 animals ⁴	2.98	Ratio	Calculated
Culling risk, stage 2 animals ⁴	2.69	Ratio	Calculated
Culling risk, stage 1 animals ⁴	1.08	Ratio	Calculated

¹All variables simulated with a normal distribution and a standard deviation of 10% of the mean.

²Light and moderate shedding values based on median cfu count for the range. Heavy shedders at minimum cutoff.

³Based on stage 4 value reduction observed in study. Other values estimated by scaling the stage 4 value to a truncated cumulative logistic probability distribution (maximum = 0.308, α = 0.308, β = 0.031).

⁴Based on stage 4 hazard ratio observed in the study. Other values estimated by scaling the stage 4 value to a truncated cumulative logistic probability distribution (maximum = 3.200, α = 3.200, β = 0.320). Stage 1 risk is based on a mean value of 1.00 with a normal distribution and standard deviation of 0.10, truncated with a minimum value of 1.00 to obtain a true mean of 1.08.

Economic Losses

To estimate region-specific economic losses, region-specific economic input variables were incorporated into the simulations. Detailed values are available in Appendix Tables A1 and A2. After each period, the MAP-positive herd was compared with the steady-state MAP-negative herd to estimate the economic losses per cow within infected herds due to MAP infection. Premature culling losses were estimated by tallying additional exits in the MAP-positive herd and assigning those exits a value according to their age-at-exit and associated replacement price. Additional aggregated labor costs of seeking out, purchasing, and introducing a replacement to the herd were also accounted for. Salvage losses were estimated by tallying MAP-positive exits and assigning them a reduced salvage value according to their stage of infection. Production losses were estimated by tallying the number of MAP-positive cows and determining the quantity of milk that would have been produced if those cows were negative instead, multiplied by the farm-gate price for milk. The sum of these 3 losses was divided by the number of cows in the herd to obtain an estimate of total losses per cow within MAP-infected herds. Total regional losses were estimated by the product of regional head count, herd-level prevalence, and total losses per cow in infected herds. Annual losses, both per cow and regional, were discounted over time at an assumed rate of 5% per annum and then averaged over the 10-yr horizon to obtain the reported annual loss estimates. This discount rate was selected because it is consistent with small private firm investment in a family enterprise; it falls between a public investment return rate of approximately 3% (USDA, 2020) and a private investment return rate of approximately 10% (Macrotrends, 2020). Similarly, the Treasury Board of Canada selected a discount rate of 7% in its 2007 Cost-Benefit Analysis Guide but noted that it would likely be reduced in future years (Treasury Board of Canada, 2007). Finally, 2 main sets of simulations were run: one using available prevalence estimates (Table 2) for a limited number of regions, and a second using a range of assumed prevalence scenarios for a comprehensive selection of major dairy-producing regions.

RESULTS

General Behavior

With a mean initial within-herd prevalence of 10% and a mean initial regional herd-level prevalence of 50%, 90% of the 10,000 iterations resulted in proportional increases of within-herd prevalence ranging from 0.51 to 1.67, with a mean of 1.02, which is ap-

proximately equivalent to a doubling of within-herd prevalence from 10% to 20% over 10 yr (Figure 1). The percentage of infected animals that shed MAP increased from 6% to 12% over the 10-yr horizon, with the percentage of moderately and heavily shedding animals steadily increasing from 6% to over 10% of all shedding animals by yr 10 (Figure 2). As prevalence increased, so did infection pressure and the severity of infections, resulting in an increased cow-culling rate relative to the steady-state MAP-negative cow-culling rate (Figure 3A). Although this increased culling rate is indicative of worsening overall health in the herd, the precise sources of potential economic losses in the model (i.e., premature culling, reduced salvage value, and reduced production) can be seen changing over the 10-yr horizon in Figure 3B: the percentage of MAP-positive culls with varying degrees of reduced salvage value increased from just over 7% to 12% of all culls; the percentage of premature culls directly attributable to MAP infection doubled from 2% to 4% of all culls; forgone production as a percentage of total production increased from 0.63% to 1.16%.

Economic Losses (Available Prevalence Estimates)

On a national herd basis, estimated annual losses per cow within MAP-infected herds based on available prevalence estimates ranged from US\$15.07 in the Netherlands to US\$48.91 in Canada, and as a percentage of gross milk revenue on MAP-infected farms, from 0.39% in the Netherlands to 1.91% in Ireland. Total annual national losses ranged from US\$1.91 million in Austria to US\$150.19 million in Germany (Table 3).

Economic Losses (Assumed Prevalence)

With an assumed within-herd prevalence of 10% in MAP-infected herds and a herd-level prevalence of 50% across major dairy-producing regions, annual losses per cow in infected herds ranged from US\$8.31 in Brazil to US\$81.53 in Japan, with a revenue-weighted average of US\$32.84 per cow per year. Annual national herd losses ranged from US\$5.84 million in Finland to US\$198.42 million in the United States. Revenue-weighted average losses as a percentage of gross milk revenue were 1.07%, with significantly higher estimates for Ireland, New Zealand, and Australia (Table 4). Results for a wider range of prevalence scenarios are presented in Appendix Table A3. When annual losses are broken down into their component sources, premature culling losses ranged from 14% of total losses in Poland and Russia to 34% in New Zealand and Australia, reduced salvage value losses ranged from 6% in Poland to 19% in Ireland, and production losses ranged from 40% in

Ireland to 80% in Poland. Revenue-weighted averages premature culling losses accounted for 24% of total losses, reduced salvage value losses accounted for 11%, and production losses accounted for 65%. Details of the breakdown of total losses into source components for all regions modeled are available in Appendix Table A4.

Annual losses due to MAP infection were also estimated with an assumed stable within-herd prevalence of 10% and the same stable herd-level prevalence of 50%. Similar results were observed (Table A5): annual losses per cow in infected herds ranged from US\$7.30 in Brazil to US\$71.57 in Japan, and annual national herd losses ranged from US\$4.87 million in Czechia to \$171.92 million in the United States. Losses per cow as a percentage of gross milk revenue ranged from 0.78% in Czechia to 1.40% in Ireland, with a revenue-weighted

average of 0.93%. Compared with the estimated losses within the dynamic 10-yr prevalence models, the single-year stable prevalence (and therefore non-discounted) losses per cow were between 10 and 16% less, and annual regional losses were between 11 and 16% less, with revenue-weighted average differences of 13% for both per-cow and per-region annual losses.

Economic Losses (Canada)

This section reexamines the results for Canada with special consideration for the implications of supply management; production losses are no longer calculated as forgone production, but instead as the cost of having additional cows to maintain a fixed level of production over the 10-yr horizon. With assumed prevalence values

Table 2. Available herd-level and regional cow-level *Mycobacterium avium* ssp. *paratuberculosis* (MAP) prevalence estimates for various dairy-producing regions

Region ¹	Herd-level prevalence (%)	Source	Regional cow-level prevalence (%)	Source
USA	21.6*	Wells and Wagner (2000)	3.4*	Wells and Wagner (2000)
WI	34.0	Collins et al. (1994)	4.8	Collins et al. (1994)
MI	66.0	Johnson-Ifeorlundu et al. (1999)	6.9	Johnson-Ifeorlundu et al. (1999)
DEU	84.7*	Hacker et al. (2004)	10.3* ²	Hacker et al. (2004)
GBR	76.1* ³	Woodbine et al. (2009)	7.3	Woodbine et al. (2009)
NLD	54.7*	Muskens et al. (2000)	1.4 ²	Muskens et al. (2000)
ITA	70.5	Pozzato et al. (2011) ⁴	6.9	Pozzato et al. (2011) ⁵
CAN	42.0	Corbett et al. (2018)	3.4*	Weighted average ⁶
QC	23.6	Corbett et al. (2018)	3.1*	Tiwari (2005) ⁷
ON	54.1	Corbett et al. (2018)	2.4*	VanLeeuwen et al. (2001)
BC	65.8	Corbett et al. (2018) ⁸	3.1*	Tiwari (2005) ⁷
AB	65.8	Corbett et al. (2018) ⁸	9.1*	Tiwari (2005)
MB	65.8	Corbett et al. (2018) ⁸	4.5*	VanLeeuwen et al. (2006)
SK	65.8	Corbett et al. (2018) ⁸	2.7*	VanLeeuwen et al. (2005)
NS	47.3	Corbett et al. (2018) ⁹	3.3*	VanLeeuwen et al. (2001)
NB	47.3	Corbett et al. (2018) ⁹	2.9*	VanLeeuwen et al. (2001)
PE	47.3	Corbett et al. (2018) ⁹	1.3*	VanLeeuwen et al. (2001)
NL	47.3	Corbett et al. (2018) ⁹	3.1*	Tiwari (2005) ⁷
AUS	14.0	Kennedy and Citer (2010) ¹⁰	1.8*	Jubb and Galvin (2004)
IRL	20.6	Good et al. (2009)	2.7	Good et al. (2009)
ESP	10.7	Diéguez et al. (2007)	3.0	Diéguez et al. (2007)
BEL	36.0	Boelaert et al. (2000)	2.0	Boelaert et al. (2000)
AUT	7.0*	Gasteiner et al. (1999)	2.0*	Gasteiner et al. (1999)

¹USA = United States; WI = Wisconsin; MI = Michigan; DEU = Germany; GBR = Great Britain; NLD = the Netherlands; ITA = Italy; CAN = Canada; QC = Québec; ON = Ontario; BC = British Columbia; AB = Alberta; MB = Manitoba; SK = Saskatchewan; NS = Nova Scotia; PE = Prince Edward Island; NL = Newfoundland; AUS = Australia; IRL = Ireland; ESP = Spain; BEL = Belgium; AUT = Austria.

²Because the simulations include both a regional replacement pool and a MAP-positive herd, both regional cow-level prevalence estimates and within-herd prevalence estimates were required. Most prevalence studies referenced provided only herd-level and regional cow-level estimates. The following equality was used to convert prevalence estimates between the various types: $p_w = p_r/p_h$, where p_w , p_r , and p_h , equal within-herd, regional cow-level, and herd-level prevalence, respectively.

³Herd-weighted average of results from first, second, and third tests.

⁴Average of Lombardy and Veneto regions and weighted by herds sampled in study.

⁵Calculated from reported within-herd prevalence for Lombardy and Veneto regions, weighted by head of cattle sampled in each region.

⁶Average of Canadian cow-level estimates weighted by head of cattle in each province.

⁷Tiwari (2005) Canadian cow-level prevalence estimate.

⁸Corbett et al. (2018) estimate for Canadian western provinces.

⁹Corbett et al. (2018) estimate for Canadian Atlantic provinces.

¹⁰Herd-level prevalence in control region (Victoria).

*Apparent prevalence estimate.

of 10% within infected herds and 50% of herds being infected, annual losses per cow ranged from US\$28.48 in Prince Edward Island to US\$53.16 in Newfoundland, and annual provincial losses ranged from US\$160,000 in Newfoundland to US\$5.73 million in Québec (Table 5). Expanded results with fixed annual production are available in the Appendix; the breakdown of total losses per cow into their source components is available in Table A6, and results for a wider range of prevalence scenarios are available in Table A7.

Sensitivity Analyses

For simplicity, an average Canadian herd with an assumed initial within-herd prevalence of 10% and an assumed herd-level prevalence of 50% in the region has been selected. Changes in estimated losses per cow were most sensitive to changes in within-herd prevalence, followed by annual production per cow, the farm-gate price, the effect of MAP infection on production, and the amount of bacteria shed by lightly shedding animals

Figure 1. Simulated changes in within-herd *Mycobacterium avium* ssp. *paratuberculosis* (MAP) prevalence over time (10,000 iterations) assuming initial mean values of 10% within-herd prevalence and 50% herd-level prevalence. (A) Distribution of proportional changes in within-herd prevalence over a 10-yr horizon with distribution mean identified by μ . (B) Within-herd prevalence and its 90% confidence interval over time.

Figure 2. Simulated changes in *Mycobacterium avium* ssp. *paratuberculosis* (MAP) shedding among animals over time (10,000 iterations) assuming initial mean values of 10% within-herd prevalence and 50% herd-level prevalence. (A) Animals in a MAP-shedding state as a percentage of total herd. (B) Degrees of shedding among MAP-shedding animals.

(Figure 4). The latter 4 variables had a similar effect on estimated losses per cow, which was significantly less than the effect of within-herd prevalence. Regional loss estimates were sensitive to similar variables, but most sensitive to herd-level prevalence. Premature culling losses were most sensitive to the culling risk associated with stage 1 MAP infection, whereas losses due to reduced salvage values and reduced production were most sensitive to within-herd prevalence. Annual production per cow, volume of bacteria shed by lightly shedding animals, effect of infection on production, and additional culling risk to stage 2 infected animals were also influential variables (Figure 5).

DISCUSSION

There are 2 main sets of results from this research: first, results for the limited group of regions for which prevalence estimates are available, and second, results for the more comprehensive group of dairy-producing regions with assumed prevalence scenarios. The estimates from the first set may be useful on a region-by-

Figure 3. Simulated changes in indicators of overall herd health over time (10,000 iterations) assuming initial mean values of 10% within-herd prevalence and 50% herd-level *Mycobacterium avium* ssp. *paratuberculosis* (MAP) prevalence. (A) Cow-culling rate compared with the MAP-negative (MAP-ve) herd over time. (B) Premature culls and MAP-positive (MAP+ve) culls as a percentage of total exits, and forgone production as a percentage of potential production.

region basis if the prevalence estimates they are based on reflect the true prevalence of MAP infection in those regions. However, relying on these prevalence estimates to value JD's economic impact across regions is problematic. Because estimated losses are highly dependent on prevalence and prevalence estimates are heterogeneously derived across studies with no centrally accepted quality assurance and quality control standards in widespread use, it is not possible to confidently compare prevalence estimates across regions. Therefore, variations in estimated losses across regions based on available prevalence estimates may reflect variations across prevalence studies as opposed to variations in economic losses due to JD.

As an example, refer to the first set of results for Germany and the Netherlands using available prevalence estimates. The neighboring countries have many similar key dairy sector characteristics with above-average annual production per cow per year, similar farm-gate prices, aggregated wage rate rates, replacement costs, and other such production variables. Due to the geo-

graphic proximity, level of integration, and similarity of economic characteristics across the 2 dairy industries, it would be intuitively reasonable to expect Germany and the Netherlands to not only have comparable MAP prevalence, but also for MAP infection to have a comparable per cow economic impact on their dairy sectors. However, based on available prevalence estimates, Germany has a herd-level prevalence of 85% and a within-herd prevalence 12.2% (Hacker et al., 2004), whereas the Netherlands has a herd-level prevalence of 55% and a within-herd prevalence of 2.5% (Muskens et al., 2000). As a result, estimated losses per cow on infected farms across the 2 regions are significantly different: MAP-infected farms in Germany are estimated to lose US\$43.08 per cow per year, or 1.41% of gross milk revenue, whereas infected farms in the Netherlands are estimated to lose only US\$15.07 per cow per year, or 0.39% of gross milk revenue. However, when instead using the assumed prevalence scenario of 10% within MAP-infected herds and 50% of herds being infected, there are much closer estimates for the 2 countries: US\$36.40 and US\$42.82 per cow for Germany and the Netherlands, respectively, both accounting for 1.11% of gross milk revenue. There is a similar situation when comparing the 2 largest dairy-producing provinces in Canada: Québec and Ontario. The neighboring regions share many dairy characteristics, have relatively similar regional cow-level prevalence estimates of 3.1% (Tiware, 2005) and 2.4% (VanLeeuwen et al., 2001), but have significantly different herd-level prevalence estimates of 24% and 54% (Corbett et al., 2018) for Québec and Ontario, respectively. Based on these herd-level and regional cow-level prevalence estimates, Québec would have a mean within-herd prevalence of 13% on infected farms, whereas Ontario would have a mean within-herd prevalence of 4%. As a result, infected herds in Québec are estimated to lose US\$60.29 per cow per year or 1.09% of gross milk revenue, whereas infected farms in Ontario are estimated to lose just US\$30.77 per cow per year or 0.56% of gross milk revenue. When prevalence is instead assumed to be uniform across the 2 regions, estimated losses are US\$56.99 and US\$55.35, or 0.97% and 1.01% of revenue for Québec and Ontario, respectively. By using assumed prevalence scenarios across regions, the differences in estimated losses can be wholly attributed to differences in the economic characteristics of the dairy sectors in the 2 regions.

In the assumed prevalence simulations, the revenue-weighted average losses per cow in MAP-positive herds are approximately 1% of gross milk revenue. Production per cow and farm-gate price are positively related to production losses, which account for an average of 65% of total losses. However, for certain countries such as Ireland, New Zealand, and Australia, which have

Table 3. Estimated 10-yr average annual losses (US\$) due to *Mycobacterium avium* ssp. *paratuberculosis* infection for various dairy-producing regions based on available prevalence estimates

Region ¹	Positive herds, losses per cow (90% CI)		Positive herds, losses as % of milk revenue (90% CI)		Regional losses in millions (90% CI)	
USA	53.30	(38.49–68.51)	1.41	(1.02–1.81)	107.92	(63.67–160.18)
WI	47.60	(33.98–61.83)	1.22	(0.87–1.58)	20.67	(11.95–30.92)
MI	43.02	(30.02–57.40)	1.00	(0.70–1.34)	12.07	(6.81–18.27)
DEU	43.08	(30.46–56.25)	1.32	(0.93–1.72)	150.19	(85.82–225.82)
GBR	34.40	(23.82–45.69)	1.07	(0.74–1.42)	49.38	(27.62–74.86)
NLD	15.07	(9.52–21.40)	0.39	(0.25–0.55)	12.85	(6.82–20.35)
ITA	33.45	(22.81–44.78)	1.04	(0.71–1.39)	40.05	(22.48–60.81)
CAN	48.91	(33.41–65.85)	0.86	(0.59–1.16)	20.02	(11.28–30.63)
QC	60.29	(42.91–78.80)	1.09	(0.78–1.43)	5.05	(2.94–7.56)
ON	30.77	(19.73–42.86)	0.56	(0.36–0.78)	5.41	(2.86–8.47)
BC	37.52	(24.56–51.92)	0.59	(0.39–0.82)	2.08	(1.13–3.24)
AB	84.04	(59.59–110.12)	1.37	(0.97–1.79)	4.39	(2.53–6.61)
MB	44.46	(29.48–60.85)	0.75	(0.50–1.03)	1.21	(0.67–1.85)
SK	33.17	(21.61–46.03)	0.55	(0.36–0.76)	0.64	(0.34–1.00)
NS	37.09	(23.49–51.93)	0.66	(0.42–0.92)	0.38	(0.20–0.60)
NB	36.21	(24.29–49.73)	0.68	(0.45–0.93)	0.33	(0.18–0.51)
PE	19.56	(12.47–27.81)	0.35	(0.22–0.49)	0.13	(0.07–0.21)
NL	57.59	(38.78–78.26)	0.76	(0.51–1.03)	0.16	(0.09–0.25)
AUS	31.25	(22.05–40.38)	1.53	(1.08–1.97)	6.68	(3.88–9.95)
IRL	42.81	(30.21–55.52)	1.91	(1.35–2.48)	12.09	(7.02–17.96)
ESP	45.99	(35.57–57.52)	1.39	(1.08–1.74)	4.03	(2.48–5.79)
BEL	21.72	(14.28–29.62)	0.72	(0.48–0.99)	4.15	(2.26–6.43)
AUT	51.21	(41.13–61.75)	1.84	(1.48–2.22)	1.91	(1.19–2.71)

¹USA = United States; WI = Wisconsin; MI = Michigan; DEU = Germany; GBR = Great Britain; NLD = the Netherlands; ITA = Italy; CAN = Canada; QC = Québec; ON = Ontario; BC = British Columbia; AB = Alberta; MB = Manitoba; SK = Saskatchewan; NS = Nova Scotia; PE = Prince Edward Island; NL = Newfoundland; AUS = Australia; IRL = Ireland; ESP = Spain; BEL = Belgium; AUT = Austria.

above-average losses as a percentage of milk revenue, there are interesting underlying structural factors that contribute to the variation across estimates; these 3 countries have average to below-average annual production per cow and farm-gate prices in conjunction with on-average replacement and salvage prices. This combination results in relatively lower milk revenue and therefore production losses, and the values of premature culling and salvage losses having disproportionate effects on total losses relative to other countries. On average for all countries, premature culling and salvage losses account for 24% and 11% of total losses, respectively, but in Ireland, New Zealand, and Australia, they account for 34% to 41% and 16% to 19%, respectively.

The proportional increase in within-herd MAP prevalence over time is perhaps the most important parameter that is not directly identified by the sensitivity analyses; it is the driver of all estimated economic losses because of its effect on within-herd prevalence. As previously mentioned, it was assumed that within-herd MAP prevalence would, on average, double from its initial value over 10 yr. Because future losses are discounted over time, the greater losses resulting from the higher within-herd prevalence toward the end of the horizon had less of an effect on the 10-yr average annual losses than the relatively lesser losses in

the early years. When within-herd prevalence was instead assumed to be stable at 10%, estimated losses decreased by a revenue-weighted average of 13% relative to the estimates obtained from the 10-yr dynamic prevalence models, but similar patterns emerged across regions and the magnitude of the losses were comparable. Other key input variables were revealed through the sensitivity analyses, aside from within-herd and herd-level prevalence, production per cow, and farm-gate price. Not surprisingly, the effect of MAP infection on production is a significant variable for estimated production losses, which account for most of losses per cow, and therefore regional losses due to MAP infection. The bacterial output of lightly MAP-shedding animals was also identified as a significant source of variation in both estimated total losses and sources of losses, particularly for premature culling losses and reduced salvage value losses. Another interesting input variable is the probability of culling associated with subclinical stage 1 MAP infections. This variable was negatively related to all components of total losses aside from premature culling losses. Although this may seem counterintuitive at first, it is logical. The most severe economic damages would occur at later stages of the disease once clinical signs emerge, but most infected animals in the herd are in the subclinical stage. As the risk of stage 1 animals being culled increases, likely for

Table 4. Estimated 10-yr average annual losses (US\$) due to *Mycobacterium avium* ssp. *paratuberculosis* infection for various dairy-producing regions assuming a mean herd-level prevalence of 50% and a mean within-herd prevalence of 10%

Region ¹	Positive herds, losses per cow (90% CI)		Positive herds, losses as % of milk revenue (90% CI)		Regional losses in millions (90% CI)	
EU-28	31.73	(21.86–42.28)	1.08	(0.75–1.44)	364.31	(205.91–551.59)
DEU	36.40	(25.19–47.83)	1.11	(0.77–1.46)	74.86	(42.13–113.37)
FRA	31.33	(21.71–41.59)	1.11	(0.77–1.48)	55.73	(31.71–83.60)
GBR	34.27	(23.66–45.46)	1.06	(0.73–1.41)	32.28	(18.24–48.74)
POL	20.77	(14.27–27.88)	0.86	(0.59–1.15)	23.05	(12.98–35.39)
NLD	42.82	(29.77–56.74)	1.11	(0.77–1.47)	33.31	(18.89–50.42)
ITA	33.06	(23.09–43.92)	1.03	(0.72–1.37)	28.08	(15.94–42.38)
IRL	37.36	(25.29–49.87)	1.67	(1.13–2.22)	25.65	(14.27–38.95)
ESP	30.76	(21.13–41.14)	0.93	(0.64–1.25)	12.61	(7.10–19.03)
DNK	47.53	(32.96–62.98)	1.14	(0.79–1.51)	13.57	(7.70–20.50)
BEL	33.64	(23.31–44.70)	1.12	(0.78–1.49)	8.92	(5.03–13.56)
AUT	33.54	(23.21–44.57)	1.21	(0.84–1.60)	8.96	(5.09–13.47)
CZE	30.33	(20.80–40.86)	0.88	(0.60–1.18)	5.46	(3.10–8.33)
SWE	40.89	(28.26–54.38)	1.14	(0.78–1.51)	6.42	(3.61–9.78)
FIN	44.10	(30.85–58.60)	1.09	(0.76–1.44)	5.84	(3.33–8.84)
USA	42.26	(29.09–56.00)	1.12	(0.77–1.48)	198.42	(112.42–300.44)
CA	41.73	(29.00–55.33)	1.10	(0.76–1.46)	36.29	(20.51–55.30)
WI	39.42	(27.19–52.44)	1.01	(0.70–1.34)	25.18	(14.26–38.06)
ID	37.23	(25.50–50.04)	0.92	(0.63–1.24)	11.37	(6.40–17.54)
NY	43.61	(30.35–57.84)	1.12	(0.78–1.49)	13.62	(7.83–20.61)
TX	40.69	(28.27–54.12)	1.05	(0.73–1.39)	10.97	(6.19–16.69)
MI	40.88	(28.06–54.44)	0.95	(0.65–1.27)	8.69	(4.91–13.14)
PA	36.40	(25.20–48.13)	1.09	(0.75–1.44)	9.47	(5.38–14.23)
MN	38.56	(26.68–51.19)	1.09	(0.75–1.44)	8.76	(4.95–13.26)
NM	38.82	(26.77–51.81)	0.95	(0.66–1.27)	6.42	(3.60–9.67)
WA	42.57	(29.54–56.43)	1.08	(0.75–1.43)	5.91	(3.36–8.96)
BRA	8.31	(5.78–11.02)	1.01	(0.71–1.35)	71.07	(40.35–107.28)
CHN	13.29	(9.17–17.83)	0.96	(0.66–1.29)	79.59	(45.14–120.88)
RUS	14.25	(9.73–19.11)	0.87	(0.59–1.16)	48.70	(27.68–75.12)
NZL	21.75	(15.05–28.85)	1.37	(0.95–1.82)	53.95	(30.52–81.69)
TUR	11.44	(7.85–15.39)	0.90	(0.62–1.21)	36.36	(20.61–55.29)
CAN	56.99	(39.35–75.72)	1.00	(0.69–1.33)	27.78	(15.60–42.04)
QC	53.30	(36.93–70.94)	0.97	(0.67–1.29)	9.47	(5.35–14.38)
ON	55.35	(38.36–73.56)	1.01	(0.70–1.34)	8.98	(5.09–13.6)
BC	62.94	(43.57–83.46)	0.99	(0.69–1.31)	2.65	(1.48–4.00)
AB	67.16	(46.36–89.14)	1.09	(0.76–1.45)	2.66	(1.51–4.04)
MB	56.64	(38.94–75.90)	0.96	(0.66–1.29)	1.17	(0.65–1.79)
SK	62.32	(43.15–82.92)	1.03	(0.71–1.37)	0.91	(0.52–1.39)
NS	52.26	(36.20–70.16)	0.93	(0.64–1.25)	0.56	(0.32–0.85)
NB	51.05	(35.08–68.36)	0.95	(0.66–1.28)	0.49	(0.28–0.75)
PE	52.63	(36.33–70.82)	0.93	(0.64–1.25)	0.38	(0.21–0.58)
NL	77.01	(53.31–102.24)	1.01	(0.70–1.34)	0.23	(0.13–0.35)
AUS	28.21	(19.51–37.61)	1.38	(0.95–1.84)	21.56	(12.19–32.84)
JPN	81.53	(56.37–108.24)	1.02	(0.70–1.35)	34.63	(19.45–52.64)

¹EU-28 = European Union; DEU = Germany; FRA = France; GBR = Great Britain; POL = Poland; NLD = the Netherlands; ITA = Italy; IRL = Ireland; ESP = Spain; DNK = Denmark; BEL = Belgium; AUT = Austria; CZE = Czechia; SWE = Sweden; FIN = Finland; USA = United States; CA = California; WI = Wisconsin; ID = Idaho; NY = New York; TX = Texas; MI = Michigan; PA = Pennsylvania; MN = Minnesota; NM = New Mexico; WA = Washington; BRA = Brazil; CHN = China; RUS = Russia; NZL = New Zealand; TUR = Turkey; CAN = Canada; QC = Québec; ON = Ontario; BC = British Columbia; AB = Alberta; MB = Manitoba; SK = Saskatchewan; NS = Nova Scotia; PE = Prince Edward Island; NL = Newfoundland; AUS = Australia; JPN = Japan.

reasons not explicitly attributable to JD but for below-average weight gain, reproductive issues and infertility, or increased susceptibility to other diseases, 2 things happen in the model: the infection pressure, or amount of MAP bacteria present in the herd, decreases, resulting in less severe infections among other animals, and second, the animals are removed before their infections

can progress to the more costly stages, from both the health and economic perspectives. However, for premature culling losses, these indirect effects are outweighed by the direct effect of less overall culling, so the overall relationship is positive. It is also important to recognize that the net costs associated with a higher culling rate may be overestimated in this model. Because only the

Table 5. Estimated 10-yr average annual losses (US\$) for Canadian dairy producers assuming a mean herd-level *Mycobacterium avium* ssp. *paratuberculosis* (MAP) prevalence of 50%, a mean within-herd prevalence of 10%, and with consideration for supply management (fixed output over time and production losses allocated as increased variable costs necessary to maintain production)

Region ¹	Variable costs per cow ² (US\$)	Positive herds, losses per cow (90% CI)	Positive herds, losses as % of milk revenue (90% CI)	Regional losses in millions (90% CI)
CAN	2,476	35.11 (24.34–46.18)	0.62 (0.43–0.81)	17.11 (9.67–25.74)
QC	2,430	32.23 (22.54–42.34)	0.59 (0.41–0.77)	5.73 (3.23–8.58)
ON	2,256	33.15 (22.80–43.70)	0.60 (0.41–0.79)	5.38 (3.03–8.13)
BC	3,204	41.39 (28.87–53.94)	0.65 (0.45–0.85)	1.74 (0.98–2.62)
AB	3,106	46.42 (32.22–61.30)	0.76 (0.53–1.00)	1.84 (1.05–2.80)
MB	3,014	36.94 (25.82–48.50)	0.63 (0.44–0.82)	0.76 (0.44–1.15)
SK	2,785	39.97 (27.69–52.58)	0.66 (0.46–0.87)	0.59 (0.33–0.89)
NS	2,515	31.00 (21.64–40.45)	0.55 (0.39–0.72)	0.33 (0.19–0.50)
NB	2,464	31.28 (21.97–40.93)	0.58 (0.41–0.76)	0.30 (0.17–0.45)
PE	2,144	28.48 (19.84–37.38)	0.50 (0.35–0.66)	0.21 (0.12–0.31)
NL	4,112	53.16 (37.11–69.50)	0.70 (0.49–0.91)	0.16 (0.09–0.24)

¹CAN = Canada; QC = Québec; ON = Ontario; BC = British Columbia; AB = Alberta; MB = Manitoba; SK = Saskatchewan; NS = Nova Scotia; PE = Prince Edward Island; NL = Newfoundland.

²STATCAN–Table 32–10–0136–01, farm operating revenues and expenses, annual (STATCAN, 2019b). Sum of “Feed, supplements, straw, and bedding,” “Veterinary fees, medicine, and breeding fees,” and “Salaries and wages, including benefits related to employee salaries” for average dairy farms across all revenue levels in 2018. Total per farm divided by number of cows per farm. Number of cows per farm obtained by number of cattle divided by number of farms: CDIC–Number of farms with shipments of milk (CDIC, 2019b). Number of cattle: STATCAN–Table 32–10–0130–01, number of cattle, by class and farm type (STATCAN, 2020).

economic impact of culling due to MAP infection was considered, this model ignores the potential benefits associated with having a greater proportion of younger animals in the herd. For example, age-related conditions such as reduced fertility, udder health, and foot health are all potential sources of economic losses that could be partially offset as a direct result of an increased cow-culling rate.

Last, we discuss the estimates for Canadian herds with consideration for supply management. Although the general method described is appropriate for most dairy industries, the Canadian industry requires special attention. Canada's dairy sector operates with planned and controlled domestic production levels, administered cost-of-production-based pricing of fluid milk, and import controls which help to insulate producers from competitive forces both domestic and foreign. There are 2 consequences relevant to this model: (1) production losses can no longer be measured as forgone milk sales due to the production quota system, and (2) Canada has an above-average farm-gate price, the highest among countries modeled (aside from Japan, which subsidizes dairy production at particularly high rates) and much higher than the farm-gate price in the United States, Canada's most comparable counterpart. Apart from a higher level of total annual output in the United States, both countries have similar dairy sector characteristics in terms of genetics, marketing, consumer preferences, and annual production per cow, and assuming the same within-herd and herd-level MAP prevalence across the 2 countries, there should be similar estimated losses per cow due to MAP infection. However, the above-average farm-gate price

in Canada results in a greater valuation of production losses and therefore total losses per cow in Canada, but those losses represent a lower percentage of gross milk revenue. Although these differences are attributable in part to varying technical and allocative efficiencies across dairy sectors, which are not addressed by this study, the effects of the differing market structures are addressed; to reflect the constraint of fixed production levels in Canada, production losses were subsequently re-estimated as the cost of having additional, less productive MAP-positive cows to maintain a fixed level of production over the 10-yr horizon. Once adjusted, estimated annual losses per cow within MAP-infected herds in Canada fell from US\$56.99 to US\$35.11. Although this is more in line with estimated losses of US\$42.26 per cow in the United States, as a percentage of gross milk revenue, Canadian losses fell from 1.00% to 0.62% compared with 1.12% in the United States. This may be an overcorrection. Although overall production and farm-gate prices in Canada are set annually by the Canadian Dairy Commission and producers can only sell the amount of milk for which they have production quota, there is still competition among producers. The overall level of production generally increases year over year (CDIC, 2019a) and producers trade quota among themselves; more profitable producers purchase quota from less profitable ones through a quota exchange market to increase the size of their operations. The number of dairy farms in Canada has steadily decreased over the last several decades while the size of herds has increased (CDIC, 2019b). In other words, producers operate in an environment somewhere in between fixed production and a purely competitive

market, and therefore true losses due to MAP infection in infected Canadian dairy herds likely lie somewhere in between the 2 estimates, or between US\$35.11 and US\$56.99 per cow per year.

Although the estimated losses due to JD in major dairy-producing regions are significant, they are likely much less than the losses associated with more easily addressable herd health issues such as mastitis. It may seem intuitive that healthier dairy herds generate more profits for producers, but dairy production is complex and producers are often forced to prioritize short-term, immediate losses from relatively acute diseases such as mastitis over long-term losses from chronic diseases such as JD. However, if left unchecked, JD will continue to spread, losses will continue to increase, and controlling the disease will become increasingly difficult. It is also important to recognize that research into potential interactions between MAP and other pathogens that affect dairy cows is still developing. For example, higher mastitis incidences (Diéguez et al., 2008) and higher culling rates due to clinical mastitis (Arrazuría et al., 2014) have been observed in MAP-positive herds, and MAP-positive cows have been shown to have a higher incidence of clinical mastitis (Rossi et al., 2017). National control programs have already been established in several countries including Australia, Ireland, Japan, the Netherlands, and the United States, and JD is

listed by the World Organisation for Animal Health as a priority disease for international trade. The dairy herd-level MAP prevalence in Canada has recently been estimated to be 42% (Corbett et al., 2018), yet Canada has no mandatory control program in place despite JD's pervasiveness. MAP infection in dairy herds may also pose a public health threat; there is concern that MAP may be associated with Crohn's disease in humans (El-Zaatari et al., 2001; Harris and Lammerding, 2001; Hermon-Taylor, 2001; Chacon et al., 2004; Naser et al., 2004; Feller et al., 2007; Abubakar et al., 2008; Waddell et al., 2015), infected cows can shed live MAP in both their feces and milk, and live MAP have been recovered from pasteurized milk (Ellingson et al., 2005; Shankar et al., 2010).

CONCLUSIONS

Although the economic impact of JD in dairy herds has been estimated before, this study is unique in 2 ways: first, it estimates economic losses due to JD across a comprehensive selection of major dairy-producing regions within one methodological framework, and second, it attempts to capture the relationship between economic losses due to JD and the market conditions that arise as a result of supply management in Canada. With assumptions of 10% within-herd prevalence, 50%

Figure 4. Sensitivity of estimated losses due to *Mycobacterium avium* ssp. *paratuberculosis* (MAP) infection in Canadian dairy herds to a range of input variables (10,000 iterations) assuming initial mean values of 10% within-herd prevalence and 50% herd-level prevalence. The color of the sensitivity bars indicates the direction of the relationship between the variable and estimated losses (gray indicates the effect of variable values below their mean value, white indicates the effect of values above their mean, and black indicates that the effect is unclear). (A) Total annual losses per cow. (B) Annual regional losses.

Figure 5. Sensitivity of estimated sources of losses due to *Mycobacterium avium* ssp. *paratuberculosis* (MAP) infection in Canadian dairy herds to a range of input variables (10,000 iterations) assuming initial mean values of 10% within-herd prevalence and 50% herd-level prevalence. The color of the sensitivity bars indicates the direction of the relationship between the variable and estimated losses (gray indicates the effect of variable values below their mean value, white indicates the effect of values above their mean, and black indicates that the effect is unclear). (A) Annual losses due to premature culling. (B) Annual losses due to reduced salvage value. (C) Annual losses due to reduced production.

herd-level prevalence, and a doubling of within-herd prevalence over 10 yr, an estimated 1% of gross milk revenue is lost annually in MAP-positive dairy herds. This translates to revenue-weighted average losses of US\$33 per cow per year on infected farms, with greater losses in regions with higher farm-gate prices and production per cow. Twenty-four percent of those losses are attributable to premature culling, 11% are attributable to reduced salvage values, and 65% are attributable to reduced production. Each year, an estimated US\$198 million is lost due to JD in the United States, US\$75 million in Germany, US\$56 million in France, US\$54 million in New Zealand, and between US\$17 million and US\$28 million in Canada, one of the smallest dairy-producing regions modeled. As research into MAP infection in dairy herds continues to expand, the input values used in these models can be adjusted and updated, perhaps providing evidence of an even greater

direct economic incentive for producers to control this disease and for the continued development of new testing methods and pharmaceutical interventions such as vaccines. This research is an important contribution to the policy discussion surrounding paratuberculosis control in Canada and internationally.

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APPENDIX

Table A1. Key dairy sector characteristics for various dairy-producing regions in order of decreasing 2018 annual production

Region ¹	Annual production ² (1,000 Mt)	Annual production ³ (kg/cow)	Dairy cattle ⁴ (1,000 head)	Farm-gate price ⁵ (US\$/100 kg)
EU-28	166,744	7,279	22,906	40.22
DEU	33,087	8,068	4,101	40.53
FRA	25,055	7,058	3,550	39.92
GBR	15,488	8,243	1,879	39.07
POL	14,171	6,401	2,214	37.71
NLD	14,090	9,079	1,552	42.50
ITA	12,340	7,289	1,693	44.08
IRL	7,831	5,720	1,369	39.20
ESP	7,336	8,968	818	36.83
DNK	5,615	9,851	570	42.41
BEL	4,178	7,898	529	37.96
AUT	3,821	7,169	533	38.77
CZE	3,162	8,808	359	39.33
SWE	2,760	8,818	313	40.85
FIN	2,398	9,083	264	44.72
USA	98,688	10,546	9,358	35.86
CA	18,331	10,572	1,734	35.86
WI	13,870	10,887	1,274	35.86
ID	6,871	11,283	609	35.86
NY	6,750	10,835	623	35.86
TX	5,830	10,856	537	35.86
MI	5,066	11,947	424	35.86
PA	4,838	9,321	519	35.86
MN	4,476	9,881	453	35.86
NM	3,758	11,388	330	35.86
WA	3,055	11,030	277	35.86
BRA	33,491	1,963	17,060	41.71
CHN ⁶	30,640	2,563	11,955	53.87
RUS	30,611	4,492	6,815	36.58
NZL	21,947	4,437	4,946	35.72
TUR	20,037	3,161	6,338	40.22
CAN	10,228	10,519	972	53.93
QC	3,673	10,369	354	53.11
ON	3,377	10,432	324	52.72
BC	906	10,803	84	58.81
AB	867	10,965	79	55.95
MB	448	10,880	41	54.14
SK	329	11,256	29	53.74
NS	226	10,566	21	53.17
NB	191	9,985	19	53.59
PE	151	10,494	14	54.02
NL	64	10,778	6	70.74
AUS	9,176	6,017	1,525	34.00
JPN	7,290	8,607	847	93.15

¹EU-28 = European Union; DEU = Germany; FRA = France; GBR = Great Britain; POL = Poland; NLD = the Netherlands; ITA = Italy; IRL = Ireland; ESP = Spain; DNK = Denmark; BEL = Belgium; AUT = Austria; CZE = Czechia; SWE = Sweden; FIN = Finland; USA = United States; CA = California; WI = Wisconsin; ID = Idaho; NY = New York; TX = Texas; MI = Michigan; PA = Pennsylvania; MN = Minnesota; NM = New Mexico; WA = Washington; BRA = Brazil; CHN = China; RUS = Russia; NZL = New Zealand; TUR = Turkey; CAN = Canada; QC = Québec; ON = Ontario; BC = British Columbia; AB = Alberta; MB = Manitoba; SK = Saskatchewan; NS = Nova Scotia; PE = Prince Edward Island; NL = Newfoundland; AUS = Australia; JPN = Japan.

²Canadian production values: CDIC–Average production based on official–Supervised records (CDIC, 2019a). US annual production values: USDA ERS–Dairy data–Milk cows and production by state and region (USDA ERS, 2019). All other regions: CLAL.it – Dairy by country (CLAL, 2019).

³Canadian annual per cow production values: CDIC–Average production based on official–Supervised records (CDIC, 2019a). US production per cow values: USDA ERS–Milk cows and production by state and region (USDA ERS, 2019). All other regions: CLAL.it–Dairy by country (CLAL, 2019).

⁴Canadian cattle values: STATCAN–Table 32–10–0130–01–Number of cattle, by class and farm type (× 1,000) (STATCAN, 2020). US cattle values: USDA ERS–Dairy data–Milk cows and production by state and region (USDA ERS, 2019). All other regions: CLAL.it–Dairy by country (CLAL, 2019).

⁵Turkey: 2018 EU-28. Australian price: Australian Dairy Industry in Focus–2018 (Dairy Australia, 2019). Canadian values: CDIC–MI011–Canadian farm cash receipts from dairying (CDIC, 2019c). All other regions: CLAL.it–Dairy by country (CLAL, 2019). Converted to 2018 US\$ using IRS.gov–Yearly average currency exchange rates (IRS, 2020).

⁶2017 values.

Table A2. Region-specific aggregated input variables used in the Monte Carlo simulations of the *Mycobacterium avium* ssp. *paratuberculosis*-positive Markov herd model¹

Region ²	gdppc ³ (US\$)	Wage ⁴ (US\$/h)	r-c ⁵ (US\$/hd)	r-oh ⁵ (US\$/hd)	r-bh ⁵ (US\$/hd)	r-m ⁵ (US\$/hd)	s-12 ⁶ (US\$/kg)	s-24 ⁶ (US\$/kg)	s-m ⁶ (US\$/kg)
EU-28	39,928	10.08	59.94	375.71	650.80	764.17	2.12	1.69	0.71
DEU	47,603	12.11	72.01	451.35	781.82	918.02	2.55	2.03	0.85
FRA	41,464	10.39	61.78	387.19	670.69	787.52	2.19	1.74	0.73
GBR	42,944	10.53	62.62	392.48	679.86	798.29	2.22	1.76	0.74
POL	15,421	3.65	21.71	136.05	235.66	276.71	0.77	0.61	0.26
NLD	53,024	14.15	84.11	527.18	913.17	1,072.25	2.98	2.37	0.99
ITA	34,483	9.54	56.73	355.59	615.94	723.24	2.01	1.60	0.67
IRL	78,806	19.39	115.29	722.64	1,251.75	1,469.81	4.08	3.25	1.36
ESP	30,371	7.02	41.75	261.65	453.24	532.19	1.48	1.18	0.49
DNK	61,350	16.33	97.10	608.60	1,054.22	1,237.87	3.44	2.73	1.15
BEL	47,519	11.32	67.32	421.97	730.94	858.27	2.39	1.90	0.79
AUT	51,462	12.53	74.47	466.79	808.56	949.41	2.64	2.10	0.88
CZE	23,079	5.70	33.88	212.33	367.79	431.86	1.20	0.95	0.40
SWE	54,608	14.00	83.26	521.84	903.92	1,061.39	2.95	2.34	0.98
FIN	50,152	14.08	83.70	524.64	908.77	1,067.08	2.97	2.36	0.99
USA	62,795	14.14	84.05	526.79	912.50	1,071.46	2.98	2.37	0.99
CA	60,359	13.59	80.79	506.36	877.11	1,029.90	2.86	2.27	0.95
WI	48,666	10.96	65.14	408.26	707.19	830.38	2.31	1.83	0.77
ID	36,441	8.20	48.77	305.71	529.54	621.79	1.73	1.37	0.58
NY	65,220	14.68	87.29	547.14	947.74	1,112.84	3.09	2.46	1.03
TX	53,737	12.10	71.92	450.80	780.88	916.91	2.55	2.02	0.85
MI	44,201	9.95	59.16	370.81	642.31	754.20	2.10	1.67	0.70
PA	51,841	11.67	69.39	434.90	753.33	884.56	2.46	1.95	0.82
MN	54,805	12.34	73.35	459.76	796.40	935.13	2.60	2.06	0.87
NM	41,619	9.37	55.71	349.15	604.79	710.14	1.97	1.57	0.66
WA	59,333	13.36	79.41	497.75	862.20	1,012.39	2.81	2.24	0.94
BRA	8,921	2.34	13.89	87.04	150.78	177.04	0.49	0.39	0.16
CHN	9,771	3.30	19.64	123.13	213.28	250.43	0.70	0.55	0.23
RUS	11,289	2.59	15.41	96.60	167.34	196.49	0.55	0.43	0.18
NZL	41,945	9.41	55.92	350.49	607.12	712.89	1.98	1.57	0.66
TUR	9,370	2.37	14.07	88.17	152.73	179.34	0.50	0.40	0.17
CAN	46,269	15.66	93.13	583.69	1,011.06	1,187.19	3.30	2.62	1.10
QC	40,389	13.47	80.06	501.77	869.16	1,020.57	2.84	2.25	0.95
ON	46,167	15.28	90.85	569.43	986.36	1,158.18	3.22	2.56	1.07
BC	45,540	16.81	99.96	626.55	1,085.31	1,274.38	3.54	2.81	1.18
AB	61,816	21.71	129.08	809.03	1,401.40	1,645.53	4.57	3.63	1.52
MB	41,409	14.08	83.68	524.51	908.55	1,066.82	2.96	2.36	0.99
SK	53,487	18.04	107.27	672.37	1,164.68	1,367.57	3.80	3.02	1.27
NS	35,641	11.90	70.73	443.34	767.95	901.73	2.51	1.99	0.84
NB	36,970	12.44	73.94	463.44	802.76	942.60	2.62	2.08	0.87
PE	35,111	11.91	70.79	443.67	768.53	902.41	2.51	1.99	0.84
NL	48,761	21.57	128.25	803.86	1,392.44	1,635.01	4.54	3.61	1.51
AUS	57,374	12.25	72.81	456.34	790.46	928.16	2.58	2.05	0.86
JPN	39,290	22.98	136.60	856.16	1,483.02	1,741.37	4.84	3.84	1.61

¹All variables simulated with a normal distribution and standard deviation of 10% of the mean.²EU-28 = European Union; DEU = Germany; FRA = France; GBR = Great Britain; POL = Poland; NLD = the Netherlands; ITA = Italy; IRL = Ireland; ESP = Spain; DNK = Denmark; BEL = Belgium; AUT = Austria; CZE = Czechia; SWE = Sweden; FIN = Finland; USA = United States; CA = California; WI = Wisconsin; ID = Idaho; NY = New York; TX = Texas; MI = Michigan; PA = Pennsylvania; MN = Minnesota; NM = New Mexico; WA = Washington; BRA = Brazil; CHN = China; RUS = Russia; NZL = New Zealand; TUR = Turkey; CAN = Canada; QC = Québec; ON = Ontario; BC = British Columbia; AB = Alberta; MB = Manitoba; SK = Saskatchewan; NS = Nova Scotia; PE = Prince Edward Island; NL = Newfoundland; AUS = Australia; JPN = Japan.³Gross domestic product per capita (gdppc). US gdppc by state (BEA, 2019) and Canadian gross domestic product by province (STATCAN, 2019c). Converted to US\$ (IRS, 2020). All other regions (World Bank, 2020).⁴Estimated aggregate dairy wage rate (wage). US 2018 (USDA NASS, 2019). All other regions (i through n) calculated using the following formula: $wage_i = \frac{wage_{USA} \times gdppc_i \times farm - gate price_i}{farm - gate price_{USA} \times gdppc_{USA}}$.⁵hd = head. Calf (c), open heifer (oh), bred heifer (bh), and mature cow (m) replacement (r) costs. US replacement prices (USDA, 2020). All other regions (i through n) calculated using the following formula: $r_i = \frac{r_{USA} \times gdppc_i \times farm - gate price_i}{farm - gate price_{USA} \times gdppc_{USA}}$.⁶0–12-mo animals (12), 12–24-mo animals (24), and mature cow (m) salvage (s) prices. Canadian salvage prices (STATCAN, 2019a). Converted to kg at 50.8023 kg/cwt (hundredweight) and converted to US\$ (IRS, 2020). All other regions (i through n) calculated using the following formula: $s_i = \frac{s_{CAN} \times gdppc_i \times farm - gate price_i}{farm - gate price_{CAN} \times gdppc_{CAN}}$.

Table A3. Estimated mean value 10-yr average annual losses (US\$ per cow in *Mycobacterium avium* ssp. *paratuberculosis*-positive herds and millions of US\$ per region) across a range of prevalence scenarios

Region ¹	Prevalence scenarios (within-herd prevalence: herd-level prevalence)							
	5%: 50%		15%: 50%		10%: 30%		10%: 70%	
	Per cow (US\$)	Region (millions of US\$)	Per cow (US\$)	Region (millions of US\$)	Per cow (US\$)	Region (millions of US\$)	Per cow (US\$)	Region (millions of US\$)
EU-28	18.77	214.92	40.82	467.49	30.40	208.89	32.41	519.62
DEU	21.48	44.03	46.93	96.22	34.89	42.92	37.19	106.77
FRA	18.34	32.55	39.93	70.87	30.85	32.85	32.50	80.76
GBR	20.30	19.07	44.02	41.35	32.82	18.50	34.99	46.02
POL	12.63	13.99	26.31	29.13	19.92	13.23	21.23	32.90
NLD	25.25	19.59	55.14	42.79	41.00	19.09	43.72	47.49
ITA	19.67	16.65	42.39	35.89	31.68	16.09	33.77	40.02
IRL	21.18	14.50	49.05	33.58	35.70	14.66	38.08	36.49
ESP	18.52	7.57	39.19	16.03	29.49	7.24	31.43	18.00
DNK	27.96	7.97	61.30	17.47	45.51	7.78	48.53	19.36
BEL	19.82	5.24	43.37	11.47	32.23	5.11	34.36	12.72
AUT	19.61	5.23	43.40	11.57	32.11	5.14	34.24	12.78
CZE	18.41	3.30	38.48	6.91	29.09	3.13	31.01	7.79
SWE	24.06	3.77	52.73	8.25	39.16	3.68	41.75	9.15
FIN	26.09	3.44	56.77	7.49	42.27	3.35	45.06	8.33
USA	24.91	116.57	54.47	254.88	40.49	113.67	43.17	282.77
CA	24.62	21.35	53.69	46.55	39.95	20.78	42.59	51.69
WI	23.51	14.97	50.51	32.18	37.79	14.44	40.28	35.92
ID	22.45	6.83	47.39	14.43	35.69	6.52	38.04	16.22
NY	25.69	8.00	56.22	17.51	41.77	7.81	44.54	19.42
TX	24.15	6.49	52.21	14.02	38.97	6.28	41.55	15.62
MI	24.54	5.20	52.17	11.06	39.18	4.98	41.77	12.40
PA	21.52	5.58	46.85	12.16	34.88	5.43	37.18	13.51
MN	22.79	5.16	49.61	11.24	36.94	5.02	39.38	12.49
NM	23.32	3.85	49.54	8.17	37.22	3.69	39.68	9.16
WA	25.19	3.49	54.73	7.58	40.77	3.39	43.47	8.43
BRA	4.95	42.25	10.65	90.87	7.97	40.78	8.49	101.43
CHN	7.97	47.62	16.96	101.40	12.73	45.67	13.57	113.59
RUS	8.67	29.53	18.08	61.61	13.68	27.97	14.58	69.54
NZL	12.56	31.06	28.31	70.01	20.81	30.87	22.19	76.82
TUR	6.93	21.95	14.56	46.14	10.98	20.88	11.71	51.93
CAN	34.00	16.53	72.99	35.48	54.62	15.93	58.23	39.63
QC	31.95	5.66	68.11	12.06	51.11	5.43	54.48	13.51
ON	33.02	5.34	70.92	11.48	53.07	5.15	56.57	12.82
BC	37.64	1.58	80.60	3.38	60.38	1.52	64.36	3.78
AB	39.67	1.57	86.44	3.42	64.33	1.53	68.59	3.80
MB	33.98	0.70	72.35	1.49	54.31	0.67	57.89	1.67
SK	37.07	0.54	79.94	1.17	59.72	0.52	63.67	1.30
NS	31.48	0.34	66.60	0.71	50.11	0.32	53.41	0.80
NB	30.65	0.29	65.16	0.63	48.95	0.28	52.17	0.70
PE	31.70	0.23	67.04	0.48	50.45	0.22	53.78	0.54
NL	45.89	0.14	98.67	0.30	73.80	0.13	78.67	0.33
AUS	16.27	12.41	36.71	27.99	26.97	12.34	28.76	30.71
JPN	48.56	20.57	104.47	44.24	78.12	19.85	83.28	49.38

¹EU-28 = European Union; DEU = Germany; FRA = France; GBR = Great Britain; POL = Poland; NLD = the Netherlands; ITA = Italy; IRL = Ireland; ESP = Spain; DNK = Denmark; BEL = Belgium; AUT = Austria; CZE = Czechia; SWE = Sweden; FIN = Finland; USA = United States; CA = California; WI = Wisconsin; ID = Idaho; NY = New York; TX = Texas; MI = Michigan; PA = Pennsylvania; MN = Minnesota; NM = New Mexico; WA = Washington; BRA = Brazil; CHN = China; RUS = Russia; NZL = New Zealand; TUR = Turkey; CAN = Canada; QC = Québec; ON = Ontario; BC = British Columbia; AB = Alberta; MB = Manitoba; SK = Saskatchewan; NS = Nova Scotia; PE = Prince Edward Island; NL = Newfoundland; AUS = Australia; JPN = Japan.

Table A4. Estimated sources of losses per cow in various dairy-producing regions assuming a *Mycobacterium avium* ssp. *paratuberculosis* herd-level prevalence of 50% and a within-herd prevalence 10%

Region ¹	Proportion of losses		
	Premature culling	Reduced salvage value	Reduced production
EU-28	0.25	0.12	0.63
DEU	0.26	0.12	0.61
FRA	0.26	0.12	0.62
GBR	0.24	0.11	0.64
POL	0.14	0.06	0.80
NLD	0.26	0.12	0.62
ITA	0.23	0.11	0.67
IRL	0.41	0.19	0.40
ESP	0.18	0.08	0.74
DNK	0.27	0.13	0.60
BEL	0.27	0.12	0.61
AUT	0.30	0.14	0.57
CZE	0.15	0.07	0.78
SWE	0.27	0.13	0.60
FIN	0.25	0.12	0.63
USA	0.27	0.12	0.61
CA	0.26	0.12	0.62
WI	0.22	0.10	0.68
ID	0.17	0.08	0.74
NY	0.27	0.12	0.61
TX	0.24	0.11	0.66
MI	0.19	0.09	0.72
PA	0.25	0.12	0.63
MN	0.25	0.12	0.63
NM	0.19	0.09	0.72
WA	0.25	0.11	0.64
BRA	0.22	0.10	0.67
CHN	0.20	0.09	0.71
RUS	0.14	0.07	0.79
NZL	0.34	0.16	0.50
TUR	0.16	0.08	0.76
CAN	0.22	0.10	0.68
QC	0.20	0.09	0.71
ON	0.22	0.10	0.68
BC	0.21	0.10	0.69
AB	0.26	0.12	0.63
MB	0.20	0.09	0.71
SK	0.23	0.11	0.66
NS	0.18	0.08	0.74
NB	0.19	0.09	0.72
PE	0.18	0.08	0.74
NL	0.22	0.10	0.68
AUS	0.34	0.16	0.50
JPN	0.22	0.10	0.67

¹EU-28 = European Union; DEU = Germany; FRA = France; GBR = Great Britain; POL = Poland; NLD = the Netherlands; ITA = Italy; IRL = Ireland; ESP = Spain; DNK = Denmark; BEL = Belgium; AUT = Austria; CZE = Czechia; SWE = Sweden; FIN = Finland; USA = United States; CA = California; WI = Wisconsin; ID = Idaho; NY = New York; TX = Texas; MI = Michigan; PA = Pennsylvania; MN = Minnesota; NM = New Mexico; WA = Washington; BRA = Brazil; CHN = China; RUS = Russia; NZL = New Zealand; TUR = Turkey; CAN = Canada; QC = Québec; ON = Ontario; BC = British Columbia; AB = Alberta; MB = Manitoba; SK = Saskatchewan; NS = Nova Scotia; PE = Prince Edward Island; NL = Newfoundland; AUS = Australia; JPN = Japan.

Table A5. Estimated mean value annual losses (US\$ per cow in *Mycobacterium avium* ssp. *paratuberculosis*-positive herds and millions US\$ per region) with an assumed stable within-herd prevalence of 10% and a herd-level prevalence of 50%

Region ¹	Annual losses (US\$ per cow)	Annual losses (% of milk revenue)	Annual losses (millions of US\$ per region)
EU-28	27.67	0.95	316.89
DEU	31.67	0.97	64.94
FRA	27.11	0.96	48.12
GBR	29.93	0.93	28.12
POL	18.60	0.77	20.59
NLD	37.24	0.97	28.90
ITA	28.99	0.90	24.54
IRL	31.30	1.40	21.43
ESP	27.28	0.83	11.16
DNK	41.23	0.99	11.75
BEL	29.23	0.98	7.73
AUT	28.94	1.04	7.71
CZE	27.10	0.78	4.87
SWE	35.48	0.99	5.55
FIN	38.46	0.95	5.08
USA	36.74	0.97	171.92
CA	36.31	0.96	31.48
WI	34.64	0.89	22.07
ID	33.06	0.82	10.07
NY	37.89	0.98	11.80
TX	35.60	0.91	9.56
MI	36.15	0.84	7.66
PA	31.73	0.95	8.23
MN	33.61	0.95	7.61
NM	34.35	0.84	5.67
WA	37.14	0.94	5.14
BRA	7.30	0.89	62.27
CHN	11.74	0.85	70.15
RUS	12.76	0.78	43.47
NZL	18.54	1.17	45.86
TUR	10.20	0.80	32.32
CAN	50.11	0.88	24.36
QC	47.07	0.85	8.34
ON	48.67	0.88	7.88
BC	55.46	0.87	2.33
AB	58.50	0.95	2.31
MB	50.06	0.85	1.03
SK	54.64	0.90	0.80
NS	46.36	0.83	0.50
NB	45.15	0.84	0.43
PE	46.69	0.82	0.34
NL	67.63	0.89	0.20
AUS	24.03	1.17	18.32
JPN	71.57	0.89	30.31

¹EU-28 = European Union; DEU = Germany; FRA = France; GBR = Great Britain; POL = Poland; NLD = the Netherlands; ITA = Italy; IRL = Ireland; ESP = Spain; DNK = Denmark; BEL = Belgium; AUT = Austria; CZE = Czechia; SWE = Sweden; FIN = Finland; USA = United States; CA = California; WI = Wisconsin; ID = Idaho; NY = New York; TX = Texas; MI = Michigan; PA = Pennsylvania; MN = Minnesota; NM = New Mexico; WA = Washington; BRA = Brazil; CHN = China; RUS = Russia; NZL = New Zealand; TUR = Turkey; CAN = Canada; QC = Québec; ON = Ontario; BC = British Columbia; AB = Alberta; MB = Manitoba; SK = Saskatchewan; NS = Nova Scotia; PE = Prince Edward Island; NL = Newfoundland; AUS = Australia; JPN = Japan.

Table A6. Estimated sources of losses per cow in Canadian regions assuming a *Mycobacterium avium* ssp. *paratuberculosis* herd-level prevalence of 50% and a within-herd prevalence 10%, and with consideration for supply management (fixed output over time and production losses allocated as increased variable costs necessary to maintain production)

Region ¹	Proportion of losses		
	Premature culling	Reduced salvage value	Reduced production
CAN	0.35	0.16	0.48
QC	0.33	0.15	0.52
ON	0.37	0.17	0.47
BC	0.32	0.15	0.53
AB	0.37	0.17	0.46
MB	0.30	0.14	0.56
SK	0.36	0.17	0.48
NS	0.30	0.14	0.56
NB	0.31	0.15	0.54
PE	0.33	0.15	0.52
NL	0.32	0.15	0.53

¹CAN = Canada; QC = Québec; ON = Ontario; BC = British Columbia; AB = Alberta; MB = Manitoba; SK = Saskatchewan; NS = Nova Scotia; PE = Prince Edward Island; NL = Newfoundland.

Table A7. Estimated mean value 10-yr average annual losses (US\$ per cow in *Mycobacterium avium* ssp. *paratuberculosis*-positive herds and millions US\$ per region) for Canadian dairy across a range of prevalence scenarios, and with consideration for supply management (fixed output over time and production losses allocated as increased variable costs necessary to maintain production)

Region ¹	Prevalence scenarios (within-herd prevalence: herd-level prevalence)							
	5%: 50%		15%: 50%		10%: 30%		10%: 70%	
	Per cow (US\$)	Region (millions of US\$)	Per cow (US\$)	Region (millions of US\$)	Per cow (US\$)	Region (millions of US\$)	Per cow (US\$)	Region (millions of US\$)
CAN	20.21	9.82	45.75	22.24	33.57	9.79	35.80	24.37
QC	18.68	3.31	41.90	7.42	30.85	3.28	32.90	8.16
ON	19.03	3.08	43.27	7.00	31.70	3.08	33.81	7.66
BC	24.05	1.01	53.76	2.26	39.63	1.00	42.26	2.48
AB	26.61	1.05	60.64	2.40	44.39	1.05	47.34	2.62
MB	21.56	0.44	47.83	0.99	35.36	0.44	37.71	1.09
SK	22.99	0.34	52.13	0.76	38.23	0.33	40.77	0.83
NS	18.08	0.19	40.15	0.43	29.67	0.19	31.64	0.47
NB	18.20	0.17	40.57	0.39	29.94	0.17	31.92	0.43
PE	16.49	0.12	37.01	0.27	27.24	0.12	29.05	0.29
NL	30.86	0.09	68.99	0.21	50.86	0.09	54.24	0.23

¹CAN = Canada; QC = Québec; ON = Ontario; BC = British Columbia; AB = Alberta; MB = Manitoba; SK = Saskatchewan; NS = Nova Scotia; PE = Prince Edward Island; NL = Newfoundland.