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UNIVERSITY OF CALGARY

The economic impact of Johne’s disease (paratuberculosis) in dairy cattle

by

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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 main objectives of this thesis were to estimate the economic impact of MAP infection and potential control practices across a comprehensive selection of dairy-producing regions within a single methodological framework. Additional objectives were to estimate the value of JD control to Canadian dairy producers and to what degree there are economic premiums associated with MAP-negative dairy replacements. Using a combination of Markov Chain Monte Carlo (MCMC) simulation methods, regression analysis, and compensating and equivalent variation analysis, the following results were generated: 1) approximately 1% of gross milk revenue, equivalent to CA$43 (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; 2) vaccination was the most promising type of JD control practice modelled, with dual-effect vaccines (reducing shedding and providing protective immunity) resulting in BCRs between 1.48 and 2.13 in Canada and a break-even period of between 6.17 and 7.61 years; 3) assuming a within-herd prevalence of 10% and a 50% reduction of that prevalence over 10 years, JD control has an estimated annual value of CA$28 per cow for the average Canadian dairy producer; and 4) MAP-negative replacements are associated with an average benefit of CA$96 per purchase in major dairy-producing regions, equivalent to a premium of 13% of aggregated replacement prices.

Preface

This thesis consists of an introductory chapter, three manuscripts (two published and one accepted for publication), a working paper that builds on the results of the three manuscripts, and a concluding chapter. For all manuscripts and the working paper, the first author led the conceptualization, design, and modelling with significant input and supervision from Dr. David Hall from the University of Calgary, Department of Ecosystem and Public Health. However, all coauthors provided input beyond the critical review of methodologies, results, and writing.

Published manuscripts (Chapters 2 and 3):

- Rasmussen P, Barkema HW, Mason S, Beaulieu E, Hall DC. 2021. Economic losses due to Johne's disease (paratuberculosis) in dairy cattle. *J. Dairy Sci.* https://doi.org/10.3168/jds.2020-19381.
- Rasmussen P, Barkema HW, Hall DC. 2021. Effectiveness and economic viability of Johne’s disease (paratuberculosis) control practices in dairy herds. *Front. Vet. Sci.* https://doi.org/10.3389/fvets.2020.614727.

Manuscripts accepted for publication (Chapter 4):

- Rasmussen P, Barkema HW, Mason S, Beaulieu E, Hall DC. Estimation of the value of Johne’s disease (paratuberculosis) control to Canadian dairy producers. *Prev. Vet. Med.* In press.

Working paper (Chapter 5):

- Rasmussen P, Beaulieu E, Barkema HW, Mason S, Hall DC. Economic premiums associated with *Mycobacterium avium* ssp. *paratuberculosis* -negative replacements in major dairy producing regions.

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The Markovian model at the core of thesis also benefitted from discussions with Dr. Jeroen De Buck, Dr. Karin Orsel, and Paul Burden from the University of Calgary, Departments of Production Animal Health and Ecosystem and Public Health, and Dr. Joseph Rasmussen from the University of Lethbridge, Department of Biological Sciences. I would also like to thank the following groups and individuals: the Canadian Dairy Commission for generously providing the results of their annual cost of production studies for the years 2014 to 2018; the provincial dairy producer organizations for their aid with the distribution of the electronic production characteristics questionnaire (from east to west across Canada: NL Dairy Farmers, Dairy Farmers of PEI, Dairy Farmers of Nova Scotia, Dairy Farmers of New Brunswick, Les Producteurs de Lait du Québec, Dairy Farmers of Ontario, Dairy Farmers of Manitoba, SaskMilk, Alberta Milk, and BC Dairy Association); Ellen De Jong and Kayley McCubbin from the University of Calgary, Department of Production Animal Health for their aid with the distribution of the questionnaire in paper form; the dairy producers across Canada that responded to the questionnaire; and Dr. Élodie Pastural from VIDO-InterVac, Saskatoon for her help with conference bookings and reimbursements. Finally, I would like to thank Genome Canada, Genome Prairie, and Genome British Columbia for their funding through grant number 225RVA and the Canadian Dairy Commission for their funding through the Workforce Development Initiative Scholarship.

Dedication

To my parents Alice and Joe, my brother Luke, and my beautiful wife Leo.

Table of Contents

List of Tables

List of Figures

CHAPTER 1. INTRODUCTION

1.1. Johne’s disease

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* subspecies *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 weeks in a dry fully shaded environment (Whittington et al., 2004). While MAP infection has also been observed in omnivores and carnivores such as wild rabbits (Greig et al., 1999), foxes (Beard et al., 2001), and non-human 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 four 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. 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). 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; Abubakar et al., 2007; Feller et al., 2007; Waddell et al., 2015), that infected cows can shed live MAP in both their feces and milk, and that live MAP has been recovered from pasteurized milk (Ellingson et al., 2005; Shankar et al., 2010).

MAP infection 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). Calves up to one year of age have demonstrated susceptibility to MAP infection (Mortier et al., 2013; Corbett et al., 2019), with calves less than one month of age being particularly vulnerable and more likely to develop JD than animals infected later in life (Quinn et al., 2011). The rate at which MAP is shed from an individual animal may change over time, sometimes with intermittent episodes of shedding and non-shedding. The intermittent nature of shedding and the transition of cattle through various levels of intensity of shedding make this disease well-suited to modeling using a Markovian approach, which is appropriate for analyzing systems that involve multi-state and dynamic elements, such as fecal shedding (Ivanek et al., 2007). There is an 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).

Animals in the initial or silent stage are often undetected even with the most sensitive tests, and organisms present in the intestinal tract may go unnoticed even upon post-mortem microscopic examination (Fecteau and Whitlock, 2010). Clinical signs of JD generally do not appear before two years of age; they develop slowly during a prolonged subclinical phase (Quinn et al., 2011) and are most often exhibited by MAP-infected cattle in the two to six-year range (Radostits et al., 2006). In the subclinical stage, although animals still do not demonstrate clinical signs of infection such as weight loss or diarrhea, they may begin to test positive on fecal culture and may shed MAP through their manure, contaminating the environment and acting as a source of infection for other animals (Fecteau and Whitlock, 2010). Once the disease has progressed to the clinical stage, the animal may begin to exhibit weight loss despite a normal or even an increased appetite. During a concurrent period of three to six months, persistent or intermittent diarrhea will occur along with decreased milk production (Tiwari et al., 2006). The rate of progression in this stage can vary considerably; the infection can progress from the subclinical stage to the final stage in a matter of weeks, but a more gradual progression is more typical (Fecteau and Whitlock, 2010). The final stage of advanced clinical infection is characterized by marked lethargy, weakness, and severe emaciation in the animal, coupled with pipestream diarrhea, hypoproteinemia, the development of intermandibular edema, or ‘bottle jaw’ (Tiwari et al., 2006), and ultimately death in animals five years or older (Collins et al., 2010).

1.2. Prevalence, economic losses, and control practices

Although the herd-level prevalence of MAP infection likely exceeds 50% in most countries with significant dairy industries (Barkema et al., 2018), herd-level prevalence estimates vary greatly across regions and studies. For example, Diéguez et al. (2007) estimated the herd-level MAP seroprevalence in Galicia, Spain to be 11% while Pozzato et al. (2011) estimated herd-level seroprevalences of 70% and 71% in the Lombardy and Veneto regions of Italy, respectively. Recently, the Canadian herd-level MAP prevalence was estimated at over 47% using environmental fecal culture tests (Corbett et al., 2018), but a lack of methodological consistency across studies makes comparisons across regions problematic. Similar variations appear across within-herd prevalence estimates, ranging from 3% in the Netherlands (Muskens et al., 2000) to 14% in Wisconsin, USA (Collins et al., 1994), with these variations in both herd-level and within-herd prevalence reflected in economic loss estimates. 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%. Intuitively, it may seem obvious that these economic losses warrant some investment in control of JD, and although national control programmes have already been established in several countries including Australia, Ireland, Japan, the Netherlands, and the United States (Whittington et al., 2019), Canada has no mandatory programme in place.

If a proactive approach to Johne’s disease control is to be taken, the precise mechanisms and economic merits of potential control practices require further investigation. It has been estimated that an average benefit of US$8.03 per animal per year is associated with vaccination in US dairy herds (Groenendaal et al., 2015), and it has also been suggested through simulation that the most profitable strategy in average Danish herds is no control practice at all, with testing and culling being the most profitable in low-hygiene herds (Kirkeby et al., 2016). Similarly, a recent stochastic simulation study found that no paratuberculosis control was the highly preferred strategy in small herds with 10% initial within-herd prevalence and frequently preferred in other herd scenarios (Smith et al., 2017). However, the merit of vaccination as a standalone control practice for JD given currently available vaccines is debatable. Mycopar®, an oil-adjuvant inactivated MAP vaccine, has been found to be ineffective at providing protective immunity from JD in cattle (Köhler et al., 2001; Uzonna et al., 2003; Thukral et al., 2020) and to cause severe inflammation at the injection site (O'Neill et al., 2005), and has now been discontinued by its manufacturer Boehringer Ingelheim (Wisconsin Department of Agriculture, 2019). Silirum®, another oil-adjuvant inactivated MAP vaccine, while still in production by its manufacturer Zoetis Australia, also fails to provide significant protective immunity resulting instead in reduced clinical signs among vaccinated MAP-infected cattle (Muñoz et al., 2005). These benefits may not outweigh the potential costs of adopting vaccination; Silirum® can cross-react with bovine tuberculosis (bTB) serological tests (Coad et al., 2013). As stated by the World Organisation for Animal Health (OIE), bTB is a confirmed zoonosis and strictly regulated in most countries with significant cattle populations, with repeated positive test results potentially leading to costly international and domestic trade bans (OIE, 2021).

Although the lack of a truly effective JD vaccine may seem strange given the consensus that there are significant economic losses associated with MAP infection in dairy herds, it is important to appreciate where the disease sits not just in terms of dairy herd health threats, but also public health threats. MAP is a bacterium found globally with yet unconfirmed zoonotic potential that primarily affects ruminants through a slowly progressing, often undetected disease process. In the context of the COVID-19 pandemic caused by SARS-CoV-2 that quickly spreads and continues to directly impact human livelihoods, the lack of an effective JD vaccine may seem more understandable; the global resources allocated to COVID-19 vaccine development efforts far outweigh those allocated to a production animal vaccine conferring protection against a disease such as JD. Nonetheless, research into more effective JD vaccines is ongoing and highly promising (Thukral et al., 2020; ReVAMP, 2021), and given the development of an effective and non-cross-reactive vaccine, vaccination has the potential to become a key component of future JD control programmes.

1.3. Hypotheses

This thesis has four main hypotheses:

1) There are significant economic losses due to MAP infection in dairy herds, and on a per-cow level, those losses should be similar across dairy sectors sharing similar economic and production characteristics;

2) Given the development of an effective vaccine, vaccination is an economically viable control practice;

3) There is value in controlling JD that can be appreciated by Canadian dairy producers, despite MAP infection being a lesser priority relative to more acute and easily addressed herd health issues;

4) MAP-negative replacement animals have greater economic value than potentially MAP-positive replacement animals with an unknown MAP infection status, and there is a potential for dairy producers to capture domestic and international trade benefits through JD control.

1.4. Objectives

The main purpose of this thesis was to contribute to the information available to both dairy producers and policymakers in the development of JD control strategies, while the main objectives were to estimate the economic impact of MAP infection and potential control practices across a comprehensive selection of dairy-producing regions within a single methodological framework. Additional objectives were to estimate the value of controlling JD to Canadian dairy producers and the degree to which there are economic premiums associated with MAP-negative dairy replacements.

1.5. Thesis outline

To address the objectives, a Markov Chain model was developed with the spread of MAP-infection within a dairy herd modelled over a 10-year horizon. In this MAP-positive model, 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 stage of infection can progress, regress, or remain the same. Each stage of infection is associated with a different risk of being culled, and each stage has some non-shedding, lightly-shedding, moderately-shedding, and heavily-shedding states within it. Infection pressure on animals in the herd is determined by the number and degree of shedding animals in the herd in each period, and all other potential outcomes are functions of that infection pressure. Region-specific economic variables for a comprehensive selection of regions were then included in Monte Carlo simulations to compare MAP-negative herds to MAP-positive herds and estimate the economic losses due to JD in dairy herds (Chapter 2). This Markovian framework was then augmented to model the changes in herd structure and the benefits and costs of various control practices (Chapter 3). Results from Chapter 2, specifically the impact of production losses due to MAP infection in supply managed Canadian dairy herds, were combined with analyses of confidential cost of production data from the Canadian Dairy Commission (CDC) and a dairy production characteristics questionnaire distributed across Canada to estimate the value of JD control to Canadian dairy producers

(Chapter 4). Lastly, the Markovian framework was once again used to estimate the economic premiums associated with the purchase of MAP-negative dairy replacements (Chapter 5).

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CHAPTER 2. ECONOMIC LOSSES IN DAIRY HERDS ACROSS REGIONS

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2.1. 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 (MCMC) 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 modelled.

2.2. 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* subspecies *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 weeks in a dry fully shaded environment (Whittington et al., 2004). While MAP infection has also been observed in omnivores and carnivores such as wild rabbits (Greig et al., 1999), foxes (Beard et al., 2001), and non-human 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 four 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 to due 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. However, the former can be addressed by modelling with region-specific economic variables and the latter by modelling with a range of assumed prevalence scenarios across regions. Accordingly, this study uses Markov Chain Monte Carlo (MCMC) 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.

2.3. 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 to baseline MAP-negative herds from each region to generate three main sets of results: the general behaviour 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. Lastly, the Canadian estimates were re-examined 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).

2.3.1. MAP-negative models

A MAP-negative baseline Markov herd model was developed with purchased replacements coming from a separately modelled MAP-negative pool. The herd and replacement pools were modelled using the same constraints and structure: 15 age categories ranging from “0 to 3 months” to “8 to 9 years” 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 one year. In the MAP-negative models, animals either age or may be culled until they reach the “8 to 9 years” category when they must be culled. Natural replacements (aged 0 to 12 months) and purchased replacements (aged 12 months to 3 years) are added to the herd each year in order 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 modelled for 50 1-year 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 one and two years 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 one and two years of age per 100 cows per year (Van Biert, 2019).

2.3.2. MAP-positive models

While in the MAP-negative models there were only two possible outcomes in each age group’s transition matrix (i.e., continue aging or be culled), the MAP-positive models are more complex. MAP infection 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 modelling 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:

$$infection\, pressure = f_t = \frac{MAP_l * L_t + MAP_m * M_t + MAP_h * H_t}{animals} \tag{1}$$

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:

$$P(infection) = \left(1 - e^{-\sum_{i=0}^{n} f_i * w}\right) * \frac{f}{\sum_{i=0}^{n} f_i} * (1 - x) \tag{2}$$

$$P(progression) = \left(1 - e^{-\sum_{i=0}^{n}\left(f_i + \frac{1}{f_i}\right) * w}\right) * \frac{f}{\sum_{i=0}^{n}\left(f_i + \frac{1}{f_i}\right)} * (1 - x) \tag{3}$$

$$P(regression) = \left(1 - e^{-\sum_{i=0}^{n}\left(f_i + \frac{1}{f_i}\right) * w}\right) * \frac{\frac{1}{f}}{\sum_{i=0}^{n}\left(f_i + \frac{1}{f_i}\right)} * (1 - x) \tag{4}$$

$$P(inertia) = \left(e^{-\sum_{i=0}^{n}\left(f_i + \frac{1}{f_i}\right) * w}\right) * \frac{(1 - x)}{a} \tag{5}$$

where:

n is the number of potential outcomes given an animal's age and stage of infection; $P(infection)$ is the probability of an animal transitioning from a MAP-negative stage to the initial stage of infection (the probability of infection); $P(progression)$ is the probability of transitioning from one stage of infection to a more severe stage (the probability of disease progression); $P(regression)$ is the probability of transitioning from one stage of infection to a less severe stage (the probability of disease regression); and, $P(inertia)$ 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 $P(infection)$, and there is a positive relationship between infection pressure f and $P(progression)$ and a negative relationship between infection pressure f and $P(regression)$. 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 modelling initial infectious dose-dependence, which would require complicated tracking of infected animals through time not readily accomplished within a Markov framework. However, the modelling approach employed here still captures the positive feedback between within-herd prevalence, infection pressure, and the rate of infection progression. Lastly, by definition, there is a negative relationship between the sum of all infection, progression, and regression probabilities and $P(inertia)$ 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 non-shedding 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 years. However, by adjusting this value, other within-herd prevalence scenarios could be modelled, from scenarios where prevalence remains relatively constant over 10 years 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 months 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 months 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 years 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 years 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 non-shedding states within them except stage 4; animals can only become infected in their first 12 months; once an animal is MAP-positive they will remain positive for their lifetime; and, progression/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 one year. 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 one year.

2.3.3. 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 2-1**), 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) were 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 50 1-year periods were simulated using the MAP-positive model transition probabilities previously described. As prevalence increased over time in this 50-year simulation, the distribution of infected animals in the herd changed, generating a range of disease distributions for every iteration within each subsequent 10-year 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.

2.3.4. Economic losses

To estimate region-specific economic losses, region-specific economic input variables were incorporated into the simulations. Detailed values are available in the Appendix **(Tables A-1** and **A-2**). After each period, the MAP-positive herd was compared to 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 labour 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 three 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-year 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, 2020a) 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 (TBC, 2007). Finally, two main sets of simulations were run: one using available prevalence estimates (**Table 2-2**) 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.

2.4. Results

2.4.1. General behaviour of the models

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 approximately equivalent to a doubling of within-herd prevalence from 10% to 20% over 10 years (**Figure 2-1**). The percentage of infected animals that shed MAP increased from 6% to 12% over the 10-year horizon, with the percentage of moderately- and heavily-shedding animals steadily increasing from 6% to over 10% of all shedding animals by year 10 (**Figure 2-2**). 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 2-3A**). While 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-year horizon in **Figure 2-3B**: 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%.

2.4.2. Economic losses using 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 dollars 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 2-3**).

2.4.3. Economic losses using assumed prevalence scenarios

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 2-4**). Results for a wider range of prevalence scenarios are presented in the Appendix (**Table A-3**). 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 modelled are available in the Appendix (**Table A-4**). 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 A-5**): 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%. When compared to estimated losses within the dynamic 10-year prevalence models, the stable 1-year, and therefore non-discounted losses per cow were between 10% and 16% less, 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.

2.4.4. Economic losses in Canadian herds

This section re-examines 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 in order to maintain a fixed level of production over the 10-year horizon. With assumed prevalence values 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 2-5**). 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 A-6**, and results for a wider range of prevalence scenarios are available in **Table A-7**.

2.4.5. 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 2-4**). The latter four variables had a similar impact on estimated losses per cow, which was significantly less than the impact 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, while 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 2-5**).

2.5. Discussion

There are two main sets of results from this research: firstly, results for the limited group of regions for which prevalence estimates are available, and secondly, 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-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 valuate 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 (QAQC) 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 rage rates, replacement costs, and other such production variables. Due to the geographic proximity, level of integration, and similarity of economic characteristics across the two dairy industries, it would be intuitively reasonable to expect Germany and the Netherlands to not only have comparable MAP prevalence, but 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 two 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 two countries: US$36.40 and US$42.82 dollars 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 two 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% (Tiwari, 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 while 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 while 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 two 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 two 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 above-average losses as a percentage of milk revenue, there are interesting underlying structural factors that contribute to the variation across estimates; these three 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 accounts 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 years. Because future losses are discounted over time, the greater losses resulting from the higher within-herd prevalence towards the end of the horizon had less impact on the 10-year 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-year 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. While this may seem counterintuitive at first, this 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 reasons not explicitly attributable to JD but for below-average weight gain, reproductive issues and infertility, or increased susceptibility to other diseases, two things happen in the model: the infection pressure, or amount of MAP bacteria present in the herd, reduces resulting in less severe infections among other animals, and secondly, 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 economic impact of culling due to MAP-infection were 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.

Lastly, we discuss the estimates for Canadian herds with consideration for supply management. While 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 two 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 modelled (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 two 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. While 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 the cost of having additional, less productive MAP-positive cows in order to maintain a fixed level of production over the 10-year horizon. Once adjusted, estimated annual losses per cow within MAP-infected herds in Canada fell from US$56.99 to US$35.11. While this is more in line with estimated losses of US$42.26 per cow in the United Sates, as a percentage of gross milk revenue, Canadian losses fell from 1.00% to 0.62% compared to 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 (CDC) 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 amongst 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 two estimates, or between US$35.11 and US$56.99 per cow per year.

2.6. Conclusions

Although JD’s economic impact in dairy herds has been estimated before, this study is unique in two ways: firstly, it estimates economic losses due to JD across a comprehensive selection of major dairy-producing regions within one methodological framework, and secondly, 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% herd-level prevalence, and a doubling of within-herd prevalence over 10 years, 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. 24% of those losses are attributable to premature culling, 11% attributable to reduced salvage values, and 65% 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 modelled. While these are significant losses, 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 like 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 programmes have already been established in several countries including Australia, Ireland, Japan, the Netherlands, and the United States, and JD is listed by the OIE 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 programme 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; Abubakar et al., 2007; Feller et al., 2007; 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). 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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Table 2-1. Input variables used in for the Monte Carlo simulations of the Mycobacterium avium subsp. paratuberculosis -positive Markov herd model. All variables simulated with a normal distribution and a standard deviation of 10% of the mean.

Variable	Mean value	Unit	Source
Effect of infection on production	0.59	proportion	McAloon et al. (2016)
Replacement pool	5000.00	cows	Assumed
Replacement cost (labour)	2.00	hours	Assumed
Bacteria shed – Light shedders[1]	5.00	CFU	Whitlock et al. (2000) and Crossley et al. (2005)
Bacteria shed – Moderate shedders[1]	25.00	CFU	Whitlock et al. (2000) and Crossley et al. (2005)
Bacteria shed – Heavy shedders[1]	50.00	CFU	Whitlock et al. (2000) and Crossley et al. (2005)
Weight at 0 to 3 months	74.24	kg	Jones and Heinrichs (2017)
Weight at 3 to 6 months	141.82	kg	Jones and Heinrichs (2017)
Weight at 6 to 9 months	214.70	kg	Jones and Heinrichs (2017)
Weight at 9 to 12 months	286.52	kg	Jones and Heinrichs (2017)
Weight at 12 to 15 months	354.86	kg	Jones and Heinrichs (2017)
Weight at 15 to 18 months	425.32	kg	Jones and Heinrichs (2017)
Weight at 18 to 21 months	477.63	kg	Jones and Heinrichs (2017)
Weight at 21 to 24 months	524.05	kg	Jones and Heinrichs (2017)
Weight at maturity (2 to 9 years)	680.39	kg	Jones and Heinrichs (2017)
Value reduction – Stage 4 animals	0.31	proportion	Kudahl and Nielsen (2009)
Value reduction – Stage 3 animals[2]	0.29	proportion	Calculated
Value reduction – Stage 2 animals[2]	0.26	proportion	Calculated
Value reduction – Stage 1 animals[2]	0.15	proportion	Calculated
Culling risk – Stage 4 animals	3.20	ratio	Hendrick et al. (2005)
Culling risk – Stage 3 animals[3]	2.98	ratio	Calculated
Culling risk – Stage 2 animals[3]	2.69	ratio	Calculated
Culling risk – Stage 1 animals[3]	1.08	ratio	Calculated

[1] Light and moderate shedding values based on median CFU count for the range. Heavy shedders at minimum cutoff.

[2] Based on Stage 4 value reduction observed in study. Other values estimated by scaling the Stage 4 value to a truncated cumulative logistic probability distribution (max=0.308, alpha=0.308, beta=0.031).

[3] Based 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 (max=3.200, alpha=3.200, beta=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.

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

Region	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-Ifearulundu et al. (1999)	6.9	Johnson-Ifearulundu et al. (1999)
DEU	84.7*	Hacker et al. (2004)	10.3*[1]	Hacker et al. (2004)
GBR	76.1*[2]	Woodbine et al. (2009)	7.3	Woodbine et al. (2009)
NLD	54.7*	Muskens et al. (2000)	1.4[1]	Muskens et al. (2000)
ITA	70.5	Pozzato et al. (2011)[3]	6.9	Pozzato et al. (2011)[4]
CAN	42.0	Corbett et al. (2018)	3.4*	Weighted Average[5]
QC	23.6	Corbett et al. (2018)	3.1*	Tiwari (2005)[6]
ON	54.1	Corbett et al. (2018)	2.4*	VanLeeuwen et al. (2001)
BC	65.8	Corbett et al. (2018)[7]	3.1*	Tiwari (2005)[6]
AB	65.8	Corbett et al. (2018)[7]	9.1*	Tiwari (2005)
MB	65.8	Corbett et al. (2018)[7]	4.5*	VanLeeuwen et al. (2006)
SK	65.8	Corbett et al. (2018)[7]	2.7*	VanLeeuwen et al. (2005)
NS	47.3	Corbett et al. (2018)[8]	3.3*	VanLeeuwen et al. (2001)
NB	47.3	Corbett et al. (2018)[8]	2.9*	VanLeeuwen et al. (2001)
PE	47.3	Corbett et al. (2018)[8]	1.3*	VanLeeuwen et al. (2001)
NL	47.3	Corbett et al. (2018)[8]	3.1*	Tiwari (2005)[6]
AUS	14.0	Kennedy and Citer (2010)[9]	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)

* Apparent prevalence estimate.

[1] Because 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

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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, p_h equal within-herd, regional cow-level, and herd-level prevalence, respectively.

[2] Herd-weighted average of results from 1st, 2nd, and 3rd tests.

[3] Average of Lombardy and Veneto regions and weighted by herds sampled in study.

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

[5] Average of Canadian cow-level estimates weighted by head of cattle in each province.

[6] Tiwari (2005) Canadian cow-level prevalence estimate.

[7] Corbett et al. (2018) estimate for Canadian western provinces.

[8] Corbett et al. (2018) estimate for Canadian Atlantic provinces.

[9] Herd-level prevalence in control region (Victoria).

Table 2-3. Estimated 10-year average annual losses (US$) due to *Mycobacterium avium* subsp. *paratuberculosis* infection for various dairy-producing regions based on available prevalence estimates.

Region	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 - 57.4)	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 - 78.8)	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)

Table 2-4. Estimated 10-year average annual losses (US$) due to *Mycobacterium avium* subsp. *paratuberculosis* infection for various dairy-producing regions assuming a mean herd-level prevalence of 50% and a mean within-herd prevalence of 10%.

Region	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 - 83.6)
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 - 20.5)
BEL	33.64	(23.31 - 44.7)	1.12	(0.78 - 1.49)	8.92	(5.03 - 13.56)
AUT	33.54	(23.21 - 44.57)	1.21	(0.84 - 1.6)	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 - 58.6)	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 - 55.3)
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	(15.6 - 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)

Table 2-5. Estimated 10-year average annual losses (US$) for Canadian dairy producers assuming a mean herd-level 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	Variable costs per cow (US$)[1]	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)

[1] STATCAN - Table 32-10-0136-01 Farm operating revenues and expenses, annual (STATCAN, 2019). 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).

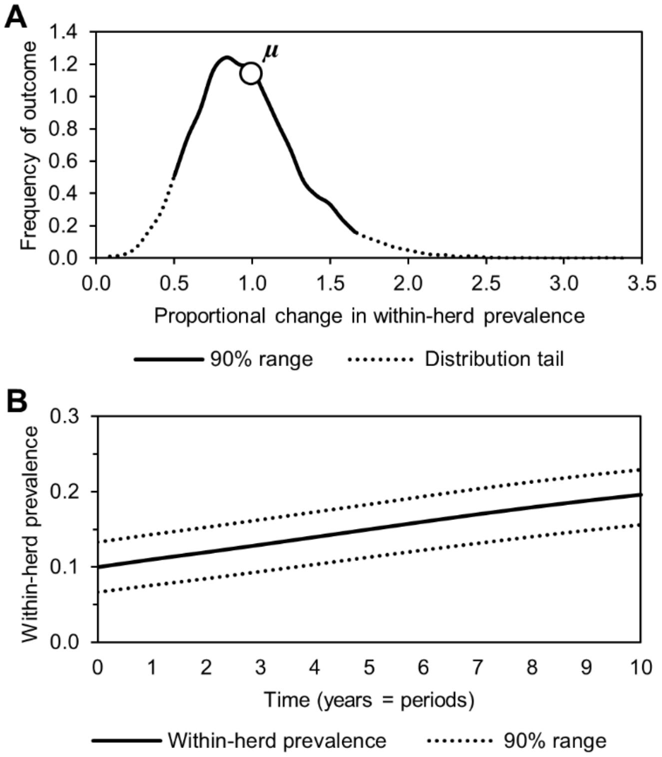

Figure 2-1. Simulated changes in within-herd MAP (*Mycobacterium avium* subsp. *paratuberculosis*) prevalence over time (10,000 iterations) assuming initial mean values of 10% within-herd prevalence and 50% herd-level prevalence. **A**) Distribution of proportional changes in within-herd prevalence over a 10-year horizon with distribution mean identified by ***μ***. **B**) Within-herd prevalence and its 90% confidence interval over time.

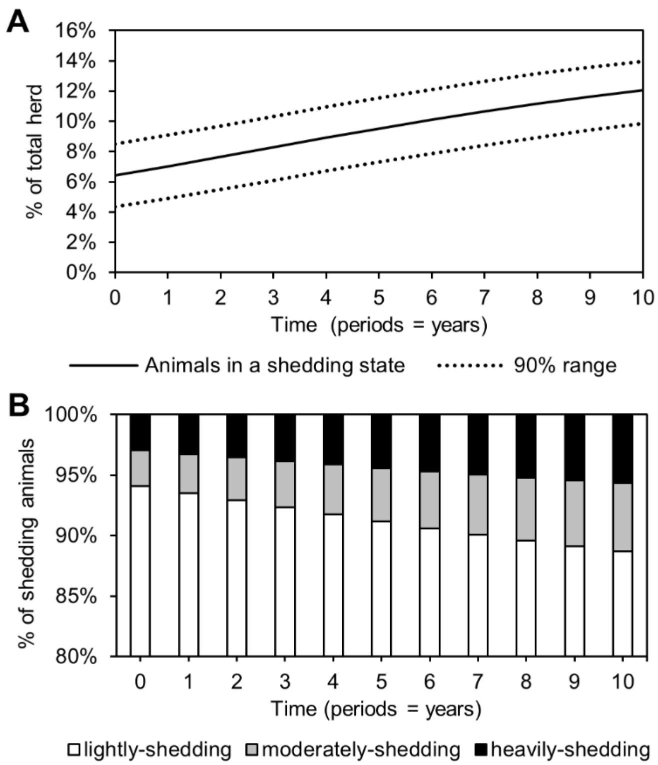

Figure 2-2. Simulated changes in MAP *(Mycobacterium avium* subsp. *paratuberculosis*) - shedding among animals over time (10,000 iterations) assuming initial mean values of 10% within-herd prevalence and 50% herd-level prevalence. **A)** Animals in a MAP-shedding state as a percentage of total herd.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

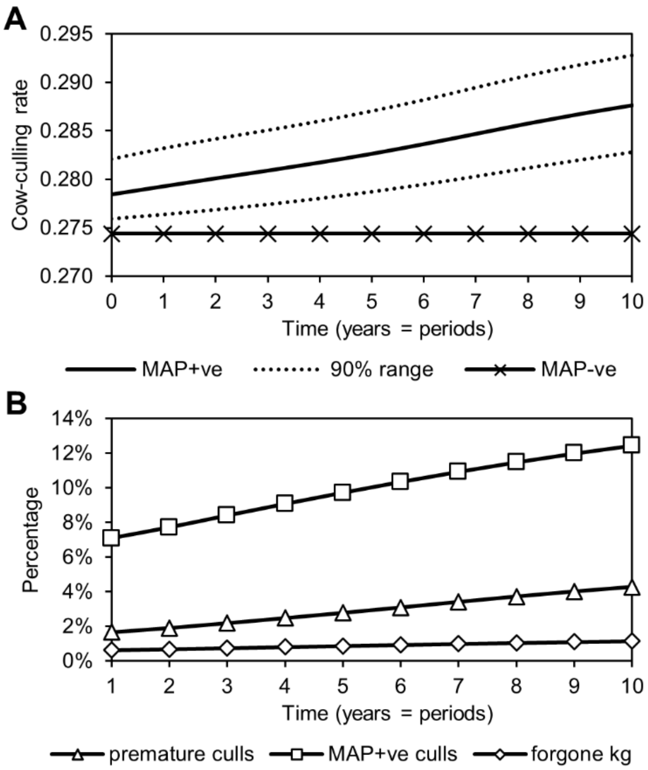

Figure 2-3. Simulated changes in indicators of overall herd health over time (10,000 iterations) assuming initial mean values of 10% within-herd prevalence and 50% herd-level MAP (*Mycobacterium avium* subsp. *paratuberculosis*) prevalence. **A)** Cow-culling rate compared to the MAP-negative herd over time. **B)** Premature culls and MAP-positive culls as a percentage of total exits, and forgone production as a percentage of potential production.

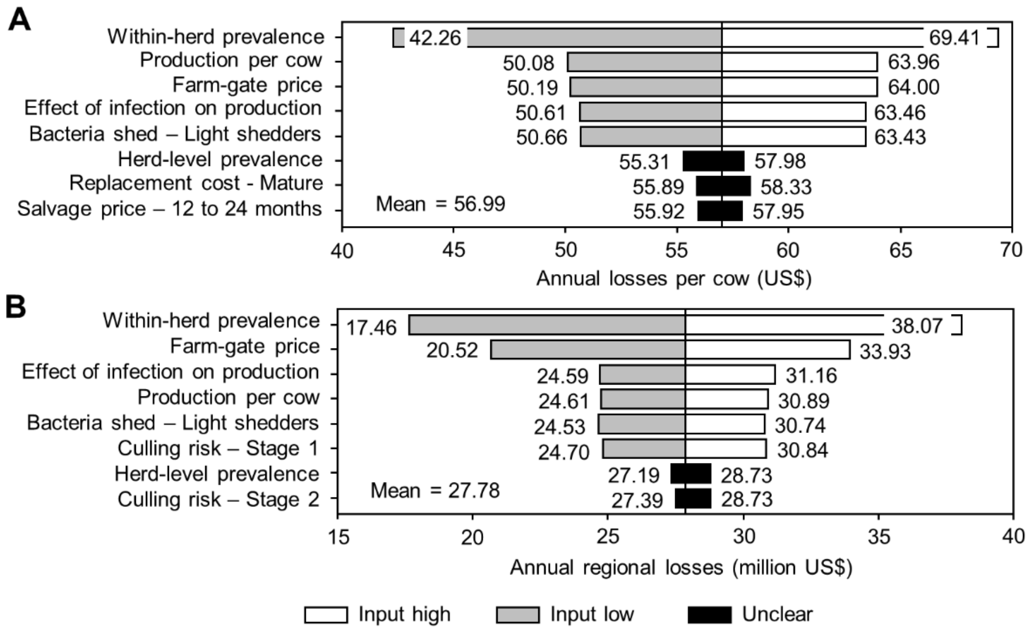

Figure 2-4. Sensitivity of estimated losses due to MAP (*Mycobacterium avium* subsp. *paratuberculosis*) infection in Canadian dairy herds to a range of input variables (10,000 iterations) assuming initial mean values of 10% within-herd prevalence and 50% herd-level prevalence. The color of the sensitivity bars indicates the direction of the relationship between the variable and estimated losses (grey 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.

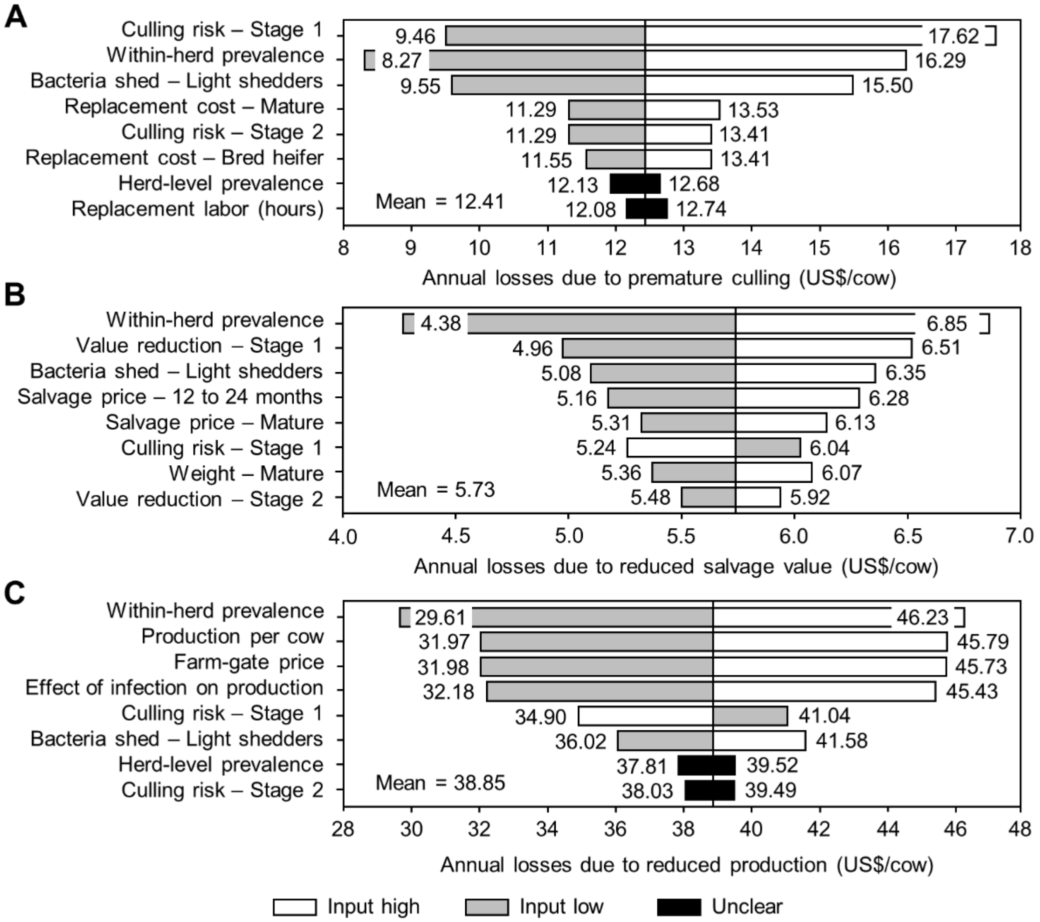

Figure 2-5. Sensitivity of estimated sources of losses due to MAP (*Mycobacterium avium* subsp. *paratuberculosis*) infection in Canadian dairy herds to a range of input variables (10,000 iterations) assuming initial mean values of 10% within-herd prevalence and 50% herd-level prevalence. The color of the sensitivity bars indicates the direction of the relationship between the variable and estimated losses (grey 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.

CHAPTER 3: EFFECTIVENESS AND ECONOMIC VIABILITY OF POTENTIAL CONTROL PRACTICES

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3.1. Abstract

Johne's disease (JD or paratuberculosis) control programmes have been established in many dairy-producing regions. However, the effectiveness (reduction of within-herd prevalence) and the relative economic impact as measured by, for example, the ratio of benefits to costs (BCR) across a comprehensive selection of regions and potential control practices require further investigation. Within a Markovian framework using region-specific economic variables, it was estimated that vaccination was the most promising type of JD control practice modelled, with dual-effect vaccines (reducing shedding and providing protective immunity) having BCRs between 1.48 and 2.13 in Canada, with a break-even period of between 6.17 and 7.61 years. Dual-effect vaccines were also estimated to yield BCRs greater than one in almost all major dairy-producing regions, with greater ratios in regions characterized by above-average farm-gate prices and annual production per cow. Testing and culling was comparably effective to a dual-effect vaccine at test sensitivities greater than 70% but would remain economically unviable in almost all regions modeled.

3.2. 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* subspecies *paratuberculosis* (MAP), a relatively resistant bacterium (Manning and Collins, 2001; Whittington et al., 2004; Donaghy et al., 2009). As the infection progresses in cattle, 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 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 of losses. Annual losses per cow among MAP-infected 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 per cow (Pillars et al., 2009), while annual losses among infected herds in Canada have been estimated at CA$49 (approximately US$40) (Tiwari et al., 2008) and between US$35 and US$57 per cow in Chapter 2. In the same chapter, it was estimated that globally, average annual losses in major dairy-producing regions are US$33 per cow, or approximately 1% of gross milk revenue. Although national control programmes have already been established in several countries including Australia, Ireland, Japan, the Netherlands, and the United States (Whittington et al., 2019), there are few estimates of the economic impact of potential control practices across major dairy-producing regions. It has been estimated that an average benefit of US$8.03 per animal per year is associated with vaccination in US dairy herds (Groenendaal et al., 2015), and it has also been suggested through simulation that the most profitable strategy in average Danish herds is no control practice at all, with testing and culling being the most profitable in low-hygiene herds (Kirkeby et al., 2016). Similarly, a recent stochastic simulation study found that no paratuberculosis control was the highly preferred strategy in small herds with 10% initial within-herd prevalence and frequently preferred in other herd scenarios (Smith et al., 2017). Intuitively, it may seem obvious that these economic losses warrant investment in control of the disease, but the precise mechanisms of control require further investigation; there is a need to estimate the effectiveness and economic impact of potential control practices with consideration for region-specific economic characteristics. Accordingly, this study estimates the effectiveness in terms of reducing within-herd prevalence, the economic impact in terms of the ratio of benefits to costs, and the break-even period in terms of years required for benefits to equal costs of various potential JD control practices across a comprehensive selection of dairy-producing regions within a Markovian framework.

3.3. Materials and methods

Within the Markovian framework described in Chapter 2, a MAP-positive herd with no intervention was modelled over a 10-year horizon. Various control practices were then introduced to the simulated herds, ranging from a vaccine that reduced shedding among MAP-positive animals to more comprehensive control programmes such as a “dual-effect” vaccine (a vaccine that both reduces shedding and also provides some protective immunity) combined with annual fecal PCR testing and culling of MAP-positive animals. The herds with JD control measures in place were then simulated over a 10-year horizon and compared to a positive herd with the same economic characteristics with no intervention to determine the changes in herd structure associated with each control practice. By incorporating economic variables into the Markovian framework, the region-specific benefits per cow, costs per cow, 10-year benefit-cost-ratios (BCRs), and break-even periods of each control practice were estimated. In all scenarios, regional adoption of the control practice was assumed, meaning that the replacement pool from which annual purchased replacements were acquired was assumed to be operating under the same conditions modelled for the herd.

3.3.1. Markovian framework

As in Chapter 2, the spread of MAP-infection within a dairy herd was modelled over a 10-year horizon using a MAP-positive herd model with a separately modelled replacement pool. In this MAP-positive model, 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 stage of infection can progress, regress, or remain the same. Each stage of infection is associated with a different risk of being culled, and each stage has some non-shedding, lightly-shedding, moderately-shedding, and heavily-shedding states within it. Infection pressure on animals in the herd is determined by the number and degree of shedding animals in the herd in each period, and all other potential outcomes are functions of that infection pressure. For MAP-negative animals, the probability of being culled remains the steady-state MAP-negative 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. After the initial age parameters were set, the herd and pool were modelled for 50 1-year 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 one and two years of age 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 one and two years of age per 100 cows per year (Van Biert, 2019). Purchased replacements enter the herd at a MAP infection prevalence according to the region’s animal-level prevalence, which is determined by the product of the region’s average within-herd prevalence and average herd-level prevalence. For each economic region, a baseline MAP-positive herd is then compared to a MAP-positive herds with various JD control practices in place to estimate changes in herd structure, JD prevalence, and three sources of losses associated with JD in dairy cattle: premature culls; MAP-positive animals salvaged; and MAP-positive cows producing reduced amounts of milk. Lastly, because the current efficacies of available MAP vaccines in terms of reduced shedding and protective immunity are unknown, a range of vaccine efficacies are modelled.

3.3.2. Vaccine to reduce shedding

In this control scenario, a vaccine that reduces shedding among MAP-infected animals is administered to the entire herd at time zero and then administered to natural replacements at birth and purchased replacements at the time of purchase. Once animals are vaccinated, two main mechanisms operate: (i) the probability of an animal transitioning from a MAP-negative state to a shedding state of MAP-infection is decreased by the percentage reduction in shedding attributable to the vaccine; and (ii) the probability of an animal transitioning from a shedding state of MAP-infection to another shedding state of MAP-infection is decreased by the percentage reduction in shedding attributable to the vaccine. In other words, shedding states of MAP-infection become less likely outcomes and non-shedding states become more likely according to the MAP shedding-reducing properties of the vaccine.

3.3.3. Vaccine to provide protective immunity

In this control scenario, a vaccine that provides protective immunity from MAP infection is administered to the entire herd at time zero and then administered to natural replacements at birth and purchased replacements at the time of purchase. Once animals are vaccinated, a percentage of the MAP-negative animals are provided with protective immunity and separated into a new, immune cohort within the model according to the vaccine’s efficacy (expressed as a percentage). The remainder of the MAP-negative animals continue in the original non-immune cohort along with the MAP-positive animals in the herd, which although vaccinated, cannot be provided with protective immunity. Animals within the immune cohort either continue aging or are culled according the MAP-negative steady-state probability for their age but can never become infected in their lifetimes. Animals that remain in the non-immune cohort are subject to infection pressure according to the number of infected animals in the herd and the degree to which those infected animals are shedding MAP. These non-immune animals can continue to age, be culled, become infected, or have their existing infections progress, regress, or remain the same.

3.3.4. Vaccine with dual effects

In this control scenario, a vaccine that both reduces shedding and provides protective immunity from MAP infection is administered to the entire herd at time zero and then administered to natural replacements at birth and purchased replacements at the time of purchase. The percentage of animals that are successfully provided with protective immunity enter the immune cohort, and because they are MAP-negative and remain so for their lifetimes, are not directly affected by the shedding-reducing effects of the vaccine. MAP-negative animals that remain in the non-immune cohort are still subject to infection pressure as previously described, while MAP-positive animals in this cohort transition from period to period according to the altered transition probabilities of the shedding-reduction vaccine model.

3.3.5. Testing and culling

In this control scenario, animals aged one to seven years are tested annually using a combination of pooled and individual fecal PCR tests. They are first tested at time zero, and then retested after each transition period (year) along with purchased replacements aged one to three years, which are tested only at the individual level. For all testing periods, the probability of a pooled test containing samples from an r number of MAP-positive animals given the pool size n, or $pr(TP) \mid C(n,r)$, is determined using the following equation:

$$pr(TP) \mid C(n,r) = \frac{n!}{r! * (n-r)!} * \left(\frac{TP_s}{animals_{(1-7)}}\right)^r * \left(1 - \left(\frac{TP_s}{animals_{(1-7)}}\right)\right)^{n-r} \qquad (1)$$

where: TP_s equals the number of true positive animals aged one to seven years in a shedding state and $animals_{(1-7)}$ equals the number of animals aged one to seven years in the herd. A testing pool size of five animals is assumed, or $n = 5$. Pooled tests and individual tests are assumed to share the same sensitivities and specificities, or that $se_p = se_i$ and $sp_p = sp_i$.

The number of true positive pools detected TP_p given pooled test sensitivity se_p is determined using the following equation:

$$TP_p = \sum_{r=1}^{n} \big(pr(TP) \mid C(n,r)\big) * \frac{animals_{(1-7)}}{n} * se_p \qquad (2)$$

The number of false-positive pools detected FP_p given pooled test specificity sp_p is determined using the following equation:

$$FP_p = \left(\frac{animals_{(1-7)}}{n} - TP_p\right) * \frac{(1 - sp_p)}{sp_p} \qquad (3)$$

The number of individual tests required T given the total number of positive pools detected, including true and false-positive pools, is determined using the following equation:

$$T = \left(TP_p + FP_p\right) * n \tag{4}$$

The number of true positive individuals detected TP_i given individual test sensitivity se_i is determined using the following equation:

$$TP_i = T * \frac{\sum_{r=1}^{n}\left(pr(TP) \mid C(n,r)\right) * r}{\left(\sum_{r=1}^{n}\left(pr(TP) \mid C(n,r)\right) + FP_p\right) * n} * se_i \tag{5}$$

Finally, the number of false-positive individuals detected FP_i given individual test specificity sp_i is determined using the following equation:

$$FP_i = (T - TP_i) * \frac{(1 - sp_i)}{sp_i} \tag{6}$$

where the total number of culls resulting from testing and culling equals the sum of true positive and false-positive individuals detected, or $TP_i + FP_i$. These culls are then distributed across the herd according to the herd structure in that period, with the false-positive culls coming from among the MAP-negative animals and the true positive culls coming from among the MAP-positive animals. The culled animals are then replaced with animals from the replacement pool, which is assumed to be operating under the same test-and-cull conditions.

3.3.6. Economic analyses

Benefits per cow, costs per cow, benefit-cost ratios, and break-even periods of the various control practices were estimated using general input variables, region-specific dairy sector characteristics, and region-specific economic variables (**Tables A-1** through **A-3**). The following values were assumed for control-specific economic variables: a fecal PCR direct testing cost of US$40 per test, a pooled testing labour cost of 30 minutes per test, an individual testing labour cost of five minutes per test, a vaccination direct cost of $US20 per dose for all vaccine types, and a vaccination labour cost of one minute per dose. After each period, the herds with control practices in place were compared to a region-specific baseline MAP-positive herd with no intervention. The reduced economic losses in the herd with control practices relative to economic losses in the herd with no intervention were recorded as economic benefits for the various control practices. Premature culling benefits were estimated by tallying additional exits in the herd with no intervention and assigning those exits a value according to their age-at-exit and associated replacement price. The aggregated labour cost of seeking out, purchasing, and introducing a replacement to the herd was also accounted for. Salvage benefits were estimated by tallying additional MAP-positive exits and assigning them a reduced salvage value according to their stage of infection. Production benefits were estimated in two different ways: (i) for the comprehensive selection of major dairy-producing regions, production benefits were measured as the value of the additional milk produced (the product of quantity and farm-gate price) by the herd due to the reduced number of MAP-positive cows; and (ii) for Canada, due to the unique market conditions that arise due to supply management, production benefits were re-estimated as the reduction in variable costs from requiring fewer cows to maintain a fixed production level. The three sources of benefits in the model (reduced premature culling losses, reduced salvage losses, and reduced production losses) were summed and divided by the number of cows in the herd to obtain an estimate of benefits per cow for each control scenario in each region.

The direct cost per dose of the vaccine was added to the labour cost per dose (*i.e.*, time required to administer a single dose multiplied by the aggregate wage rate) to obtain an estimated total cost per dose. At time zero, the entire herd was vaccinated, with only purchased and natural replacements being vaccinated after each transition period. As overall herd health improved in the model, the culling rate decreased and animals remained in the herd for a longer period, leading to fewer doses being required over time. Each period, the total cost of vaccination was divided by the number of cows in the herd to obtain an estimate of annual vaccination costs per cow for each control practice that included vaccination in each region. Similarly, the direct cost per fecal PCR test was added to the labour cost per test, with pooled tests requiring more labour than individual tests. Syringe and alcohol swab material costs for vaccine delivery were trivial (pennies per cow) at the herd-level and were not accounted for in the simulations. However, in the case of a national or widespread JD control campaign, these costs would likely be significant when aggregated across thousands of herds. The direct cost of replacing culled animals that tested positive was added to the labour cost per replacement, with the direct cost being dependent on the age of the replacement animal. The total costs of testing and replacing animals were summed each period and divided by the number of cows in the herd to obtain an estimate of annual testing and culling costs per cow for each control scenario that included testing and culling in each region.

Annual benefits and costs per cow were discounted over time at an assumed rate of 5% per annum, averaged over the 10-year horizon to obtain the reported benefit and cost estimates. This discount rate is consistent with small private firm investment in a family enterprise, falling between a public investment return rate of approximately 3% (USDA NRCS, 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 (TBC, 2007). Once discounted, these benefits and costs were summed over the 10-year horizon, then divided by the sum of the costs to obtain an estimate of the benefit-cost ratio for each control scenario in each region. The annual cumulative costs were subtracted from the annual cumulative benefits, and for scenarios and regions where this value was greater than zero within the 10-year horizon, the number of years required for the benefits to equal costs were recorded to obtain an estimate of the break-even period.

3.3.7. Monte Carlo simulations

Monte Carlo simulations of 10,000 iterations were used to estimate the distribution of possible outcomes of the Markov chain models and their sensitivity to various input variables. For these simulations, assumptions of an initial mean within-herd prevalence of 10% and an initial mean herd-level prevalence of 50% were used in all scenarios, both with normal distributions and standard deviations of 20% of their mean values. Also assumed were mean values of 50% for the vaccine’s reduction in shedding, 50% for the vaccine’s protective immunity efficacy, 50% for both pooled and individual fecal PCR testing sensitivities, and 99% for testing specificities. These variables were also simulated with normal distributions but with standard deviations of 20% of their means, except for testing specificities; these were simulated with normal distributions truncated from 95% to 100% and standard deviations of 10% of their means. All general input variables, region-specific economic variables, and control-specific economic variables were assumed to have normal distributions and standard deviations of 10% of their mean values. Although the data required to determine the true standard deviations of these variables are unavailable, the selected standard deviations capture a wide range of input values without destabilizing the simulations and their results.

3.4. Results

3.4.1. Distribution of possible outcomes

The proportional changes in within-herd prevalence (the differences between the final 10-year within-herd prevalence and the initial within-herd prevalence divided by the initial within-herd prevalence) from its initial mean value of 10% based on 10,000-iteration simulations of the various control practices are presented in **Figure 3-1** and **Table 3-1**. For the MAP-positive herd with no intervention, 90% of the iterations resulted in proportional increases of within-herd prevalence ranging from approximately 0.5 to 1.65, with a mean of 1.02, equivalent to a doubling of within-herd prevalence from 10% to 20% over 10 years. Only vaccines that provided protective immunity, dual-effect vaccines, and testing and culling combined with various vaccine types had 90% confidence ranges that did not overlap with the positive herd with no intervention. Additionally, only dual-effect vaccination and testing and culling combined with either a protective immunity vaccine or a dual-effect vaccine had 90% confidence ranges entirely below zero indicative of absolute decreases in within-herd prevalence over 10 years relative to its initial value.

3.4.2. Effects of JD control on herd structure

The effects of the various control practices on within-herd prevalence, the percentage of shedding animals within the herd, and the cow-culling rate over time can be seen in **Figure 3-2**. In all control scenarios, prevalence decreased relative to the MAP-positive herd with no intervention. The greatest decreases relative to no intervention were observed in the scenarios of dual-effect vaccination, testing and culling combined with protective immunity vaccination, and testing and culling combined with dual-effect vaccination. After year three, the within-herd prevalence in the testing and culling scenario began to increase relative to its minimum value within the 10-year horizon. When looking at the percentage of animals shedding in the herd, overall trends are similar to those observed when looking at within-herd prevalence, including the same upward trend after year three in the testing and culling scenario. The greatest decreases were observed in the dual-effect vaccination, testing and culling combined with vaccination to reduce shedding, and testing and culling combined with dual-effect vaccination scenarios. A sharp and immediate decrease in shedding animals as a percentage of animals in the herd was observed in scenarios involving vaccines with a shedding reduction effect. As within-herd MAP prevalence and the prevalence of MAP-shedding animals changed over time in the various scenarios, so did the cow-culling rates. In the various vaccination scenarios, after two years the cow-culling rate began to decrease relative to the rate observed in the MAP-positive herd with no intervention, approaching the MAP-negative baseline rate of 0.275. This was indicative of both improving overall herd health and a decline in the severity of infections among MAP-positive animals as infection pressure in the herd began to fall due to the various control practices. In scenarios involving testing and culling, an initial increase in culling of cows was observed relative to the scenario with no intervention as MAP-positive animals were detected and removed from the herd. However, as the number of animals detected began to decrease with time, culling rates also fell, and by year 4, in the scenario combining testing and culling with a dual-effect vaccine, they were near or below the culling rate of cows in the positive herd with no intervention. Once again, only in the exclusive testing and culling scenario was there an eventual upward trend in the culling rate after an initial decline.

Changes in the sources of economic losses in the models (forgone production, premature culling, and reduced salvage value due to MAP-positive culls) over time are presented in **Figure**

3-3. In all scenarios, forgone production as percentage of potential production decreased relative to the MAP-positive herd with no intervention. The greatest reductions were observed in scenarios with dual-effect vaccination and scenarios where and testing and culling was combined with either a protective immunity vaccine or a dual-effect vaccine. The previously observed upward trend in the testing and culling scenario was once again observed for all sources of losses in the model. Premature culls (culls that would not have occurred in the MAP-negative baseline herd) as a percentage of total culls decreased relative to the MAP-positive herd with no intervention within 10 years in all scenarios except testing and culling, with dual-effect vaccination showing the greatest decrease. The greatest decreases in MAP-positive culls as a percentage of total culls were observed in scenarios combining testing and culling with protective immunity vaccination, testing and culling combined with dual-effect vaccination, and dual-effect vaccination only.

3.4.3. Economic analysis for major dairy-producing regions

With a 50% reduction in shedding and a 50% efficacy of protective immunity, dual-effect vaccination resulted in BCRs greater than one for all regions except Poland, Brazil, China, Russia, and Turkey with revenue-weighted average values of 1.24 and 7.88 years for the scenario's BCR and break-even period respectively (**Table 3-2**). Even at the 90% efficacy level in the dual-effect vaccination scenario, the BCRs remain less than 1 for these countries. For control practices involving testing and culling (**Table 3-3**), all revenue-weighted average BCR values are less than one, with the exception of testing and culling combined with a dual-effect vaccine at the 90% efficacy and test sensitivity levels, which resulted in a BCR value of 1.22 and a break-even period of 9.17 years.

3.4.4. Economic analysis for Canada

Benefits and costs for the various control practices were first estimated using the same method used for other major dairy-producing regions. They were then estimated again with consideration for the market conditions that arise due to supply management: fixed annual production and higher farm-gate prices. To account for these conditions, production losses were estimated as the increase in variable costs due to the presence of additional less productive MAP-positive cows in the herd required to maintain a fixed production level. Once again, the results are summarized using revenue-weighted average values at the bottom of each table. With production losses measured as forgone production (**Table 3-4**), protective immunity vaccination and dual-effect vaccination scenarios resulted in mean BCRs greater than 1 for all provinces within Canada, with the highest revenue-weighted average BCRs resulting from scenarios with dual-effect vaccination until control variables reach the 90%, when protective immunity vaccination has a slightly higher BCR. Testing and culling did not result in a BCR greater than one for any province at any test sensitivity modelled, and testing and culling combined with a shedding reduction vaccine only resulted in a BCR greater 1 in Alberta and Newfoundland and Labrador in the 90% vaccine efficacy and 90% test sensitivity scenario. Testing and culling combined with a protective immunity vaccine had a revenue weighted average BCR greater than 1 (1.03) only at the 70% efficacy and sensitivity level, while testing and culling combined with dual-effect vaccination resulted in revenue-weighted average BCRs and provincial BCRs greater than 1 at all vaccine efficacy and testing sensitivities modelled. Dual-effect vaccination also had the shortest break-even periods across vaccine efficacy scenarios. When production losses were instead measured as increased variable costs from additional cows in the herd being required to maintain production levels (**Table 3-5**), similar trends were observed but with lower BCRs and longer break-even periods. Dual-effect vaccination was still the most promising control practice, resulting in BCRs greater than one for all provinces with a revenue-weighted average of 1.48 in the 50% control variable scenario, and the shortest break-even periods across all efficacy and test sensitivity scenarios.

3.4.5. Sensitivity analyses

For simplicity, a generalized MAP-positive herd with no region-specific variables was selected to test the sensitivity of estimated within-herd prevalence to various input variables. For the shedding reduction vaccine, once the shedding reduction reached 70%, a slight overall downward trend in within-herd prevalence was observed (**Figure 3-4**). However, it was not until the shedding reduction exceeded 90% that an absolute decrease in within-herd prevalence relative to its initial value within the 10-year horizon was observed. For the protective immunity vaccine, at only 50% protective immunity a downward trend was observed, and an absolute decrease in within-herd prevalence within the 10-year horizon relative to its initial value was observed at less than 60% protective immunity. The relationship between protective immunity, shedding reduction, and the final 10-year within-herd prevalence in the dual-effect vaccination scenario is explored in **Figure 3-5**; the results suggest that the protective immunity effect drove the overall effectiveness of dual-effect vaccines in the model, particularly at moderate control variable values. For example, a vaccine with 0% shedding reduction but 70% protective immunity resulted in a final 10-year within-herd prevalence of approximately 0.08 (assuming an initial within-herd prevalence of 0.10), whereas a vaccine with 70% shedding reduction and 0% protective immunity resulted in a final prevalence of 0.13.

There was no significant 10-year decrease in within-herd prevalence relative to its initial value resulting from testing and culling until test sensitivity exceeded 50% (**Figure 3-6**). However, even within the 50% to 70% sensitivity range, within-herd prevalence began to trend upwards in the later periods of the 10-year horizon. This upward trend did not clearly disappear until test sensitivity exceeded the 70% level. The sensitivity of the proportional changes in within-herd prevalence over the 10-year horizons to a variety of input variables based on 10,000 iteration Monte Carlo simulations are presented in **Figures 3-7** and **3-8**. In the shedding reduction vaccine scenario, the proportional change was most sensitive to the initial within-herd prevalence, with above-mean within-herd prevalence values resulting in lesser proportional increases and therefore more effective JD control. Other impactful and negatively related variables were the shedding reduction efficacy of the vaccine and the additional culling risk associated with Stage 1 MAP infection. The degree of bacterial shedding among lightly shedding infected animals and herd-level prevalence were also determined to be impactful, but positively related to the proportional increase in within-herd prevalence, with above-mean values resulting in greater proportional increases in within-herd prevalence. The protective immunity vaccine estimate was sensitive to similar variables, with the percentage of protective immunity being the most impactful, as was the dual-effect vaccine scenario estimate, with protective immunity having a significantly larger impact than shedding reduction. In all scenarios involving testing and culling, both alone and in combination with some type of vaccination, proportional changes to within-herd prevalence were most sensitive to test sensitivity, with initial within-herd prevalence, vaccine efficacy, and the degree of bacterial shedding among lightly shedding animals being consistently impactful to lesser degrees. Similar variables were identified as impactful in the 10,000 iteration Monte Carlo simulation sensitivity analyses of estimated 10-

year BCRs using an average Canadian dairy herd (**Figures 3-9** and **3-10**). However, additional economic and production variables such as the vaccine price per dose, farm-gate price of milk, annual production per cow, and the effect of MAP infection on milk production were also identified. The degree of bacterial shedding among lightly shedding animals was once again consistently found to be impactful and positively related to BCR estimates in all scenarios. All significantly impactful variables in these BCR sensitivity analyses were positively related to estimated BCRs, aside from the vaccine price per dose, which was negatively related. In all control scenarios, within-herd prevalence was inversely related to the 10-year proportional change in within-herd prevalence and directly related to the benefit-cost ratio of the control practice.

3.5. Discussion

With the assumptions of mean within-herd MAP infection prevalence of 10%, a mean herd-level MAP infection prevalence of 50%, vaccine efficacies (reduction in shedding and protective immunity) of 50%, mean test sensitivity of 50%, and mean test specificity of 99%, no scenarios resulted in the elimination of JD within a 10-year horizon. However, all control practices reduced within-herd MAP prevalence relative to no intervention within a 10-year horizon. However, at the 50% vaccine efficacy and 50% test sensitivity level, the only control practices that resulted in absolute reductions relative to initial within-herd MAP prevalence within the horizon were dual-effect vaccines, and protective immunity and dual-effect vaccines combined with testing and culling. Testing and culling alone did not; after three to four periods, an upward trend in within-herd prevalence was observed as new MAP infections occurred. Kudahl et al. (2007) found that testing and culling alone only delayed an increase in within-herd prevalence, whereas Kirkeby et al. (2016) found that that even with currently available testing tools, eradication of JD was attainable within seven to 10 years through testing and culling in Danish dairy herds. However, in the latter model, MAP infection was treated as an endemic situation, and therefore modelled using a density-dependent transition model as opposed to modelling the probability of infection as a function of the number and degree of infected animals in the herd. Also, their model explicitly considered a range of hygiene levels across herds, whereas in this model, variations in herd hygiene are instead implicitly captured using a range of possible disease progression rates and MAP-specific input variables. The upward trend observed in the testing and culling scenarios was also accentuated by the 10-year horizon of the simulations; at test sensitivity levels in the 50% to 70% range, testing and culling did not lower infection pressure within the herd quickly enough to overcome the disease progression of false-negative, subclinically infected, and non-shedding animals to stages of infection characterized by moderate and heavy shedding. As infections in those strata progressed, infection pressure within the herd, and therefore within-herd prevalence, began to rise again. If testing and culling were continued, with each passing five- or 10-year horizon these oscillations would lessen in amplitude and an overall downward trend would be observed. However, from an economic and epidemiologic modelling perspective, it is unrealistic to assume that herd compositions, management techniques, testing procedures, and even market structures would remain unchanged for more than 10 years. Therefore, the time horizon of the model was not extended.

Control variable values such as vaccine efficacy and testing sensitivity were clearly impactful on the effectiveness (ability to reduce within-herd prevalence within a 10-year period), economic impact (the ratio of benefits to costs per cow accrued as a result of implementation), and break-even period (years for cumulative benefits to equal cumulative costs). The results suggest that the effectiveness of the dual-effect vaccine was primarily driven by the protective immunity effect of the vaccine as opposed to the shedding reduction effect. At higher ranges of protective immunity, the reduced-shedding effect of the dual-effect vaccine ceased to have impact on the final MAP prevalence; at levels greater than 80% protective immunity, reduced shedding among MAP-positive animals actually had the reverse effect, resulting in a final prevalence greater than the final prevalence that would have been achieved using a single-effect protective immunity vaccine. In the model, disease progression is related to the degree and number of shedding animals in the herd. Therefore, a reduction in shedding among MAP-infected animals resulted in less severe but more prolonged subclinical infections; these non-shedding, subclinically infected animals remained in the herd rather than developing clinical signs of JD and being culled. Once again, if the horizon of the model were extended by five or 10 periods, this result would likely not be observed as the remaining subclinically infected animals would eventually exit the herd. However, for reasons already described, the model was not extended past its 10-year horizon.

Through the Monte Carlo sensitivity analyses, the degree of bacterial shedding among lightly shedding animals was identified as an impact variable, highlighting the need for further research into this area. Also impactful were the farm-gate price of milk and annual production per cow due to their positive relationships with production, and therefore forgone production losses due to MAP infection. For the selection of major dairy-producing regions that were modelled, production benefits were measured as potential increases in milk sales. Dual-effect vaccines were the among most successful control practices in terms of their reduction in within-herd prevalence and were economically viable with BCRs greater than one in all countries except Poland, Brazil, China, Russia, and Turkey. These countries are five of the seven countries with the lowest annual milk production per cow that were modelled, along with Ireland and New

Zealand. However, Ireland and New Zealand have significantly greater aggregated salvage prices and replacement costs than the other five countries. The combination of relatively low costs and low annual production resulted in lower economic losses due to JD, and therefore less economic benefits from controlling JD in those five countries.

Two interesting patterns emerged across a range of control variable values (test sensitivity, shedding reduction, and protective immunity), both related to testing and culling. Firstly, testing and culling and testing and culling combined with a protective immunity vaccine were the only control scenarios where estimated annual costs per cow increased as the control variable values increased. In the vaccine scenarios without testing and culling, as within-herd MAP prevalence decreased with more effective controls, the culling rate also decreased as overall herd health improved. Because the vaccine was only administered to natural and purchased replacements after the initial time 0 whole-herd vaccination, costs per cow decreased over time as there were relatively fewer replacements requiring vaccination in each period. However, with testing and culling, this effect was outweighed by the fact that a more sensitive test detected more positive animals, which then needed to be culled and replaced at a relatively high cost. While testing and culling was effective at reducing within-herd prevalence relative to its initial value at test sensitivities greater than 70%, this effectiveness depended entirely on aggressive culling of test-positive animals which may be impractical in a real-world setting, particularly in moderate and high prevalence herds. Similarly, in their simulations, Groenendaal et al. (2003) found that while a test with 80% sensitivity in all infected animals was effective at reducing within-herd prevalence, the strategy was economically unviable because of the high culling rate of test-positive animals, particularly young ones, required to achieve that reduction in prevalence. Unless the costs of replacing test-positive and subsequently culled animals can be reduced for producers, this model also suggests that the benefits of testing and culling may not equal or exceed the costs, even if new, more sensitive and specific tests are developed. However, it is important to note that the simulated testing protocol remained static throughout the 10-year horizon; a desirable real-world testing and culling programme would not only need to reduce replacement costs, but also reduce testing costs by using a dynamic testing strategy (*e.g.*, environmental testing instead of pooled and individual testing once within-herd prevalence is reduced to a certain level). For herds with low initial within-herd prevalence, a dynamic testing strategy alone could reduce costs to the point where testing and culling becomes economically viable, particularly in closed herd scenarios where all replacements come from within the herd. If more sensitive tests were also developed, these low prevalence closed herds could become reliable and certifiable sources of MAP-negative replacements for higher prevalence open herds seeking to reduce within-herd MAP prevalence or low prevalence herds seeking to rapidly expand, with these replacements potentially being sold at an economic premium. The second interesting pattern that emerged related to testing and culling was that when combined with a vaccine that reduced shedding and when combined with a dual-effect vaccine, benefits per cow decreased as the control variable values (vaccine efficacy and test sensitivity) increased from 70% to 90%. Because a fecal PCR test was modelled, the test could only detect animals in shedding states of infection. Therefore, as the shedding-reducing effects of the vaccine were increased, the number of animals detectable by fecal PCR testing was reduced, and the prevalence-reducing effects of improved testing sensitivity were partially offset. Because of this reduced ability to detect positive animals, the replacement costs associated with testing and culling also decreased. When these decreased costs were combined with the overall improvement in herd health due to vaccination and less aggressive testing and culling, the total costs per cow decreased at a greater rate than did benefits; the BCRs still increased with the control variable values despite the combination of vaccine-induced shedding reduction and fecal PCR testing being relatively inefficient.

While 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 production levels, administered cost-of-production-based pricing, and import controls. There are two consequences relevant to this model: (i) production losses, a significant contributor to the benefits of JD control, can no longer be measured as forgone milk sales due to the production quota system; and (ii) Canada’s above-average farm-gate price, which is the highest among countries modelled and much higher than the farm-gate price in the United States, Canada’s most comparable counterpart. Apart from a higher level of 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 two countries, there should be similar per-cow benefits and costs associated with controlling JD. However, the above average farm-gate price in Canada results in a greater valuation of production losses and therefore benefits from JD control in Canada. While these differences are attributable in part to differing technical and allocative efficiencies across US and Canadian 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, production losses were also estimated as the cost of having additional, less productive MAP-positive cows to maintain a fixed level of production. Once adjusted, the estimated BCRs of all control practices in Canada dropped and their break-even periods increased. For example, the Canadian revenue-weighted average BCR for dual-effect vaccination at 50% efficacy decreased from 2.13 to 1.48

when production levels were treated as fixed. While this is more in line with the BCR of 1.66 in average US herds for the same type of vaccination, this may be an overcorrection. Although overall production and farm-gate prices in Canada are set predetermined and producers are not paid for production that exceeds their quota-based targets, the overall level of production generally increases year-over-year (CDIC, 2019a) and producers trade quota through an exchange market; essentially, more technically efficient producers purchase quota from less technically efficient ones to increase the size of their operations. Evidence of this competition is clear: 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, Canadian producers operate in an environment between fixed production and pure competition. Therefore, the true BCRs of the various potential JD control practices for Canadian dairy herds likely lie between the fixed production and variable production estimates.

Finally, it is also important to recognize the limitations of this study. The net costs associated with a higher culling rate may be overestimated in this model. Because only the economic impacts of culling due to MAP-infection were 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, mastitis, and lameness are all potential sources of economic losses that could be partially offset as a direct result of an increased cow-culling rate. Also, the production benefits due to an increased conception rate resulting from JD control were not explicitly estimated. Instead, these benefits were only implicitly considered through the variations around the mean milk yield reduction estimated by McAloon et al. (2016). Lastly, it is also important to note that production systems, grazing periods, cattle breeds, etc. were assumed to be uniform across regions at the mean level. However, variations in these production factors were implicitly captured through variations around the mean values used in the 10,000 iteration simulations.

3.6. Conclusions

Vaccination was the most economically viable type of JD control practice modelled, with dual-effect vaccines (reducing shedding and providing protective immunity) being the most promising. Even with modest 50% reductions in shedding and 50% protective immunity conferred by vaccination, BCRs for this type of vaccine were between 2.13 and 1.48 in Canada, with a break-even period of between 6.17 and 7.61 years. At this same level of efficacy, dual-effect vaccines were also estimated to be desirable with BCRs greater than one in almost all major-dairy producing regions, with a revenue-weighted average BCR of 1.24 and a revenue-weighted average break-even period of 7.88 years. Testing and culling was comparably effective to a dual-effect vaccine at test sensitivities greater than 70% but would remain economically unviable in almost all regions modelled, even at levels of testing sensitivity above 70%. The results suggest that the main barrier to testing and culling programmes for JD is the impractical nature of the aggressive culling that would have to accompany highly sensitive tests. Without a reduction in the replacement cost of culled animals, vaccination, particularly dual-effect vaccination, is the most promising potential JD control practice for dairy producers. This research is an important contribution to the policy discussion surrounding paratuberculosis control in Canada and internationally.

3.7. References

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Table 3-1. Summary statistics of the distributions of 10-year proportional changes in within-herd *Mycobacterium avium* subsp. *paratuberculosis* (MAP) prevalence for various JD (paratuberculosis) control practices (10,000 iteration simulations).

Statistic	**No intervention**	**Vaccine (shedding)**	**Vaccine (immunity)**	**Vaccine (dual-effect)**
Minimum	-0.03	-0.25	-0.47	-0.52
Maximum	3.35	1.75	1.14	0.61
Mean	1.02	0.53	0.13	-0.13
90% range	0.51 to 1.66	0.18 to 0.92	-0.13 to 0.44	-0.22 to -0.20
Standard deviation	0.36	0.23	0.18	0.13

Statistic	**Test-and-cull**	**Test-and-cull with vaccine (shedding)**	**Test-and-cull with vaccine (immunity)**	**Test-and-cull with vaccine (dual-effect)**
Minimum	-0.75	-0.53	-0.83	-0.66
Maximum	2.26	1.51	1.16	0.79
Mean	0.01	0.09	-0.35	-0.26
90% range	-0.36 to 0.66	-0.20 to 0.44	-0.62 to -0.02	-0.46 to -0.04
Standard deviation	0.32	0.20	0.19	0.13

Table 3-2. Estimated benefit-cost ratios (BCRs), and revenue-weighted average benefits and costs per cow (US$), BCRs, and break-even periods (BEP) of various JD (paratuberculosis) vaccine types in major dairy-producing regions across a range of vaccine shedding reduction and protective immunity percentages. Assumes an initial within-herd *Mycobacterium avium* subsp. *paratuberculosis* (MAP) prevalence of 10% and a herd-level prevalence of 50%.

Region	**Vaccine (shedding)**			**Vaccine (immunity)**			**Vaccine (dual-effect)**		
	50%	**70%**	**90%**	**50%**	**70%**	**90%**	**50%**	**70%**	**90%**
European Union (28)	0.69	0.94	1.18	0.99	1.32	1.60	1.23	1.47	1.60
Germany	0.80	1.10	1.37	1.14	1.52	1.84	1.43	1.70	1.85
France	0.69	0.95	1.18	0.99	1.31	1.59	1.23	1.46	1.59
Great Britain	0.73	1.00	1.26	1.07	1.42	1.72	1.32	1.57	1.71
Poland	0.36	0.51	0.65	0.62	0.82	1.01	0.73	0.87	0.95
Netherlands	0.94	1.28	1.61	1.34	1.78	2.16	1.67	1.99	2.16
Italy	0.69	0.95	1.19	1.02	1.36	1.65	1.26	1.50	1.63
Ireland	1.03	1.38	1.70	1.27	1.67	2.00	1.66	1.96	2.13
Spain	0.59	0.81	1.03	0.93	1.24	1.51	1.12	1.34	1.46
Denmark	1.06	1.45	1.80	1.49	1.98	2.40	1.87	2.22	2.42
Belgium	0.75	1.02	1.27	1.06	1.41	1.71	1.33	1.58	1.71
Austria	0.78	1.06	1.32	1.07	1.42	1.72	1.35	1.61	1.75
Czechia	0.54	0.76	0.97	0.90	1.21	1.48	1.07	1.29	1.40
Sweden	0.91	1.25	1.55	1.29	1.71	2.07	1.61	1.92	2.08
Finland	0.95	1.31	1.63	1.38	1.83	2.22	1.71	2.04	2.21

United States	0.93	1.27	1.59	1.33	1.76	2.14	1.66	1.97	2.14
California	0.91	1.24	1.56	1.31	1.73	2.10	1.63	1.93	2.10
Wisconsin	0.81	1.11	1.40	1.21	1.61	1.96	1.49	1.77	1.93
Idaho	0.70	0.97	1.23	1.12	1.50	1.83	1.35	1.61	1.75
New York	0.96	1.32	1.65	1.37	1.82	2.20	1.71	2.04	2.21
Texas	0.85	1.17	1.47	1.26	1.68	2.04	1.56	1.85	2.01
Michigan	0.79	1.10	1.39	1.24	1.65	2.02	1.50	1.80	1.95
Pennsylvania	0.79	1.08	1.35	1.14	1.51	1.84	1.42	1.69	1.83
Minnesota	0.84	1.14	1.43	1.21	1.60	1.94	1.50	1.78	1.94
New Mexico	0.75	1.04	1.32	1.18	1.57	1.92	1.43	1.71	1.86
Washington	0.91	1.25	1.57	1.33	1.76	2.14	1.65	1.96	2.13
Brazil	0.17	0.24	0.30	0.26	0.34	0.42	0.32	0.38	0.41
China	0.26	0.36	0.46	0.41	0.54	0.66	0.49	0.59	0.64
Russia	0.25	0.35	0.45	0.42	0.57	0.70	0.50	0.60	0.66
New Zealand	0.55	0.74	0.91	0.71	0.94	1.14	0.92	1.09	1.18
Turkey	0.21	0.29	0.37	0.34	0.46	0.56	0.41	0.49	0.54
Australia	0.71	0.96	1.18	0.92	1.22	1.47	1.19	1.41	1.53
Japan	1.66	2.28	2.87	2.48	3.30	4.01	3.05	3.63	3.95
Revenue-weighted average benefits and costs (US$/cow/year), BCRs (ratio), and BEPs (years)									
Benefit	6.20	8.48	10.60	9.00	11.94	14.47	11.14	13.24	14.37
Cost	9.05	9.02	9.01	9.05	9.03	9.02	9.02	9.00	8.99
BCR	0.69	0.94	1.18	0.99	1.32	1.60	1.24	1.47	1.60

BEP	8.38	8.67	8.22	8.47	7.60	6.89	7.88	7.05	6.58

Table 3-3. Estimated benefit-cost ratios (BCRs), and revenue-weighted average benefits and costs per cow (US$), BCRs, and break-even periods (BEP) of various JD (paratuberculosis) control practices involving testing and culling in major dairy-producing regions across a range of testing sensitivities and vaccine shedding reduction and protective immunity percentages. Assumes an initial within-herd MAP (*Mycobacterium avium* subsp. *paratuberculosis*) prevalence of 10% and a herd-level prevalence of 50%.

Region	**Test-and-cull**			**Test-and-cull with vaccine (shedding)**			**Test-and-cull with vaccine (immunity)**			**Test-and-cull with vaccine (dual-effect)**		
	50%	**70%**	**90%**	**50%**	**70%**	**90%**	**50%**	**70%**	**90%**	**50%**	**70%**	**90%**
European Union (28)	0.44	0.54	0.59	0.42	0.52	0.58	0.59	0.71	0.79	0.69	0.85	1.07
Germany	0.46	0.56	0.60	0.47	0.57	0.65	0.64	0.74	0.82	0.76	0.93	1.19
France	0.43	0.52	0.57	0.42	0.51	0.58	0.58	0.69	0.77	0.68	0.84	1.05
Great Britain	0.46	0.57	0.62	0.45	0.55	0.62	0.63	0.75	0.84	0.73	0.90	1.13
Poland	0.39	0.53	0.62	0.30	0.37	0.38	0.48	0.64	0.78	0.49	0.63	0.73
Netherlands	0.50	0.59	0.64	0.52	0.64	0.74	0.70	0.80	0.88	0.85	1.04	1.34
Italy	0.47	0.57	0.63	0.44	0.54	0.60	0.62	0.75	0.85	0.71	0.89	1.10
Ireland	0.39	0.44	0.45	0.47	0.57	0.68	0.56	0.61	0.64	0.74	0.89	1.19
Spain	0.48	0.61	0.70	0.42	0.51	0.56	0.63	0.78	0.92	0.68	0.86	1.04
Denmark	0.51	0.60	0.64	0.56	0.68	0.79	0.73	0.83	0.89	0.90	1.11	1.44
Belgium	0.45	0.54	0.58	0.44	0.54	0.61	0.60	0.71	0.79	0.71	0.88	1.12
Austria	0.43	0.51	0.54	0.44	0.54	0.62	0.59	0.68	0.74	0.71	0.87	1.11
Czechia	0.50	0.66	0.76	0.41	0.51	0.54	0.64	0.83	0.99	0.68	0.86	1.03
Sweden	0.48	0.57	0.62	0.51	0.62	0.71	0.67	0.77	0.85	0.82	1.00	1.29

Finland	0.52	0.61	0.66	0.54	0.65	0.75	0.72	0.83	0.91	0.87	1.07	1.37
United States	0.50	0.59	0.63	0.52	0.63	0.73	0.69	0.80	0.87	0.84	1.03	1.33
California	0.50	0.59	0.64	0.51	0.63	0.72	0.69	0.80	0.88	0.83	1.03	1.32
Wisconsin	0.52	0.63	0.69	0.50	0.61	0.69	0.70	0.84	0.94	0.82	1.01	1.27
Idaho	0.55	0.69	0.78	0.48	0.60	0.65	0.72	0.89	1.03	0.80	1.00	1.23
New York	0.50	0.59	0.64	0.53	0.64	0.75	0.70	0.80	0.88	0.85	1.05	1.36
Texas	0.51	0.62	0.67	0.51	0.62	0.71	0.70	0.83	0.92	0.83	1.02	1.30
Michigan	0.55	0.68	0.76	0.52	0.64	0.71	0.75	0.90	1.03	0.85	1.06	1.32
Pennsylvania	0.47	0.57	0.62	0.47	0.57	0.65	0.64	0.76	0.84	0.76	0.94	1.19
Minnesota	0.48	0.58	0.63	0.49	0.60	0.68	0.66	0.78	0.86	0.79	0.98	1.24
New Mexico	0.54	0.67	0.75	0.50	0.61	0.68	0.72	0.88	1.01	0.82	1.02	1.26
Washington	0.51	0.61	0.66	0.52	0.64	0.73	0.71	0.82	0.91	0.85	1.05	1.34
Brazil	0.18	0.25	0.29	0.14	0.17	0.17	0.21	0.28	0.35	0.22	0.28	0.32
China	0.27	0.36	0.41	0.20	0.25	0.27	0.32	0.42	0.52	0.33	0.42	0.50
Russia	0.29	0.40	0.48	0.21	0.26	0.27	0.35	0.47	0.59	0.35	0.45	0.52
New Zealand	0.33	0.39	0.42	0.32	0.39	0.44	0.43	0.51	0.57	0.51	0.63	0.79
Turkey	0.24	0.33	0.39	0.17	0.22	0.22	0.29	0.39	0.48	0.29	0.37	0.43
Australia	0.37	0.44	0.47	0.39	0.47	0.55	0.51	0.58	0.63	0.62	0.76	0.97
Japan	0.69	0.80	0.85	0.79	0.96	1.16	1.02	1.13	1.21	1.30	1.59	2.13
Revenue-weighted average benefits and costs (US$/cow/year), BCRs (ratio), and BEPs (years)												
Benefit	15.36	23.82	29.45	14.29	17.25	16.34	20.84	27.16	31.10	18.26	20.60	19.46
Cost	31.65	40.59	45.98	29.85	29.41	24.65	31.52	34.79	35.68	23.49	21.41	16.01

BCR	0.49	0.59	0.64	0.48	0.59	0.66	0.66	0.78	0.87	0.78	0.96	1.22
BEP	-	-	-	-	-	10.00	10.00	10.00	10.00	10.00	10.00	9.17

Table 3-4. Estimated benefit-cost ratios (BCRs), and revenue-weighted average benefits and costs per cow (US$), BCRs, and break-even periods (BEP) of various JD (paratuberculosis) control practices in Canadian regions across a range of vaccine shedding reduction, protective immunity percentages, and testing sensitivities. Assumes an initial within-herd MAP (*Mycobacterium avium* subsp. *paratuberculosis*) prevalence of 10% and a herd-level prevalence of 50.

Region	**Vaccine (shedding)**			**Vaccine (immunity)**			**Vaccine (dual-effect)**		
	50%	**70%**	**90%**	**50%**	**70%**	**90%**	**50%**	**70%**	**90%**
Canada	1.15	1.59	2.00	1.74	2.32	2.82	2.14	2.55	2.77
Québec	1.05	1.45	1.83	1.62	2.16	2.63	1.97	2.35	2.56
Ontario	1.12	1.55	1.95	1.69	2.26	2.74	2.08	2.48	2.69
British Columbia	1.26	1.74	2.19	1.92	2.55	3.11	2.34	2.80	3.04
Alberta	1.45	1.98	2.48	2.08	2.76	3.35	2.59	3.08	3.35
Manitoba	1.11	1.53	1.93	1.71	2.29	2.79	2.08	2.49	2.71
Saskatchewan	1.29	1.77	2.22	1.91	2.54	3.09	2.36	2.81	3.05
Nova Scotia	0.99	1.37	1.74	1.57	2.10	2.56	1.90	2.27	2.47
New Brunswick	0.99	1.37	1.73	1.54	2.06	2.51	1.88	2.24	2.44
Prince Edward Isl.	0.99	1.38	1.75	1.58	2.11	2.58	1.91	2.28	2.48
Nfld. and Labrador	1.56	2.15	2.70	2.34	3.12	3.80	2.88	3.43	3.73
Revenue-weighted average benefits and costs (US$/cow/year), BCRs (ratio), and BEPs (years)									
Benefit	10.44	14.34	18.03	15.80	21.00	25.51	19.29	22.97	24.94
Cost	9.10	9.08	9.06	9.11	9.09	9.07	9.07	9.06	9.05
BCR	1.15	1.58	1.99	1.73	2.31	2.81	2.13	2.54	2.76

BEP	9.14	7.56	6.64	7.05	5.97	5.32	6.17	5.45	5.08

Region	**Test-and-cull**			**Test-and-cull with vaccine (shedding)**			**Test-and-cull with vaccine (immunity)**			**Test-and-cull with vaccine (dual-effect)**		
	50%	**70%**	**90%**	**50%**	**70%**	**90%**	**50%**	**70%**	**90%**	**50%**	**70%**	**90%**
Canada	0.61	0.73	0.79	0.64	0.79	0.91	0.87	1.00	1.10	1.05	1.30	1.68
Québec	0.62	0.75	0.82	0.62	0.76	0.87	0.86	1.02	1.13	1.02	1.27	1.61
Ontario	0.61	0.72	0.78	0.63	0.77	0.89	0.85	0.99	1.09	1.03	1.27	1.64
British Columbia	0.65	0.77	0.83	0.69	0.84	0.98	0.93	1.06	1.16	1.13	1.39	1.81
Alberta	0.60	0.69	0.74	0.69	0.84	1.01	0.88	0.98	1.04	1.13	1.37	1.84
Manitoba	0.64	0.77	0.85	0.65	0.80	0.91	0.90	1.05	1.17	1.07	1.32	1.69
Saskatchewan	0.62	0.73	0.78	0.68	0.82	0.97	0.89	1.01	1.10	1.10	1.35	1.78
Nova Scotia	0.64	0.79	0.87	0.62	0.76	0.86	0.89	1.06	1.19	1.03	1.27	1.61
New Brunswick	0.62	0.75	0.83	0.61	0.74	0.84	0.85	1.01	1.14	1.00	1.24	1.57
Prince Edward Isl.	0.65	0.79	0.88	0.62	0.77	0.86	0.89	1.06	1.20	1.03	1.28	1.61
Nfld. and Labrador	0.68	0.79	0.85	0.77	0.94	1.12	1.00	1.12	1.20	1.26	1.54	2.06
Revenue-weighted average benefits and costs (US$/cow/year), BCRs (ratio), and BEPs (years)												
Benefit	23.79	37.15	46.34	21.79	26.36	24.86	32.38	42.51	48.98	28.12	31.78	29.95
Cost	37.67	49.45	56.71	33.01	32.66	26.65	36.17	41.11	43.08	25.92	23.79	17.33
BCR	0.63	0.75	0.82	0.66	0.81	0.93	0.90	1.03	1.14	1.08	1.34	1.73
BEP	-	-	-	-	-	-	-	10.00	10.00	10.00	9.72	8.17

Table 3-5. Estimated benefit-cost ratios (BCRs), and revenue-weighted average benefits and costs per cow (US$), BCRs, and break-even periods (BEP) of various JD (paratuberculosis) control practices in Canadian regions across a range of vaccine shedding reduction, protective immunity percentages, and testing sensitivities, and with consideration for supply management (fixed output over time and production losses allocated as increased variable costs necessary to maintain production). Assumes an initial within-herd MAP (*Mycobacterium avium* subsp. *paratuberculosis*) prevalence of 10% and a herd-level prevalence of 50%.

Region	**Variable cost^1 (US$/cow/year)**	**Vaccine (shedding)**			**Vaccine (immunity)**			**Vaccine (dual-effect)**		
		50%	**70%**	**90%**	**50%**	**70%**	**90%**	**50%**	**70%**	**90%**
Canada	2,476	0.89	1.20	1.48	1.15	1.52	1.83	1.48	1.76	1.91
Québec	2,430	0.79	1.07	1.33	1.05	1.39	1.67	1.34	1.59	1.72
Ontario	2,256	0.85	1.15	1.42	1.09	1.44	1.74	1.42	1.68	1.82
British Columbia	3,204	1.00	1.35	1.68	1.34	1.77	2.13	1.70	2.02	2.19
Alberta	3,106	1.20	1.62	1.99	1.53	2.01	2.42	1.98	2.34	2.54
Manitoba	3,014	0.87	1.18	1.46	1.18	1.57	1.89	1.50	1.78	1.93
Saskatchewan	2,785	1.02	1.37	1.69	1.31	1.73	2.08	1.69	2.00	2.17
Nova Scotia	2,515	0.73	0.99	1.23	1.00	1.32	1.59	1.26	1.50	1.63
New Brunswick	2,464	0.75	1.02	1.26	1.01	1.34	1.61	1.28	1.52	1.65
Prince Edward Isl.	2,144	0.70	0.95	1.18	0.93	1.23	1.48	1.19	1.41	1.53
Nfld. and Labrador	4,112	1.27	1.73	2.14	1.70	2.25	2.72	2.17	2.58	2.80
	Revenue-weighted average benefits and costs (US$/cow/year), BCRs (ratio), and BEPs (years)									
	Benefit	8.04	10.85	13.38	10.48	13.80	16.59	13.44	15.88	17.21

Cost				9.10	9.08	9.06	9.11	9.09	9.07	9.07	9.06	9.05
BCR				0.88	1.20	1.48	1.15	1.52	1.83	1.48	1.75	1.90
BEP				9.05	9.05	7.61	9.11	7.60	6.75	7.61	6.71	6.23

Region	**Test-and-cull**			**Test-and-cull with vaccine (shedding)**			**Test-and-cull with vaccine (immunity)**			**Test-and-cull with vaccine (dual-effect)**		
	50%	**70%**	**90%**	**50%**	**70%**	**90%**	**50%**	**70%**	**90%**	**50%**	**70%**	**90%**
Canada	0.41	0.47	0.49	0.45	0.55	0.64	0.57	0.64	0.68	0.71	0.87	1.14
Québec	0.40	0.47	0.50	0.43	0.52	0.60	0.55	0.63	0.69	0.68	0.83	1.07
Ontario	0.39	0.45	0.47	0.44	0.53	0.62	0.55	0.61	0.65	0.69	0.84	1.09
British Columbia	0.45	0.52	0.55	0.50	0.61	0.72	0.64	0.71	0.77	0.80	0.98	1.29
Alberta	0.44	0.50	0.51	0.53	0.64	0.78	0.64	0.69	0.72	0.84	1.02	1.38
Manitoba	0.44	0.52	0.55	0.47	0.57	0.66	0.61	0.70	0.76	0.75	0.92	1.19
Saskatchewan	0.43	0.49	0.51	0.49	0.59	0.71	0.60	0.67	0.71	0.77	0.94	1.25
Nova Scotia	0.41	0.49	0.52	0.42	0.51	0.58	0.55	0.64	0.71	0.67	0.82	1.04
New Brunswick	0.40	0.48	0.51	0.42	0.51	0.59	0.55	0.64	0.70	0.67	0.82	1.05
Prince Edward Isl.	0.38	0.45	0.48	0.39	0.48	0.55	0.52	0.59	0.65	0.62	0.77	0.98
Nfld. and Labrador	0.49	0.56	0.59	0.59	0.71	0.86	0.72	0.79	0.83	0.94	1.14	1.53
Revenue-weighted average benefits and costs (US$/cow/year), BCRs (ratio), and BEPs (years)												
Benefit	16.23	24.68	29.79	15.73	18.86	18.08	21.83	27.86	31.36	19.59	22.00	20.91
Cost	37.92	49.83	57.17	33.15	32.79	26.74	36.37	41.38	43.39	26.02	23.89	17.38
BCR	0.43	0.50	0.52	0.47	0.58	0.68	0.60	0.67	0.72	0.75	0.92	1.20
BEP	-	-	-	-	-	-	-	-	-	-	9.26	8.48

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[1] STATCAN - Table 32-10-0136-01 Farm operating revenues and expenses, annual (STATCAN, 2019). 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, 2019). Number of cattle: STATCAN – Table 32-10-0130-01 – Number of cattle, by class and farm type (STATCAN, 2020).

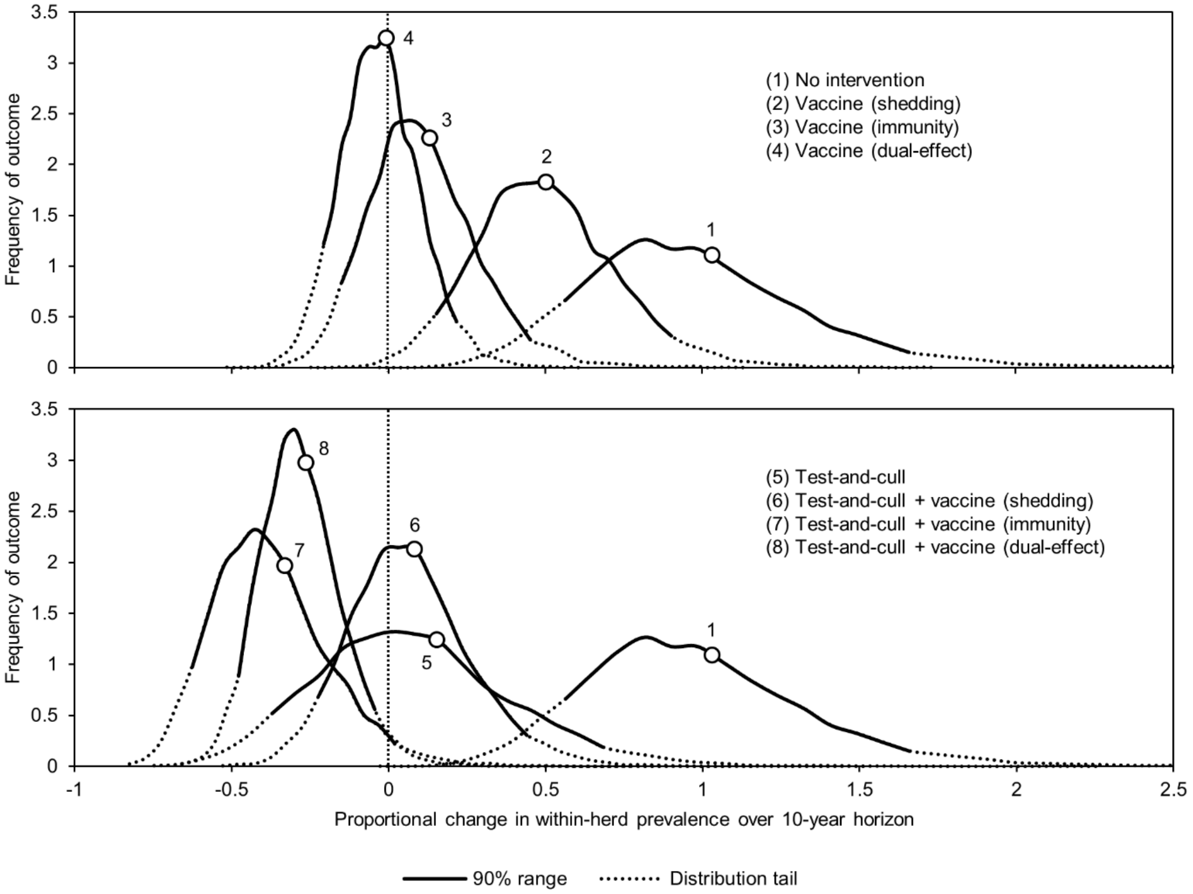

Figure 3-1. Distributions of 10-year proportional changes in within-herd prevalence for various JD (paratuberculosis) control practices compared to no intervention (10,000 iteration simulations). Assumes initial mean values of 10% for within-herd *Mycobacterium avium* subsp. *paratuberculosis* (MAP) prevalence, 50% for herd-level prevalence, 50% for vaccine efficacies, and 50% for testing sensitivities**.**

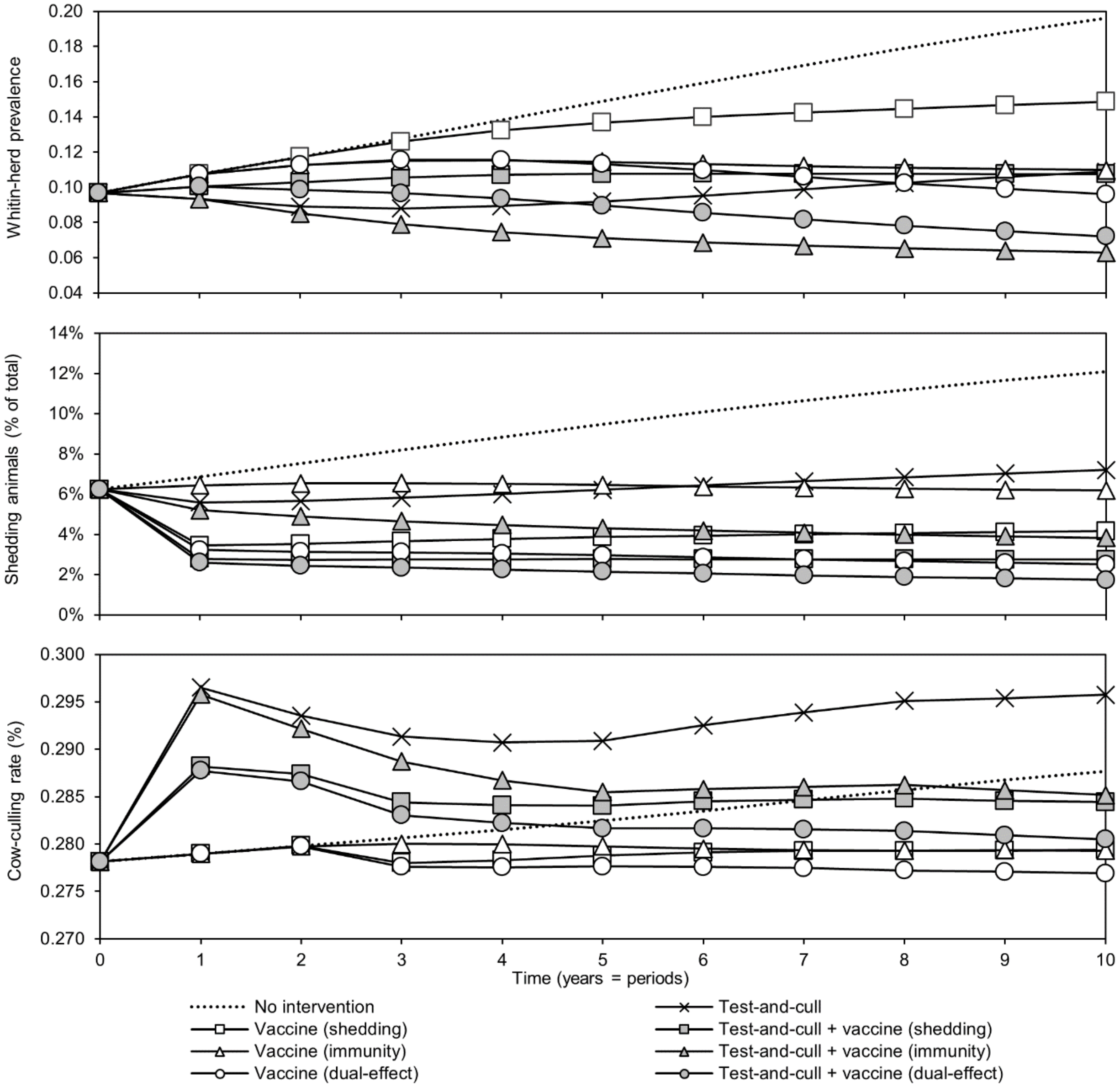

Figure 3-2. Within-herd prevalence, percentage of animals shedding, and culling rates of cows over time for various JD (paratuberculosis) control practices compared to no intervention. Assumes an initial value of 10% for within-herd *Mycobacterium avium* subsp. *paratuberculosis* (MAP) prevalence, 50% for herd-level prevalence, 50% for vaccine efficacies, and 50% for testing sensitivities.

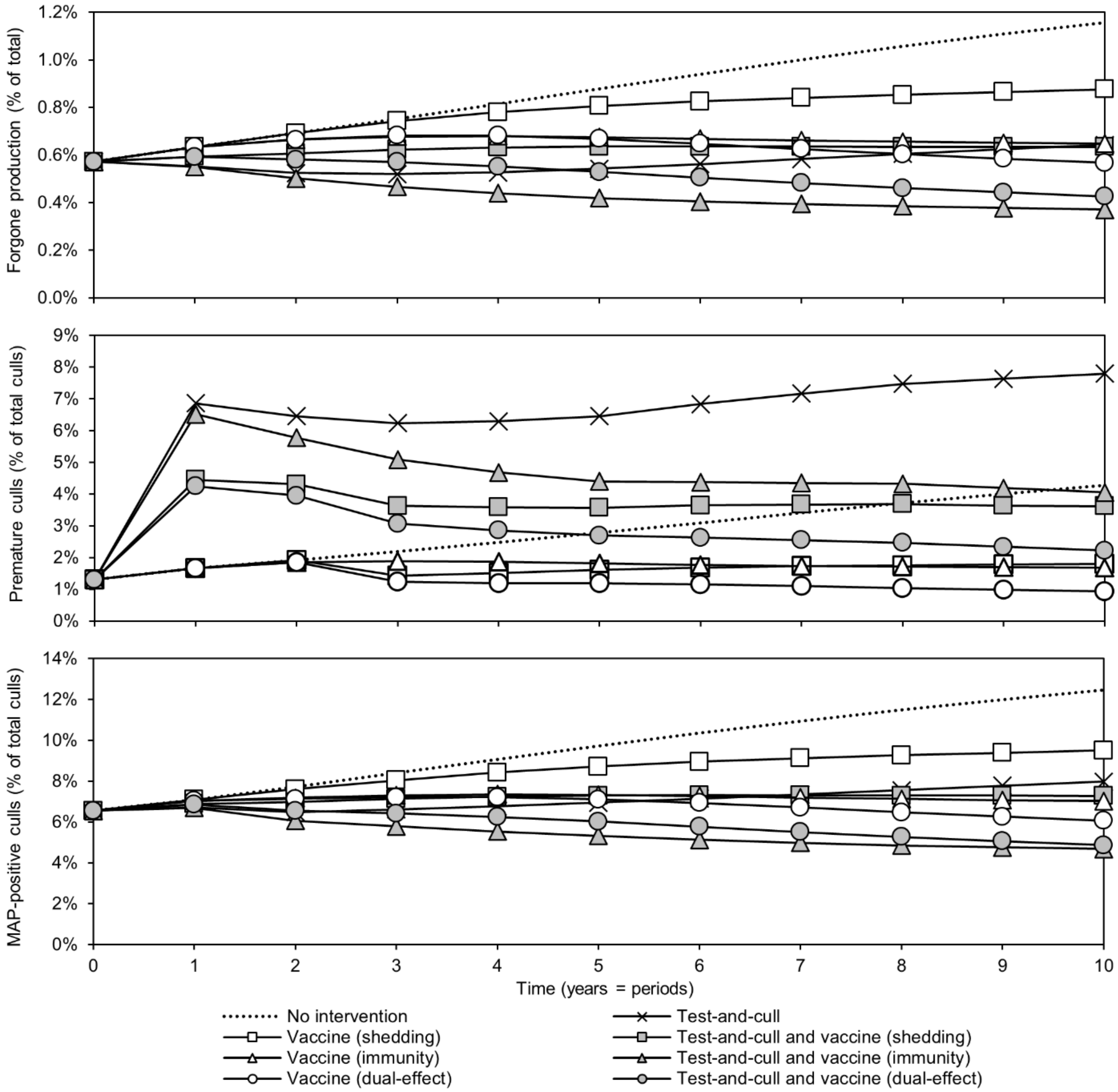

Figure 3-3. Sources of economic losses due to JD (paratuberculosis) over time for various control practices compared to no intervention. Forgone production as a percentage of potential production over time, premature culls as a percentage of total culls, and *Mycobacterium avium* subsp. *paratuberculosis* (MAP) -positive culls as a percentage of total culls. Assumes an initial value of 10% for within-herd MAP prevalence, 50% for herd-level prevalence, 50% for vaccine efficacies, and 50% for testing sensitivities.

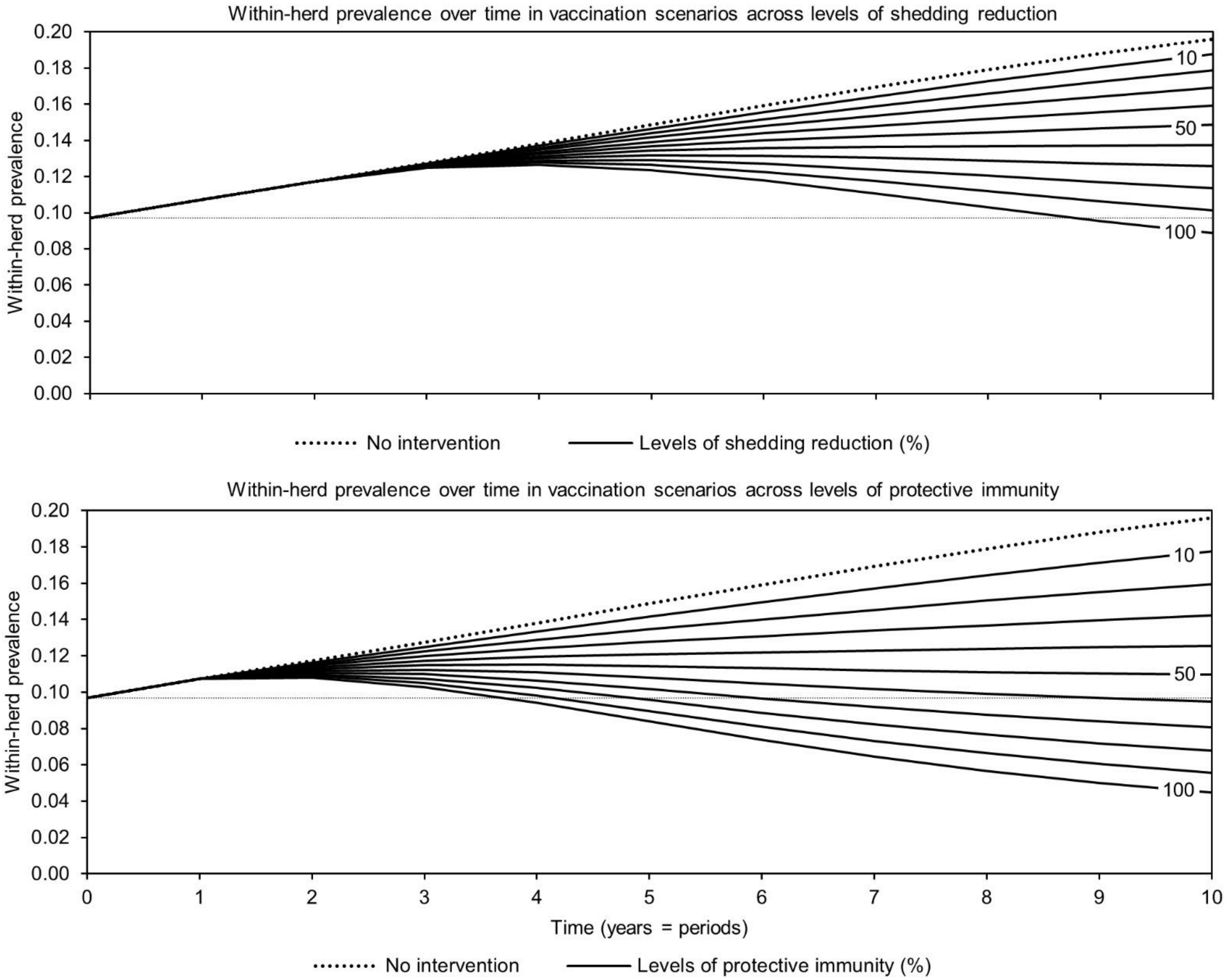

Figure 3-4. Estimates of within-herd *Mycobacterium avium* subsp. *paratuberculosis* (MAP) prevalence over time for JD (paratuberculosis) vaccines across a range of control-specific variable values.

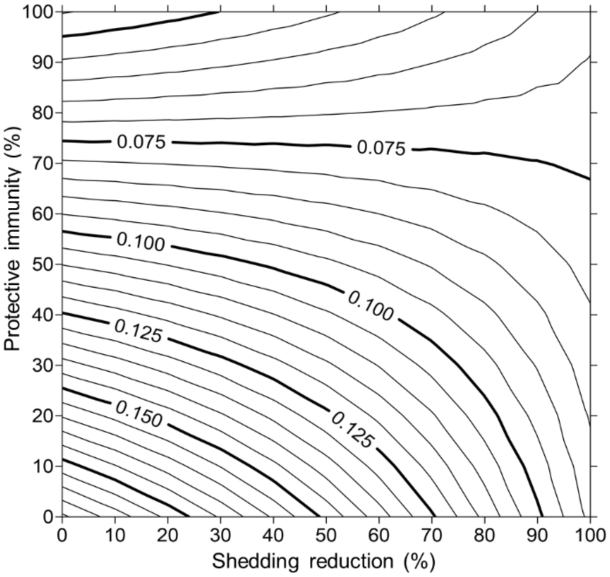

Figure 3-5. Estimates of final 10-year within-herd *Mycobacterium avium* subspecies *paratuberculosis* (MAP) prevalence across a range of protective immunities and shedding reductions given an initial within-herd prevalence of 0.10.

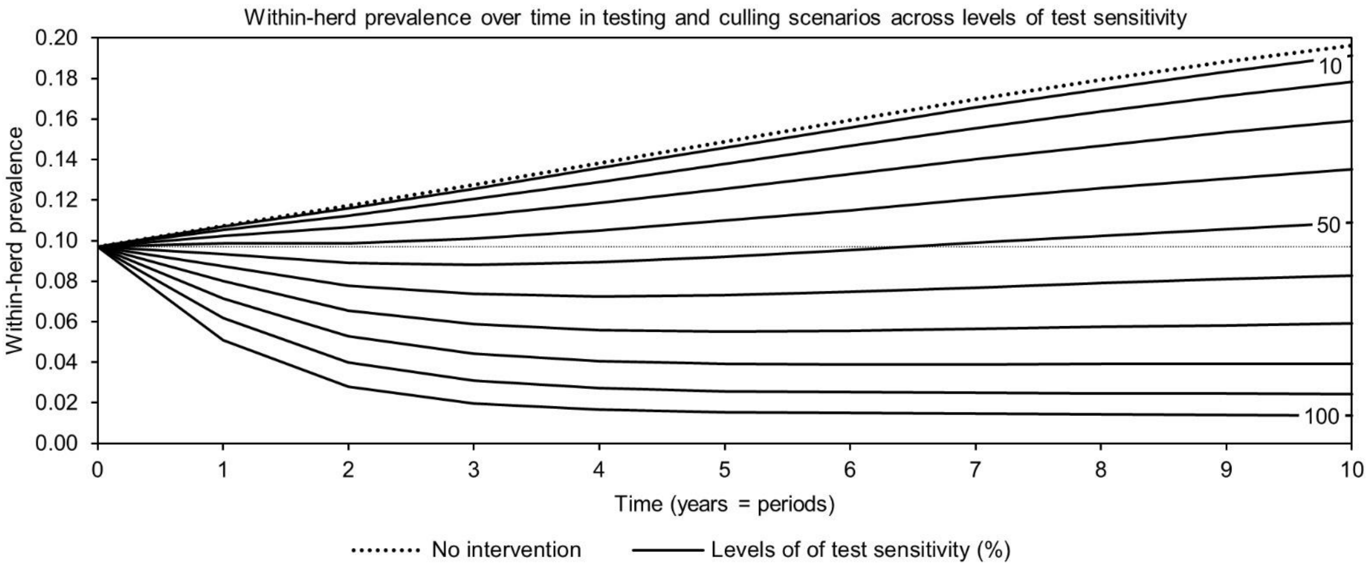

Figure 3-6. Estimates of within-herd *Mycobacterium avium* subspecies *paratuberculosis* (MAP) prevalence over time for testing and culling across a range of test sensitivities.

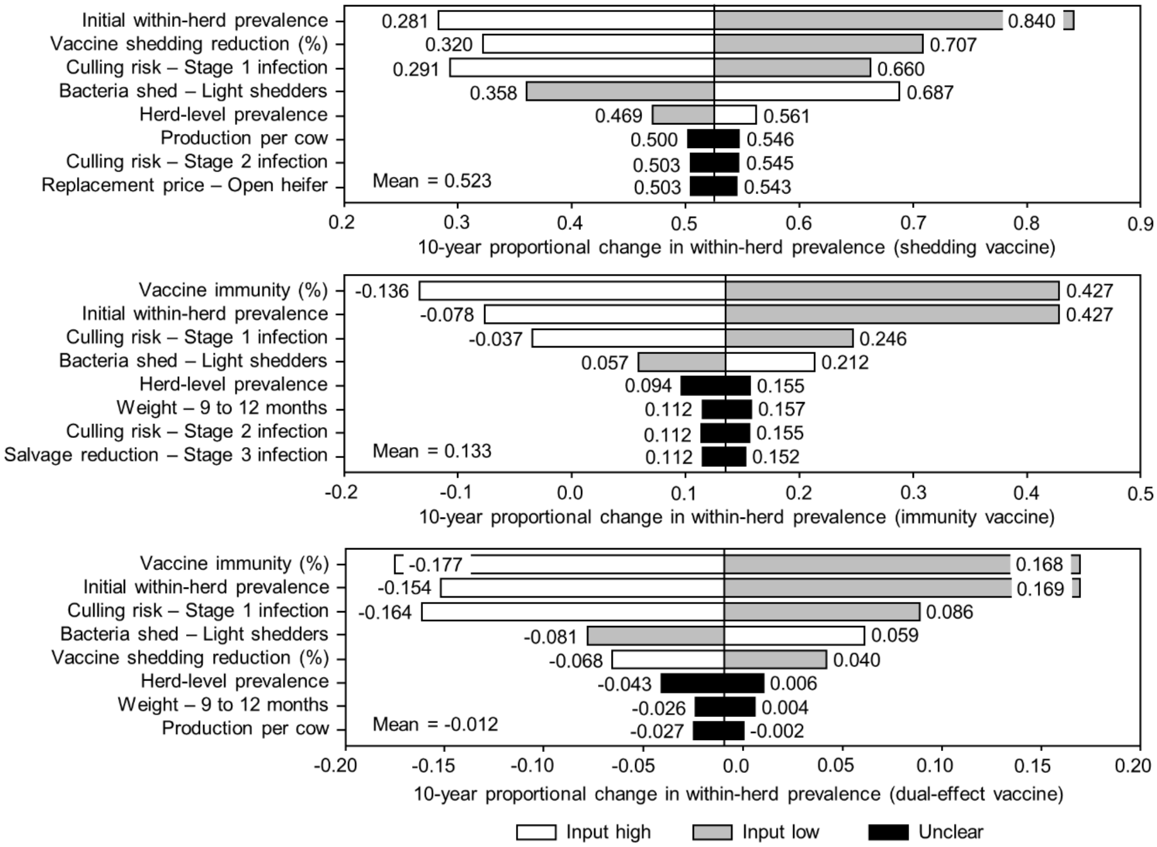

Figure 3-7. Sensitivity of 10-year proportional changes in within-herd prevalence due to various JD (paratuberculosis) vaccine types to a range of input variables. Assumes initial mean values of 10% for within-herd *Mycobacterium avium* subsp. *paratuberculosis* (MAP) prevalence, 50% for herd-level prevalence, 50% for vaccine efficacies, and 50% for testing sensitivities. The color of the sensitivity bars indicates the direction of the relationship between the variable and estimated losses (grey 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).

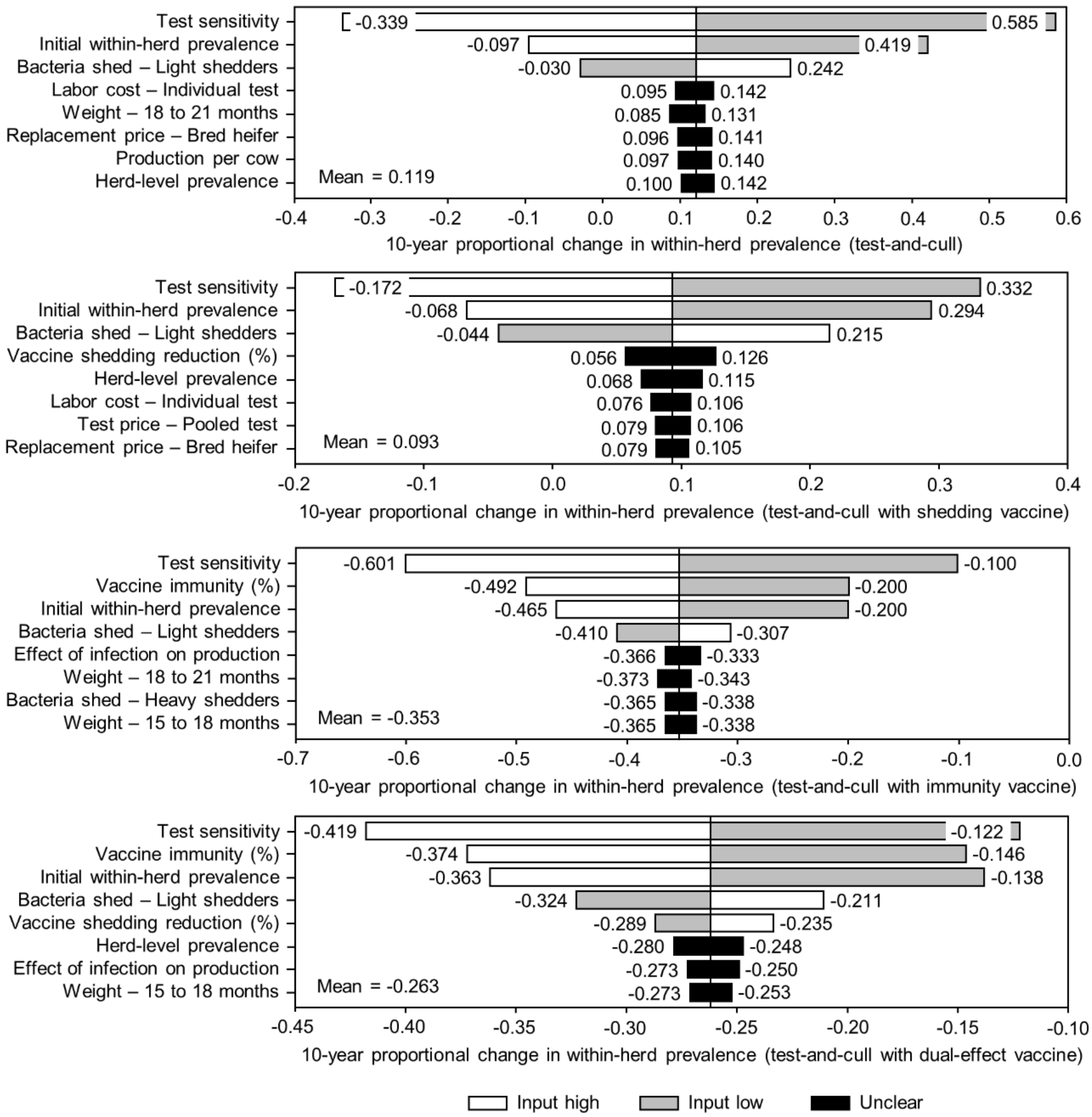

Figure 3-8. Sensitivity of 10-year proportional changes in within-herd prevalence due to various JD (paratuberculosis) practices involving testing and culling to a range of input variables. Assumes initial mean values of 10% for within-herd *Mycobacterium avium* subsp. *paratuberculosis* (MAP) prevalence, 50% for herd-level prevalence, 50% for vaccine efficacies, and 50% for testing sensitivities. The color of the sensitivity bars indicates the direction of the relationship between the variable and estimated losses (grey 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).

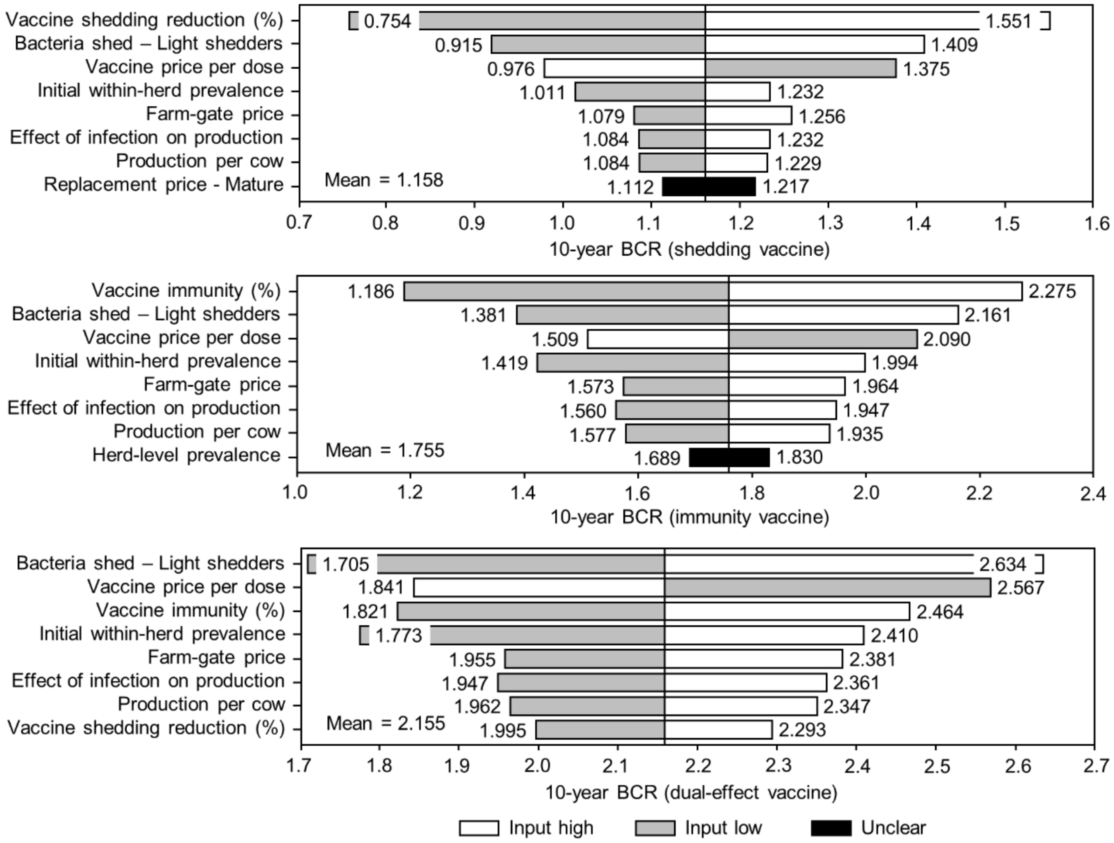

Figure 3-9. Sensitivity of 10-year benefit-cost ratios (BCRs) associated with various JD (paratuberculosis) vaccine types in average Canadian dairy herds to a range of input variables. Assumes initial mean values of 10% for within-herd *Mycobacterium avium* subsp. *paratuberculosis* (MAP) prevalence, 50% for herd-level prevalence, 50% for vaccine efficacies, and 50% for testing sensitivities. The color of the sensitivity bars indicates the direction of the relationship between the variable and estimated losses (grey 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).

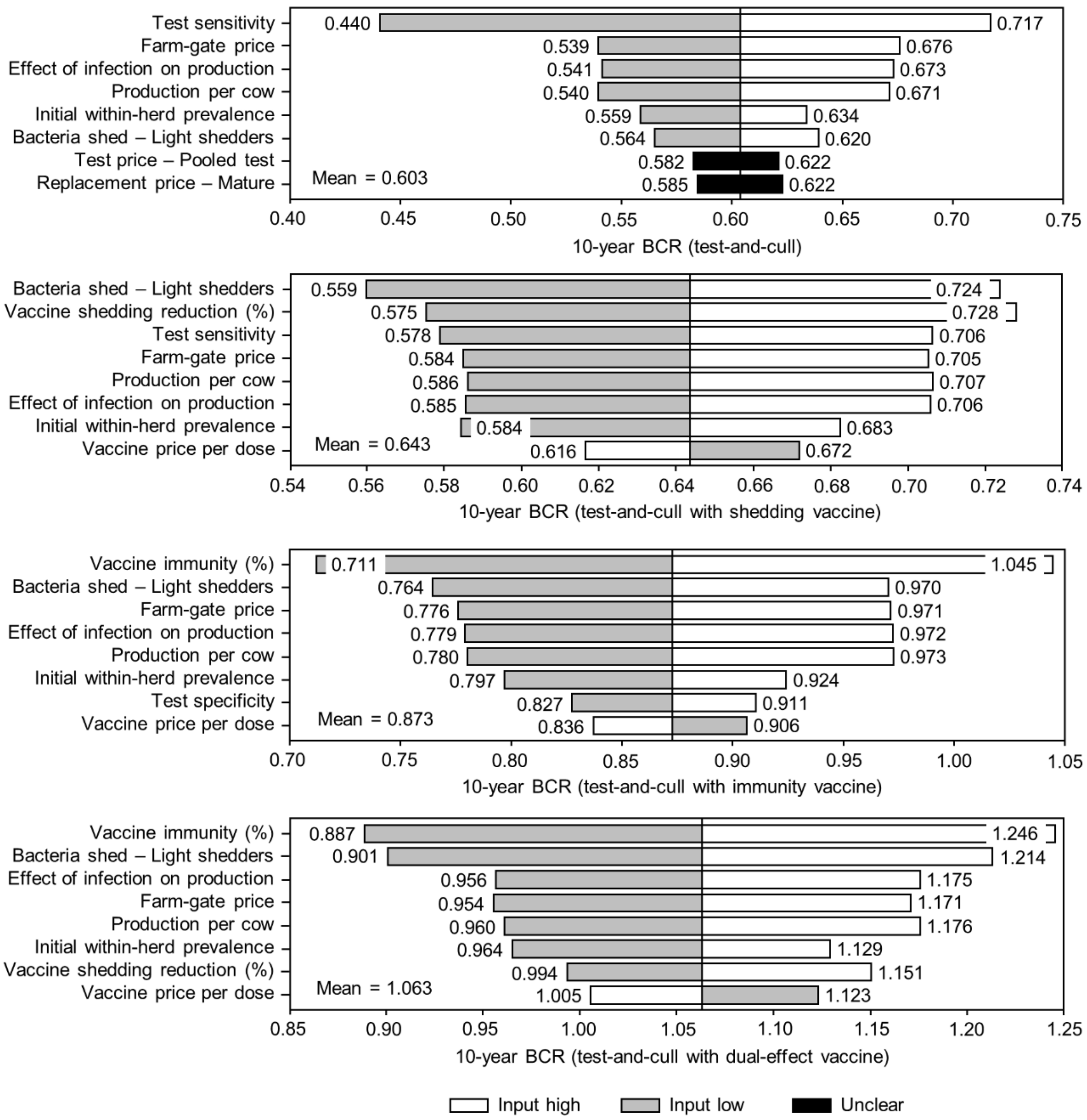

Figure 3-10. Sensitivity of 10-year benefit-cost ratios (BCRs) associated with various JD (paratuberculosis) control practices involving testing and culling in average Canadian dairy herds to a range of input variables. Assumes initial mean values of 10% for within-herd *Mycobacterium avium* subsp. *paratuberculosis* (MAP) prevalence, 50% for herd-level prevalence, 50% for vaccine efficacies, and 50% for testing sensitivities. The color of the sensitivity bars indicates the direction of the relationship between the variable and estimated

losses (grey 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).

CHAPTER 4: THE VALUE OF CONTROL TO CANADIAN PRODUCERS

Rasmussen P, Barkema HW, Mason S, Beaulieu E, Hall DC. Estimation of the value of Johne's disease (paratuberculosis) control to Canadian dairy producers. Prev. Vet. Med. In press.

4.1. Abstract

Johne's disease (JD), or paratuberculosis, is an infectious disorder often associated with cattle and resulting in significant economic losses for dairy producers. The dairy herd-level prevalence in Canada has recently been estimated to be greater than 40%, but the willingness to pay for JD control practices such as testing-and-culling and vaccination among Canadian dairy producers is unknown. This study used confidential cost-of-production data from the Canadian Dairy Commission to develop a Canadian dairy production model incorporating feed, land, labour, and machinery. A second dataset from a nationally distributed questionnaire (closed in March 2020) was used to estimate individual dairy producer valuations of the reduced per-cow cost of milk production that would result from JD control. This is a novel application of compensating variation and equivalent variation (CV and EV), with dairy producers framed as consumers of production inputs and milk output as a proxy for utility. Assuming a within-herd prevalence of 10% and a 50% reduction of that prevalence over 10 years, it was estimated JD control has an annual value of CA$28 per cow for the average Canadian dairy producer. Within-herd prevalence, the effectiveness of control at reducing within-herd prevalence, and the time required to achieve that reduction were identified as important factors.

4.2. Introduction

Johne's disease (JD), or paratuberculosis, is an infectious disorder of the intestines that can affect wild and domestic ruminants including dairy cattle (Fecteau and Whitlock, 2010) caused by an infection with *Mycobacterium avium* subspecies *paratuberculosis* (MAP). As the infection progresses in cattle, the clinical effects increase in severity from diarrhea and reduced milk production to lethargy, hypoproteinemia, and severe emaciation (Tiwari et al., 2006). JD results 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) as the primary causes. In Chapter 2, it was estimated that infected herds in major dairy-producing regions lose an average of US$33 per cow annually, or approximately 1% of gross milk revenue with annual losses among MAP-infected herds in Canada estimated between US$35 and US$57 per cow. Although national control programmes have already been established in several countries including Australia, Ireland, Japan, the Netherlands, and the United States (Whittington et al., 2019), Canada has no national control programme in place despite an estimated 42% of Canadian dairy herds being MAP-infected (Corbett et al., 2018). Intuitively, it may seem obvious that these economic losses warrant investment in control of the disease, but it is important to recognize that economic losses due to JD do not directly translate into producer valuation of JD control programmes. While economic loss estimates provide important information and are an indication of the value of controlling the disease, they do not always take into consideration how producers allocate their resources in response to herd health threats, and therefore cannot be interpreted as dollar-to-dollar reflections of how producers themselves value disease control. This study aimed to estimate the value of JD control while accounting for the complex resource allocation decisions faced by milk producers given their initial within-herd prevalence of MAP infection, the reduction in within-herd prevalence associated with control, the time required to achieve that reduction, and most importantly, their consumption patterns.

4.3. Materials and methods

This study can be separated into two main parts: 1) development of a Canadian dairy production model using cost of production data from the CDC; 2) estimation of the value of JD control among Canadian producers using a nationally-distributed production characteristics questionnaire. The first part consists of multiple regressions of logarithmically transformed data to develop a Canadian dairy production model. This process yields a set of Cobb-Douglas production functions, a classic and frequently used economic functional form often applied in agricultural economics (Sarma et al., 2014; Tanwar et al., 2015; Vishnoi et al., 2015; Larue et al., 2017; Michler et al., 2019). The ubiquity of this functional form in agricultural economics literature reflects not only its significance, but also its simplicity and suitability to economic modelling. The yearly regression models are then tested for multicollinearity by verifying that that regressors have variance inflation factors (VIFs) less than five and no correlation between regressors exceeds 0.8 within pairwise correlation matrices. Lastly, the yearly regression with the highest adjust R^2 (AR^2) was selected as the representative model for Canadian dairy production.

The second part of this study uses this Cobb-Douglas production function with constrained optimization and Lagrange multiplier methods to solve for expenditure-minimizing demand functions for capital, labour, and feed resources. In a novel approach, dairy producers are framed as consumers of input goods (capital, labour, and feed) that are seeking to minimize expenditures subject to the constraint of some minimum level of production, a proxy for utility. The resulting expenditure minimization problem is common in economic consumer theory, and the methodology is outlined in detail by Bersekas (1982). Within this context, JD control is framed as a change in the per-cow prices of variable inputs faced by dairy producers; the per-cow prices of labour and feed decrease because the herd size required to maintain milk output decreases as animals in the herd become healthier and more productive. The functional forms of these demand functions are then populated with respondent-specific data from the nationally distributed production characteristics questionnaire to estimate compensating variation (CV) and equivalent variation (EV) for each respondent. CV and EV are measures of welfare change introduced by Hicks (1939) that are commonly used to estimate the economic impact of policies and price changes on consumers (Chipman and Moore, 1980; Zhao and Kling, 2004; Robledo and Wagener, 2007; Morey and Rossmann, 2008).

4.3.1. Production models

Farm-gate prices for Canadian dairy producers are determined through a complicated process involving regional milk pools, provincial milk boards, milk pool costs and revenues, set daily quotas, and negotiated harmonized pricing. This process is based in part on the results of the annual CDC cost of production studies (CDC, 2020), which record production input quantities and prices, expenditure values, and key production characteristics for a representative sample of Canadian dairy producers. This confidential dataset, which was generously provided by the CDC for years 2014 to 2018, was standardized to 2014 CA$ values using the annual Canadian consumer price index (STATCAN, 2020) and is summarized across years in **Table 4-1**. In accordance with the confidentiality agreement between the CDC and the researchers, only nationally aggregated values are reported, and no regionally stratified analyses were conducted. Note that the complete CDC dataset contains approximately 240 observations per year, whereas the dataset summarized here contains only observations where all key variables for the production analyses were populated. Also, due to the small number of fully populated observations from 2014, data from that year were not included in the subsequent analyses.

Although no producer identifiers were provided in the dataset, it is highly likely that there was significant producer overlap across years as the data are collected from key informant farms. Therefore, the data were treated as longitudinal data and analyzed on a year-by-year basis instead of being combined into a single, larger dataset. For each yearly sample, the data were then logarithmically transformed, and annual output in hL milk was regressed on total capital expenditures in CA$, labour in hours, and feed expenditures in CA$. Annual output in hL milk was directly reported in the dataset; capital in CA$ was determined by the sum of machinery value in CA$ and land value in CA$ which were both directly reported in the dataset; labour hours were determined by the sum of CDC-validated administration, direct, and indirect labour hours for owners, family members, full-time employees, and part-time employees, which were directly reported in the dataset; total feed in CA$ was determined by the quotient of purchased feed in CA$ over the ratio of purchased feed to total feed used in production, which were both directly reported in the dataset. These regressions generated results of the following form for each yearly sample:

$$\ln(output) = \beta_0 + \beta_1 \ln(capital) + \beta_2 \ln(labour) + \beta_3 \ln(feed) \tag{1}$$

This functional form is identical to the logarithmic transformation of a 3-input Cobb-Douglas production function:

$$\ln(Q) = \ln(A) + \alpha \ln(K) + \beta \ln(L) + \gamma \ln(F) \tag{2}$$

where Q is output, A is a measure of productivity given the weighted average of inputs, K is capital, L is labour, F is feed, and α, β, and γ are the output elasticities of their associated inputs. For example, α is the quotient of percentage change in output over percentage change in capital.

These regression models were then exponentially transformed to obtain traditional Cobb-Douglas production functions of the following form for each yearly sample:

$$Q(K, L, F) = AK^{\alpha}L^{\beta}F^{\gamma} \tag{3}$$

where α, β, γ equal β_1, β_2, and β_3 from the logarithmic multiple regressions, respectively. In addition to these production models, the analysis of the CDC dataset also provided two important sets of indices that were applied to the production characteristics questionnaire data in order to estimate the value of JD control among the respondents: year-specific ratio of land to machinery in dollars and year-specific ratio of feed to machinery in dollars.

4.3.2. Production characteristics questionnaire

A production characteristics questionnaire (**Document S-1**) was distributed to Canadian dairy producers from November 2019 to March 2020 in both paper and electronic forms. In paper form, the questionnaire was distributed directly to producers already participating in other unrelated research projects throughout Alberta and British Columbia. Electronically, provincial dairy producer organizations across Canada posted a link to the online questionnaire on their social media and producer portal websites. In total, 152 respondents completed the questionnaire in a usable manner with key variables required for this analysis entirely populated. Some adjustments were required to the annual milk output (kg/cow) field: in 21 cases, respondents entered values ranging from 30 to 41 with no units indicated. It was assumed that these values represented kg/day per cow and were thus converted to kg/year per cow assuming an average lactation time of 305 days. In three cases, respondents entered values ranging from 1.4 to 1.5

with no units indicated. It was assumed that these values represented kg of butterfat/day and were thus converted to milk kg/year per cow assuming an average butterfat of 0.04 kg/L (Van Biert, 2019) divided by 1.03 kg/L (DAIReXNET, 2020) and multiplied by the same lactation period of 305 days. Eight otherwise usable responses were dropped because the field was either left blank or a value was entered that did not result in annual production per cow that was within three standard deviations of the mean after adjustment. The questionnaire data are summarized in **Table 4-2**. The ratios of land to machinery and feed to machinery obtained from the CDC data analysis were then used to estimate land and feed expenditures for the questionnaire respondents. During the development of the questionnaire, it was decided that these questions could be problematic for several reasons: while land value may be known off-hand by the respondents, it would be difficult to determine what percentage of that land was being used specifically for dairy production. The CDC dataset, on the other hand, provided consistent pre-allocation land values. Feed costs are similarly difficult to determine, and it was considered unlikely that reported feed costs would provide accurate valuations of self-produced feed and ration correctly. Once again, the CDC dataset provided consistent values for total feed. It is also important to note that due to a lack of responses, Newfoundland and Labrador, which contains less than 1% of dairy farms in Canada (CDIC, 2019), was excluded from the analyses.

4.3.3. Optimal demand functions for capital, labour, and feed

The three-input Cobb-Douglas production models resulting from the CDC data regressions were then reinterpreted as utility functions, framing producers as consumers of input goods with output as a proxy for utility U:

$$U(K, L, F) = AK^{\alpha}L^{\beta}F^{\gamma} \tag{4}$$

where A is a measure of utility given the weighted average of goods consumed, K is capital consumed, L is labour consumed, F is feed consumed, and α, β, and γ are the utility elasticities of their associated goods (for example, α is the quotient of percentage change in utility over percentage change in feed). Next, a simple linear budget function relating budget M to quantities of goods consumed given the prices of those goods was defined:

$$M(K, L, F) = K * P_K + L * P_L + F * P_F \tag{5}$$

where P_K is the price of capital, P_L is the price of labour, and P_F is the price of feed. Canadian dairy producers, who are consumers of capital, labour, and feed, were assumed to be expenditure-minimizing in that they seek to attain a certain level of utility $\overline{U}$ (output) as inexpensively as possible, given prices and their budget function M. Each individual producer therefore faces the following expenditure minimization problem:

$$\min_{K,L,F} M(K, L, F) \qquad s.t \qquad U(K, L, F) \geq \overline{U} \tag{6}$$

This constrained optimization problem was then rewritten as the Lagrange function $\mathcal{L}$:

$$\mathcal{L}(K, L, F, \lambda) = K * P_K + L * P_L + F * P_F - \lambda\left(\overline{U} - AK^{\alpha}L^{\beta}F^{\gamma}\right) \tag{7}$$

where λ is the Langrange multiplier, a scalar value that captures the relationship between budget M and minimum attainable utility $\overline{U}$. By finding the partial derivatives of $\mathcal{L}$ with respect to K, L,

F, and λ and setting them equal to zero (taking the first-order conditions of $\mathcal{L}$), the expenditure-minimizing demand functions for capital K^*, labour L^*, and feed F^* as functions of prices and some minimum level of utility $\bar{U}$ were solved for. In their general forms, these optimal demand functions are defined as:

$$K^*(P_K, P_L, P_F, \bar{U}) = \left(\bar{U} * \left(\frac{p_L\alpha}{p_K\beta}\right)^{\beta} \left(\frac{p_F\alpha}{p_K\gamma}\right)^{\gamma}\right)^{\frac{1}{\alpha+\beta+\gamma}} \tag{8}$$

$$L^*(P_K, P_L, P_F, \bar{U}) = \left(\bar{U} * \left(\frac{p_K\beta}{p_L\alpha}\right)^{\alpha} \left(\frac{p_F\beta}{p_L\gamma}\right)^{\gamma}\right)^{\frac{1}{\alpha+\beta+\gamma}} \tag{9}$$

$$F^*(P_K, P_L, P_F, \bar{U}) = \left(\bar{U} * \left(\frac{p_K\gamma}{p_F\alpha}\right)^{\alpha} \left(\frac{p_L\gamma}{p_F\beta}\right)^{\beta}\right)^{\frac{1}{\alpha+\beta+\gamma}} \tag{10}$$

Where, again, α, β, γ equal β_1, β_2, and β_3 from the logarithmic multiple regressions, respectively. The expenditure-minimizing demand functions were then substituted into the budget function M to obtain the following expenditure function E, which maps expenditures as a function of prices and some minimum level of utility $\bar{U}$ (output):

$$E(P_K, P_L, P_F, \bar{U}) = K^* * P_K + L^* * P_L + F^* * P_F \tag{11}$$

The impact of JD control on herd size was then quantified. Because JD has been estimated to result in production losses of 5.9% per MAP-infected cow per year (McAloon et al., 2016) and the Canadian dairy sector operates with fixed annual production, one impact of reducing within-herd MAP-infection prevalence is a reduction in the number of cows required to maintain that fixed production level. To begin this quantification, annual production per cow among MAP-negative cows q_n was estimated for each respondent using the following equation:

$$q_n = \frac{q_a}{(1 - p * e)} \tag{12}$$

where q_a is the overall average annual production per cow in kg as reported in the questionnaire, p is the assumed within-herd prevalence prior to JD control, and e is the effect of MAP infection on production. Annual production per cow among MAP-infected cows q_p was then estimated using the following equation:

$$q_p = (1 - e) * q_n \tag{13}$$

The overall average annual post-control production per cow $q_a{}'$ given some percent reduction in prevalence r was estimated using the following equation:

$$q_a{}' = q_n * (1 - p + p * r) + q_p * (p - p * r) \tag{14}$$

The post-control herd size h', given the initial herd size h as reported in the questionnaire (the sum of lactating cows and dry cows) and post-control production per cow $q_a{}'$, was estimated using the following equation:

$$h' = h * \frac{q_a}{q_a{}'} \tag{15}$$

With the herd size-reducing effect of JD control now quantified, the economic impact of that reduction was quantified. It was assumed that capital prices would remain unaffected by the reduced herd size, but that variable costs such as feed and labour would be reduced accordingly. Region-specific prices (**Table 4-3**) were used to define a set of unique per-cow prices $P = (P_K, P_L, P_F)$ faced by each questionnaire respondent based on their province and the number of cows in their herd. For example, the annual per-cow price of labour was estimated as labour expenditures based on the aggregated dairy wage rate faced by that producer divided by the number of cows in that herd. A set of post-control per-cow prices given a reduced herd size $P' = (P_K, P_L', P_F')$ such that $P_L > P_L'$ and $P_F > P_F'$ was estimated using the following equation:

$$P' = \frac{X-(h-h')*P}{h} \tag{16}$$

where X is the expenditure in dollars on labour or feed for each respondent.

4.3.4. Estimation of CV, EV, and the Value of JD Control

In their most general forms, CV estimates the adjustment in income needed to return a consumer to their original utility level after an economic change has occurred. In other words, what amount of compensation, either positive or negative, would be required to make a consumer indifferent between their situation after a price change and the situation they faced before the price change. EV, on the other hand, estimates the adjustment in income needed to move a consumer from their current utility level to the level they would be at if an economic change did occur. In other words, what amount of compensation, either positive or negative, would be required to make a consumer indifferent between their current situation and the situation they would face if a price change occurred. Similarly, in the case of this study, these two estimates approach producer valuation of JD control from two different views: from the post-control perspective, CV answers the question “What is the dollar amount that this producer would have to *lose* to be as well off as they were *before* JD control?”; from the pre-control perspective, EV answers the question “What is the dollar amount that this producer would have to *gain* to be as well off as they would have been *after* JD control?” Together, CV and EV form the lower and upper bounds, respectively, of the welfare change associated with decreased per-cow prices of feed and labour due to a reduced within-herd JD prevalence. Interpreted from the producer’s perspective, CV and EV represent the range that a producer should be willing to pay for JD control.

The compensating variation CV, or the dollar amount that a producer would have to lose to be as well off as they were before JD control, was estimated using the following formula:

$$CV = E(P, \bar{U}) - E(P', \bar{U}) \qquad (17)$$

where $\bar{U}'$ is the level of utility (output) attainable at the post-JD control prices P' given the respondent’s budget function and expenditure-minimizing demands for capital, labour, and feed. The equivalent variation EV, or the dollar amount that a producer would have to gain to be as well off as they would be after JD control, was estimated using the following formula:

$$EV = E(P, \bar{U}') - E(P, \bar{U}) \qquad (18)$$

Together, CV and EV form the lower and upper bounds, respectively, of the value of JD control to Canadian dairy producers given within-herd prevalence p, percent reduction in prevalence due to JD control r, and their observed consumption patterns. The CV and EV estimates were then averaged to generate a mean value estimate for each respondent and stratified by region to provide mean estimates across Canadian provinces. However, these estimates were based solely on production losses, and therefore ignored losses due to reduced salvage value and premature culling associated with MAP-infection in dairy herds. These estimates also had no time component and therefore ignored the time required to achieve the reduction in within-herd prevalence through JD control. Accordingly, the estimates were adjusted in two ways: first, other sources of losses due to MAP-infection were incorporated using estimates of the percentage of total losses attributable to production losses in Canadian dairy herds with fixed production (**Table A-7**). Secondly, the estimates were discounted over time at a rate of 5% per annum according to the timeframe of the control scenario. This discount rate was selected because it reflects small private firm investment; it falls between a public investment return rate of approximately 3% (USDA NRCS, 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 stated that it would likely be reduced in future years (TBC, 2007).

4.4. Results

4.4.1. Production models

All yearly regression models using the CDC dataset generated similar results, with labour consistently estimated to be the most impactful factor on milk production, with capital and feed having comparably less impact. All regressions had highly significant coefficients with variance inflation factors well below 5, suggesting that multicollinearity was not an issue in these regressions. To further verify this, pairwise correlation coefficient matrices were generated (**Table A-8**) with no correlation between regressors being problematic. Of the yearly regression models, 2017 had the best fit (AR^2 of 0.81) and was therefore selected to generate the three-input Cobb-Douglas production model used in the subsequent CV and EV analyses. However, the value estimates when using the production models generated by other yearly samples yielded similar results (**Table A-9**).

4.4.2. CV, EV, and the value of JD control

Results of the CV and EV analyses are presented in **Table 4-5**. Assuming an initial within-herd MAP prevalence of 10% and a 50% reduction in that prevalence, unadjusted estimates of the value of JD control (with no consideration for time and ignoring losses due to reduced salvage values and premature culling) ranged from CA$20.00 per cow per year in New Brunswick to CA$24.84 in Alberta, with a Canadian weighted average of CA$21.73. Once adjusted to account for additional sources of losses and assuming the 50% reduction occurs over 10 years, annual estimates ranged from CA$22.74 in New Brunswick to CA$33.15 in Alberta, with a Canadian weighted average of CA$27.79 per cow per year. The impacts of reduction in within-herd prevalence and the time required to achieve that reduction on the adjusted value estimates are presented in Fig. 1. With lower reductions in within-herd prevalence (less than approximately 30%), the timeframe of JD control had little impact whereas with higher reductions, the time became relevant. For example, assuming an initial within-herd prevalence of 10%, for an instantaneous 100% reduction in within-prevalence, the value of JD control exceeds CA$90 per cow per year. However, if that same reduction required 5 years, the value would be just over CA$70, and for 10 years, it would be just over CA$55. The impact of percent reduction in prevalence and initial within-herd prevalence are presented in Fig. 2. Not surprisingly, these two variables have comparable impacts on the estimated value. For example, the value of JD control is similar, just under CA$15 per cow per year, whether there is a 10% reduction given an initial within-herd prevalence of 25% or a 100% reduction given an initial prevalence of 2.5%.

4.5. Discussion

This study generated a Canadian dairy production model in a convenient Cobb-Douglas functional form suitable to a wide range of economic analyses. The production model was interpreted as an indirect indicator of utility, populated with respondent-specific data obtained from a nationally distributed questionnaire, and applied in a CV and EV framework to estimate the value of JD control among Canadian dairy producers. This novel approach adds to the information available both to producers and policymakers, who must make decisions about MAP infection and other herd-level health threats. The robust production function derived from the CDC dataset based on 2017 cost-of-production data (adjusted $R^2 = 0.81$) indicates that Canadian milk production is strongly dependent on labour input; the estimated regression coefficient for labour is nearly double that of either capital or feed (**Table 4-4**). With labour being the most impactful factor on milk production, the relatively higher aggregated wage rates in Alberta, British Columbia, and Saskatchewan (**Table 4-3**) were a major contributing factor to higher MAP-related losses per cow in those provinces, and therefore higher CV and EV estimates compared to the rest of Canada (**Table 4-5**). Relatively higher farm-gate prices for milk in Alberta and British Columbia (**Table 4-3**) were also a contributing factor to those regional differences due their direct impact on estimated production losses due to JD, the largest component of total losses.

However, the primary determinants of estimated CV and EV, and therefore the value of JD control, were initial within-herd MAP prevalence, effectiveness of JD control, and time required to achieve reduction. These are important factors that should be considered when evaluating the adoption of a JD control practice. For example, in Chapter 3 it was estimated that a dual-effect vaccine providing a 70% reduction in shedding and 70% protective immunity would reduce within-herd MAP prevalence by 25% over a 10-year period assuming that within-herd MAP prevalence would otherwise double. For this same level of reduction, this model estimates a value of approximately CA$15 per cow per year for JD control. However, it is important to recognize that the estimated per-cow value of JD control is not equivalent to estimated willingness to pay (WTP) per dose of a JD vaccine (the maximum possible price per dose that a producer would likely pay). Estimating WTP per dose would require additional knowledge, aside from within-herd MAP prevalence, the effectiveness of JD control, and the timeframe of control; it would require detailed knowledge of the vaccination protocol, and among other important determinants, the replacement rate in the herd, the expected lifespan of cattle in the herd, and the rate of spread of MAP infection within the herd. For example, if this vaccine were to be administered annually to mature cows only (no young stock) and the culling rate were unaffected by overall herd health, the annual value of JD control per cow and the WTP per vaccine dose would be roughly equivalent. On the other hand, if the vaccine required only a few doses across an animal's lifespan and the culling rate realistically decreased as herd health improved, WTP per cow would far exceed the 10-year average annual per cow cost of the vaccination programme. The effects of JD control on herd structure and cow-culling rates are important factors, as are the details of the control protocol.

The results generated in this study can only be interpreted as estimates of WTP for JD control among Canadian dairy producers if we assume that producers have perfect information. In other words, that producers are perfectly aware of how JD affects their herds and how potential control practices would benefit them. There are, however, more direct methods to estimate WTP such as stated preference techniques, hypothetical auction experiments, preference ranking, or even explicitly asking consumers, in this case dairy producers who are potential consumers of a JD vaccine, to assign a value to JD control. While it has been demonstrated that some of these methods can be good indicators of actual market behaviour (Loureiro et al., 2003), overall results have been mixed. WTP estimates can differ across methodologies (Gracia et al., 2011) and gaps between stated preferences and exercised preferences have been observed (Parker and Souleles, 2019; Paakala et al., 2020), with these gaps shrinking as more information and context are provided (De Martino et al., 2016; Su et al., 2017; Zawojska and Czajkowski, 2017). This suggests that in terms of real-world applicability, the difference between the value of JD control estimated in this study and what Canadian dairy producers are actually willing to pay for JD control is largely dependent on the level and quality of information available to them; the more knowledge about the economic impact of JD on their herd, within-herd MAP prevalence in their herd, herd-level MAP prevalence in their region, the effectiveness of potential control practices, the time required, and the details of potential control protocols, the smaller that gap will become.

4.6. Conclusions

Assuming an initial within-herd MAP prevalence of 10% and a 50% reduction in that prevalence over 10 years, the value of JD control to average Canadian dairy producers was estimated at $28 per cow per year. Within-herd prevalence and the percent reduction in prevalence due to JD control were positively related to the estimated value of control, with the time required being negatively impactful, particularly at higher percent reductions. Although it is logical that JD control continues to remain a lesser priority to Canadian dairy producers than more immediate and more easily addressable herd health concerns such as mastitis, it is important to recognize that research into potential interactions between MAP and other pathogens that affect dairy cows is still developing. For example, higher incidences of mastitis (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). Additionally, JD control will likely also reduce the incidence of similarly transmitted infections in calves such as rota- and corona-virus, *Escherichia coli*, *Cryptosporidium parvum* and *Cryptosporidium bovis*, and *Salmonella* spp. (Barkema et al., 2018). While this current study adds to the information available to Canadian dairy producers regarding the value of JD control, it also provides evidence that further research into the effects of JD on dairy herds and the specifics of potential control practices is required before both producers and policymakers can properly estimate the financial investment that Canadian dairy producers are willing to make in JD control.

4.7. References

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Table 4-1. Summary of selected Canadian Dairy Commission cost-of-production data for 2015 to 2018 in standardized 2014 Canadian dollar (CA$) values, with only entirely populated responses remaining in the sample.

Year:	2014	2015	2016	2017	2018
Observations:	31	184	192	197	198
Variable			Mean (standard deviation)		
Herd size (cows)	129.65	65.57	80.91	83.90	88.56
	(87.59)	(36.97)	(60.98)	(60.74)	(63.40)
Output (hL milk /year)	12,135.46	5,799.30	7,519.36	7,850.35	8,445.06
	(9,170.41)	(3,960.97)	(6,523.17)	(6,334.91)	(6,799.39)
Land (CA$)	990,765.89	334,052.87	439,520.60	424,885.35	495,576.44
	(1,179,462.34)	(407,765.74)	(660,120.85)	(521,226.38)	(612,352.02)
Machinery (CA$)	528,553.94	228,932.34	298,183.99	299,259.02	304,844.13
	(632,951.75)	(164,096.64)	(290,705.47)	(260,084.21)	(269,990.70)
Labour (hours)[1]	7,861.54	6,213.67	6,710.85	7,090.47	7,329.50
	(3,936.56)	(2,608.31)	(3,025.82)	(3,372.53)	(3,670.78)
Total feed (CA$)[2]	4,356,107.32	463,724.84	913,433.72	876,144.55	1,239,204.43
	(7,248,155.92)	(401,495.28)	(2,424,506.51)	(2,591,620.92)	(3,265,041.90)

All dollar values standardized using Table 18-10-0005-01 Consumer Price Index, annual average, not seasonally adjusted (STATCAN, 2020).

[1] Sum of validated administration, direct, and indirect labour hours for owners, family members, full-time employees, and part-time employees.

[2] Total annual purchased feed as a cash cost divided by ratio of purchased feed to total feed.

Table 4-2. Summary of applicable Canadian dairy production characteristics questionnaire results by province of respondent from east to west across Canada.

	PE	NS	NB	QC	ON	MB	SK	AB	BC	TOTAL
Observations	11	8	15	8	40	12	16	25	17	152
Variable	Mean									
(questionnaire label)	(standard deviation)									
Lactating cow count	113.36	155.25	133.13	113.88	109.45	179.67	149.88	201.54	171.41	146.59
(S1.Q1)	(92.78)	(104.83)	(108.12)	(136.88)	(86.84)	(166.84)	(86.47)	(109.92)	(116.73)	(110.89)
Dry cow count	19.82	26.13	22.80	17.63	18.93	28.58	27.44	33.30	27.18	24.63
(S1.Q1)	(15.54)	(22.22)	(17.51)	(25.96)	(12.00)	(23.91)	(13.79)	(19.38)	(24.25)	(18.81)
Output (kg/cow)	10,368.64	11,071.36	10,291.70	10,448.33	10,654.13	11,935.58	10,741.27	11,617.71	11,535.12	10,976.19
(S1.Q2)	(1,343.50)	(1,689.09)	(1,297.46)	(1,329.24)	(1,436.42)	(1,512.20)	(1,498.87)	(1,495.78)	(1,609.34)	(1,530.01)
Labour per week (hours)	193.45	215.63	209.00	195.25	174.20	253.92	400.13	241.20	187.94	224.95
(S1.Q8)	(110.41)	(121.29)	(153.02)	(147.94)	(115.26)	(225.37)	(512.97)	(134.61)	(99.55)	(215.00)
Tractors < 60 hp	1.00	1.00	0.80	0.88	1.08	0.92	1.63	0.88	1.47	1.09
(S2.Q1)	(1.00)	(1.07)	(0.94)	(0.83)	(1.53)	(1.16)	(1.71)	(0.88)	(0.87)	(1.22)
60 hp ≥ Tractors ≤ 149 hp	3.55	3.63	4.13	3.13	2.83	2.25	2.75	1.44	3.53	2.86
(S2.Q2)	(1.63)	(1.30)	(2.00)	(0.99)	(1.75)	(1.36)	(1.77)	(0.92)	(1.62)	(1.72)
Tractors > 149 hp	1.45	1.13	1.07	1.50	1.00	2.08	2.50	1.60	1.35	1.45
(S2.Q3)	(1.69)	(1.13)	(1.75)	(1.41)	(1.43)	(0.79)	(1.93)	(1.22)	(1.22)	(1.43)
Vehicle count[1]	1.73	1.00	2.07	1.38	1.55	2.25	3.44	2.20	1.82	1.97
(S2.Q4)	(1.56)	(0.93)	(0.88)	(0.92)	(1.18)	(1.29)	(2.25)	(1.85)	(1.33)	(1.55)
Farm truck count	1.82	1.13	1.20	0.75	1.05	2.33	3.00	1.20	1.35	1.47
(S2.Q5)	(1.60)	(2.03)	(1.15)	(1.04)	(0.99)	(1.37)	(1.71)	(1.26)	(1.11)	(1.42)

Combine and swather count	0.82	0.88	0.30	0.75	0.40	1.08	3.38	0.52	0.00	0.81
(S2.Q6)	(0.98)	(2.10)	(0.46)	(0.89)	(0.55)	(1.00)	(2.63)	(0.82)	(0.00)	(1.46)
Other machinery count[2]	3.18	4.13	3.53	2.63	2.48	2.92	3.13	1.84	2.88	2.77
(S2.Q7)	(1.17)	(1.46)	(1.55)	(0.74)	(2.16)	(1.98)	(1.82)	(1.84)	(1.65)	(1.85)

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[1] Appears as “cars, pick-ups, cargo vans, and passenger vehicles” in questionnaire.

[2] Appears as “forage harvesters, balers, mower-conditioners, etc.” in questionnaire.

2961

Table 4-3. Price variables used in the estimation of Canadian dairy producer valuation of Johne's disease control across provinces from east to west across Canada, standardized to 2014 Canadian dollar values (CA$).

Price variable	PE	NS	NB	QC	ON	MB	SK	AB	BC
Aggregate wage rate (CA$/hr)[1]	14.50	14.49	15.14	16.40	18.60	17.14	21.96	26.43	20.46
Tractors < 60 hp (CA$/unit)[2]	7,784.62	9,280.24	8,621.75	7,209.29	7,784.62	6,139.78	6,633.84	8,621.75	9,280.24
60 hp ≥ Tractors ≤ 149 hp (CA$/unit)[2]	27,632.46	32,766.31	29,254.45	29,939.79	27,807.98	24,146.32	23,145.68	27,632.46	26,771.60
Tractors > 149 hp (CA$/unit)[2]	104,340.27	96,314.15	93,040.17	90,228.37	88,354.70	90,338.31	84,447.79	87,971.79	64,560.74
Vehicles (CA$/unit)[2]	13,180.26	13,852.13	13,679.53	13,625.46	15,618.04	14,555.44	16,030.00	15,622.81	14,738.14
Farm trucks (CA$/unit)[2]	12,431.87	15,784.17	16,590.37	20,857.94	19,863.53	20,294.21	19,295.41	20,972.98	16,655.53
Combines and swathers (CA$/unit)[2]	45,310.93	35,702.55	27,305.73	68,168.69	62,261.06	67,154.04	71,265.18	67,021.92	24,771.70
Other machinery (CA$/unit)[2]	11,414.36	10,198.36	10,045.69	11,932.81	10,718.89	13,181.08	13,028.30	14,670.42	11,667.46
Farm-gate price (CA$/hL)[3]	67.73	66.66	67.19	66.59	66.10	67.88	67.38	70.15	73.74

All dollar values standardized using Table 18-10-0005-01 Consumer Price Index, annual average, not seasonally adjusted (STATCAN, 2020a).

[1] Estimated aggregate dairy wage rates (Chapter 2) converted to CA$ using IRS.gov – Yearly Average Currency Exchange Rates (IRS, 2020).

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[2] Table 32-10-0437-01 Farm capital (farm machinery and equipment, livestock and poultry, land and buildings). 2016 “Number owned and leased” divided by “Market value in dollars” (STATCAN, 2020b).

[3] CDIC - MI011 - Canadian farm cash receipts from dairying (CDIC, 2019c).

Table 4-4. Regression results for the natural logarithm of milk output in hL (the outcome variable) on the natural logarithms of capital in Canadian dollars (CA$), total labour in hours, and feed in CA$ (the regressors), with all dollar amounts standardized to 2014 values. Number of observations (*n*), variance inflation factor (VIF), adjusted R^2 (AR^2), and root-mean-squared-error (RMSE) are also reported. Data obtained from the annual Canadian Dairy Commission cost-of-production studies (2015 to 2018).

Year	*n*	Regressor	Estimate	Std. Error	P-value	VIF	Fit
2015	184	*ln_feed_$* [1]	0.286	0.041	<0.001	1.96	AR^2
		ln_labour_hr [2]	0.353	0.068	<0.001	1.44	0.743
		ln_capital_$ [3]	0.310	0.039	<0.001	1.90	RMSE
		constant	-2.228	0.515	<0.001		0.300
2016	192	*ln_feed_$*	0.272	0.032	<0.001	2.25	AR^2
		ln_labour_hr	0.480	0.070	<0.001	2.02	0.797
		ln_capital_$	0.267	0.037	<0.001	1.63	RMSE
		constant	-2.544	0.494	<0.001		0.307
2017	197	*ln_feed_$*	0.261	0.035	<0.001	2.49	AR^2
		ln_labour_hr	0.564	0.065	<0.001	1.74	0.806
		ln_capital_$	0.256	0.039	<0.001	2.13	RMSE
		constant	-2.975	0.457	<0.001		0.297
2018	198	*ln_feed_$*	0.215	0.029	<0.001	1.92	AR^2
		ln_labour_hr	0.614	0.065	<0.001	1.58	0.780
		ln_capital_$	0.240	0.038	<0.001	1.95	RMSE
		constant	-2.588	0.475	<0.001		0.313

All dollar values standardized using Table 18-10-0005-01 Consumer Price Index, annual average, not seasonally adjusted (STATCAN, 2020a).

[1] Natural logarithm of feed expenditures in 2014 CA$.

[2] Natural logarithm of labour expenditures in hours.

[3] Natural logarithm of capital (sum of machinery and land) expenditures in 2014 CA$.

Table 4-5. Estimated annual value of Johne's disease control among Canadian dairy producers in 2019 CA$ per cow, firstly based on production losses only and then adjusted to account for additional premature culling losses, reduced salvage value losses, and the time required to achieve a reduction in within-herd prevalence. Assumes an initial within-herd Mycobacterium avium subspecies paratuberculosis infection prevalence of 10% and a 50% reduction in within-herd prevalence over 10 years. Regions ordered from east to west across Canada.

Region	Value of JD control in CA$/cow per year (CV - EV range)	Production losses as percentage of total losses[1]	Adjusted value of JD control in CA$/cow per year (CV - EV range)
Prince Edward Island	20.91 (13.93 - 27.89)	52	24.68 (16.45 - 32.92)
Nova Scotia	21.58 (14.38 - 28.79)	56	23.66 (15.76 - 31.56)
New Brunswick	20.00 (13.32 - 26.67)	54	22.74 (15.15 - 30.33)
Québec	21.37 (14.24 - 28.50)	52	25.23 (16.81 - 33.65)
Ontario	20.79 (13.85 - 27.73)	47	27.15 (18.09 - 36.22)
Manitoba	22.48 (14.98 - 29.99)	56	24.65 (16.42 - 32.88)
Saskatchewan	21.56 (14.36 - 28.76)	48	27.58 (18.37 - 36.78)
Alberta	24.84 (16.55 - 33.13)	46	33.15 (22.09 - 44.22)
British Columbia	24.16 (16.09 - 32.22)	53	27.98 (18.64 - 37.32)
CANADA[2]	21.73 (14.48 - 28.98)	48	27.79 (18.51 - 37.06)

[1] Estimated percentage of total losses due to Johne's disease attributable to production losses in Canadian dairy herds with the constraint of fixed annual production considered (Chapter 2).

[2] Average of provincial estimates weighted by head of cattle in each province from STATCAN – Table 32-10-0130-01 – Number of cattle, by class and farm type (x 1,000) (STATCAN, 2020b).

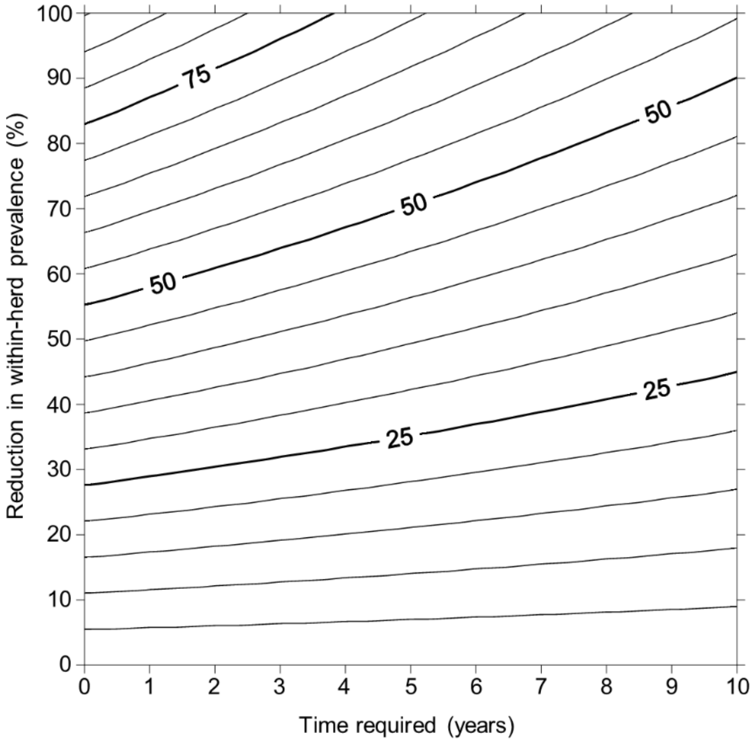

Figure 4-1. Annual estimated value of Johne's disease control in 2019 CA$ per cow among average Canadian dairy producers across percentage reduction in within-herd prevalence resulting from control and time required in years to achieve that reduction. Assumes an initial within-herd *Mycobacterium avium* subspecies *paratuberculosis* infection prevalence of 10%.

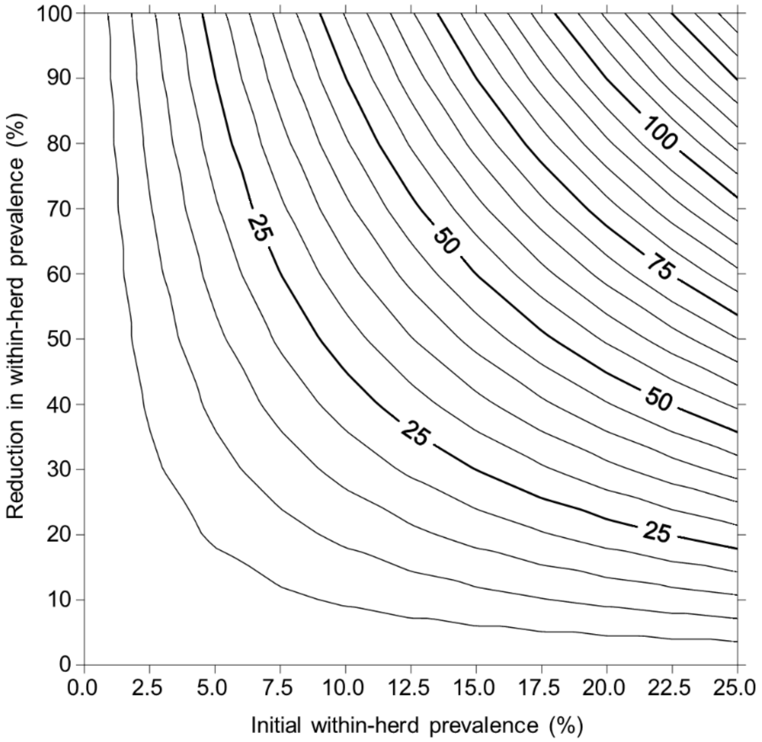

Figure 4-2. Annual value of Johne's disease (JD or paratuberculosis) control in 2019 CA$ per cow estimated among average Canadian dairy producers across percentage reduction in within-herd *Mycobacterium avium* subspecies *paratuberculosis* infection prevalence resulting from control and initial within-herd prevalence. Assumes a 10-year period is required to achieve reductions in within-herd prevalence.

CHAPTER 5: THE VALUE OF MAP-NEGATIVE REPLACEMENTS

5.1. Abstract

Johne's disease (JD), or paratuberculosis is an infectious disorder of the intestines that can affect domestic and wild ruminants and that is caused by an infection with Mycobacterium avium subspecies paratuberculosis (MAP). While the economic losses due to JD in dairy herds and the benefits and costs of various potential control practices have been estimated before, little is known about the economic value of purchasing MAP-negative dairy replacements in major dairy-producing regions. This study used Markov Chain Monte Carlo (MCMC) simulation techniques to compare two sets of MAP-negative and MAP-positive herds across a comprehensive selection of regions: herds purchasing MAP-negative replacement animals and herds purchasing replacement animals with unknown MAP infection status. The economic benefits per MAP-negative replacement purchased were then estimated over a 10-year horizon, and the additional value of MAP-negative replacements when compared to unknown status replacements were calculated as a percentage premium of the average aggregated dairy replacement price in each region. An average benefit of CA$96 per MAP-negative replacement purchase was estimated in major dairy-producing regions, equivalent to a premium of 13%, with higher premiums in regions characterized by below-average replacement prices and on-average farm-gate prices. It was also estimated that the greatest benefits from MAP-negative replacement purchases are associated with MAP-negative herds that successfully remain uninfected.

5.2. Introduction

Johne's disease (JD), or paratuberculosis, is an infectious disorder of the intestines that can affect domestic and wild ruminants including cattle (Fecteau and Whitlock, 2010). The disease is caused by an infection with *Mycobacterium avium* subspecies *paratuberculosis* (MAP), a resistant bacterial organism that can persist for extended periods outside of its host environment (Manning and Collins, 2001; Whittington et al., 2004; Donaghy et al., 2009). As its clinical symptoms progress, JD in dairy cattle leads to diarrhea, lethargy, and reduced milk production, and eventually hypoproteinemia, severe emaciation, and potentially death. These animal health burdens are passed on to dairy producers in the form of substantial economic losses (Garcia and Shalloo, 2015), with reduced milk production (Lombard et al., 2005; McAloon et al., 2016), reduced 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) as primary sources. Annual economic losses per cow among MAP-infected dairy herds in the United States (US) 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 herds in Canada have been estimated at CA$49 per cow (Tiwari et al., 2008) and between US$35 and US$57 per cow (Chapter 2), whereas annual losses in major dairy-producing regions have been estimated at US$33 per cow annually, or approximately 1% of gross milk revenue (Chapter 2). The herd-level prevalence of MAP infection likely exceeds 50% in most countries with significant dairy industries (Barkema et al., 2018), and there is a need to comprehensively estimate the value of JD control to dairy producers. While estimates exist for the effectiveness and economic benefits of various potential control practices (Groenendaal et al., 2002; Groenendaal et al., 2003; Kudahl et al., 2007; Groenendaal et al., 2015; Kirkeby et al., 2016; Smith et al., 2017), little is known about the economic benefits associated with purchasing MAP-negative replacements. Accordingly, this chapter used the Markovian framework established in Chapter 2 to estimate economic premiums associated with MAP-negative replacement purchases across a comprehensive selection of dairy-producing regions over a 10-year horizon.

5.3. Materials and methods

Two sets of herds were analyzed in each region: 1) MAP-negative herds purchasing replacements with unknown MAP infection status were compared to MAP-negative herds purchasing MAP-negative replacements and 2) MAP-positive herds purchasing replacements with unknown MAP infection status were compared to MAP-positive herds purchasing MAP-negative replacements. Based on an assumed MAP infection herd-level prevalence of 50% and a within-herd prevalence of MAP infection of 10% within infected herds, the economic benefits associated with MAP-negative replacement purchases were estimated. The expected value of those benefits across both MAP-negative and MAP-positive herds was then calculated to estimate the premium as a percentage of aggregated replacement prices associated with MAP-negative replacements.

5.3.1. Within-herd prevalence and sources of Losses

The spread of MAP-infection within dairy herds was modelled over a 10-year horizon using a MAP-positive herd model with a separately modelled replacement pool within the Markovian framework established in Chapter 2. Within this framework, animals can remain MAP-negative and continue aging, become infected and continue aging, or be culled. Once an animal becomes MAP-positive, it can either be culled or its stage of infection can progress, regress, or remain the same, with each stage associated with a different risk of being culled. Each stage also has some non-shedding, lightly-shedding, moderately-shedding, and heavily-shedding states within it, and the MAP burden on the herd, or the infection pressure on animals in the herd, is determined by the number and degree of shedding animals in the herd in each period. All potential outcomes are functions of that infection pressure. For MAP-negative animals, the probability of being culled remains the steady-state MAP-negative value according to their age category, as determined by the initial age structure and model initialization over a 50-year 10,000 iteration simulation. The baseline herd came to a steady-state with the following characteristics: 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 one and two years of age being purchased each year. These numbers are similar to those observed in Canadian 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 one and two years of age per 100 cows per year (Van Biert, 2019).

For MAP-positive animals, the probability of being culled depends on the stage of their infection, increasing with severity. For each economic region, two sets of models are compared. For the set with replacements of unknown MAP infection status, purchased replacements entered the herd from the replacement pool with a MAP-infection prevalence based on the mean within-herd prevalence and the mean herd-level prevalence in that region. It was assumed that all regions had an initial within-herd MAP infection prevalence of 10% and a herd-level prevalence of 50%, resulting in a regional cow-level prevalence of 5% among replacement purchases. For the set with MAP-negative replacements, the regional cow-level prevalence is assumed to be 0%. 10,000 iteration Monte Carlo simulations are then used to estimate the changes in herd structure, MAP infection prevalence, and the three sources of losses associated with JD in dairy cattle in the model: premature culls; MAP-positive animals salvaged; and MAP-positive cows producing reduced amounts of milk. The benefits in terms of reduced losses were then compared across the replacement with unknown MAP infection status and MAP-negative replacement sets to estimate the economic benefits associated with MAP-negative replacements. The complete assortment of

MAP-specific variables and region-specific economic input variables used in this chapter, including 2019 milk production across regions, are presented in the Appendix (**Tables A-1** to **A-3**). The comparisons across the various herds are summarized in **Table 5-1** of the Results.

5.3.2. Economic premiums

The mean benefits associated with MAP-negative replacement purchases compared to replacement purchases with unknown MAP infection status over the 10-year horizon are then divided by the total number of replacements purchased across all replacement age categories (12 to 15 months, 15 to 18 months, 18 to 21 months, and 21 months to 24 months) to obtain an estimate of the economic benefits per replacement purchased. The estimated economic benefits per replacement purchased were then divided by the average aggregated replacement price across all replacement age categories to obtain an estimate of the percent economic premium per MAP-negative replacement purchased. This was repeated in both MAP-negative and MAP-positive herds across a comprehensive selection of major dairy-producing regions using region-specific economic variables (**Tables A-2** and **A-3**), assuming a mean within-herd MAP infection prevalence of 10% and mean herd-level MAP prevalence of 50%. Due to the unique market conditions that arise due to supply management in Canada (fixed annual output and above-average farm-gate prices for milk), this comparison was repeated a second time for Canada with production losses instead measured as an increase in the variable costs associated with milk production (labour, veterinary fees, bedding, feed, etc.).

5.4. Results

5.4.1. Impact of MAP-negative replacements on herd structure

For simplicity, generic MAP-negative and MAP-positive herds with no region-specific economic variables were used to describe the behaviour of the model with the assumptions of an initial within-herd MAP infection prevalence of 10%, a herd-level MAP infection prevalence of 50%, and a resulting regional cow-level MAP infection prevalence of 5% among animals in the replacement pool (**Table 5-1**). In MAP-negative herds with MAP-negative replacements, there were no changes in the sources of losses associated with MAP infection in dairy cattle as within-herd prevalence remained at 0%. However, with purchased replacements of unknown MAP infection status entering the herd from the regional replacement pool, the mean within-herd prevalence increased from 0% in year 0 to 5.32% (approximately the regional cow-level prevalence) in year 10. Premature culls due to MAP as a percentage of total culls increased from 0% to 0.6%, MAP-positive culls as a percentage of total culls increased from 0% to 3.35%, and forgone production increased from 0% to 0.31% over the 10-year horizon. In MAP-positive herds with MAP-negative replacements, within-herd prevalence increased from its initial value of 9.99% in year 0 to 16.53% in year 10. Premature culls as a percentage of total culls increased from 1.56% to 3.61%, MAP-positive culls as a percentage of total culls increased from 6.90% to 11.11%, and forgone production increased from 0.60% to 0.98%. With replacements with unknown MAP infection status instead, within-herd prevalence approximately doubled to 19.57% (a 30% increase in within-herd prevalence relative to its initial value when compared to the MAP-negative replacement scenario). Similar increases relative to the MAP-negative replacement scenarios were observed in premature culls, MAP-positive culls, and forgone production.

5.4.2. Economic premiums

The average aggregated replacement prices, benefits per replacement associated with MAP-negative purchased replacements, and premiums as a percentage of aggregated replacement prices across major dairy-producing regions are presented in **Table 5-2**. In MAP-negative herds, 10-year average benefits per MAP-negative replacement purchased ranged from CA$27 in Brazil to CA$262 in Japan, with a revenue-weighted average of CA$100. These benefits, when measured as a percentage of the region-specific aggregated replacement price for replacements of all ages, resulted in economic premiums associated with MAP-negative replacement purchases ranging from 7% in Ireland to 26% in Poland, with a revenue-weighted average of 14%. In MAP-positive herds, aggregate replacement prices were higher than in MAP-negative herds as relatively costly mature cows remained in the herd for shorter periods. Benefits per MAP-negative replacement and economic premiums associated with those replacements were also lower; benefits ranged from CA$24 in Brazil to CA$237 in Japan with a revenue-weighted average of CA$92, and premiums ranged from 7% in Ireland to 20% in Poland, with a revenue-weighted average of 12%. The expected value of aggregated replacement prices, economic benefits, and economic premiums across major dairy-producing regions based on 50% of herds being MAP-negative and 50% of herds being MAP-positive are presented in **Table 5-3**. Benefits ranged from CA$25 in Brazil to CA$249 in Japan with a revenue-weighted average of CA$96, while premiums ranged from 7% in Ireland to 23% in Poland with a revenue-weighted average of 13%.

Canadian estimates for MAP-negative herds under the both the assumptions of variable annual production used in the estimates for other major dairy-producing regions and fixed annual production reflective of supply management are presented in **Table 5-4**. For MAP-negative herds and in the variable annual production scenario, benefits and premiums are generally greater than those estimated for other regions. 10-year average annual benefits per MAP-negative replacement purchased ranged from CA$168 in New Brunswick to CA$248 in Newfoundland and Labrador, with a Canadian average of CA$184. Canadian average values were based on Canadian average input variable values weighted according to provincial dairy cattle head counts. Economic premiums as a percentage of replacement price ranged from 13% in Alberta to 19% in Nova Scotia and in Prince Edward Island, with a Canadian average of 15%. When instead estimated with the constraint of fixed annual production, benefits were still generally above those estimated in other regions, but premiums were now below-average. Benefits per replacement ranged from CA$84 in Prince Edward Island to CA$159 in Newfoundland and Labrador, with a Canadian average of CA$102. Economic premiums as a percentage of aggregated replacement prices ranged from 8% in Alberta to 10% in British Columbia, Manitoba, New Brunswick, Nova Scotia, and Newfoundland and Labrador, with a Canadian average of 9%. Canadian estimates for MAP-positive herds under the both the assumptions of variable annual production and fixed annual production are presented in **Table 5-5**. 10-year average annual benefits per MAP-negative replacement purchased ranged from CA$149 in New Brunswick to CA$223 in Newfoundland and Labrador, with a Canadian average of CA$166. Economic premiums as a percentage of replacement price ranged from 11% in Alberta to 16% in Nova Scotia and in Prince Edward Island, with a Canadian average of 13%. When instead estimated with the constraint of fixed annual production, benefits were still generally above those estimated in other regions, but premiums were below those of other regions. Benefits per replacement ranged from CA$81 in Prince Edward Island to CA$152 in Newfoundland and Labrador, with a Canadian average of CA$100. Economic premiums as a percentage of aggregated replacement prices ranged from 7% in Alberta to 9% in Manitoba, with a Canadian average of 8%.

The expected value of aggregated replacement prices, economic benefits, and economic premiums across Canadian provinces based on 50% of herds being MAP-negative and 50% of herds being MAP-positive are presented in **Table 5-6**. In the variable production scenario, benefits ranged from CA$158 in New Brunswick to CA$236 in Newfoundland and Labrador with a Canadian average of CA$175, while premiums ranged from 12% in Alberta to 18% in Prince Edward Island with a Canadian average of 14%. In the fixed production scenario, benefits ranged from CA$83 in Prince Edward Island to CA$156 in Newfoundland and Labrador with a Canadian average of CA$101, while premiums ranged from 8% in Alberta, Saskatchewan, and Ontario to 10% in Manitoba and Nova Scotia with a Canadian average of 8%.

5.4.3. Sensitivity analyses

The sensitivity of the estimated economic premiums in average Canadian MAP-negative and MAP-positive dairy herds to a variety of input variables over 10,000 iterations is presented in **Figure 5-1**. Premiums associated with MAP-negative replacement purchases were greater in MAP-negative herds compared to their regional MAP-positive counterparts, despite within-herd prevalence being positively related to premiums and the most impactful variable in MAP-positive herds. In both types of herds, herd-level prevalence was substantially impactful and positively related to the estimated premium. Farm-gate price and production per cow were also identified as impactful variables in both cases, as was the dairy replacement price, particularly for mature cows. However, the replacement price variables were the only variables that were inversely related to the estimated economic premium. The impact of the price of bred (pregnant) heifers was substantial in MAP-negative herds, but like the price of open heifers, not substantial enough to reveal the direction of its relationships to the estimated premiums in MAP-positive herds. However, logically all replacement prices must be negatively related to the estimated economic premium in both sets of herds because the premium is inversely related to the aggregated replacement price. Detailed sensitivity analyses for the Markov framework itself are available in Chapter 2.

5.5. Discussion

Sensitivity analyses revealed the importance of within-herd and herd-level MAP prevalence when estimating economic premiums associated with MAP-negative replacements relative to replacements with unknown MAP infection status entering the herd at the regional cow-level prevalence. The benefits to MAP-negative herds were greater than the benefits to MAP-positive herds despite the positive relationship between within-herd prevalence and the economic premiums associated with MAP-negative replacements. This surprising and somewhat counterintuitive finding suggests that the greatest benefits from JD control are associated with the prevention of MAP infection at the herd level; although economic losses due to MAP infection increase with within-herd prevalence, those losses are primarily driven by the initial periods as the herd transitions from MAP-negative to MAP-positive. With assumed values of an initial within-herd MAP infection prevalence of 10% and a herd-level prevalence of 50% for all regions, region-specific economic variables such as the farm-gate price of milk, annual production per cow, and the aggregated price of dairy replacements were responsible for the majority of the variation in the expected value of economic premiums across regions (**Table 5-3**). When excluding Canada due to the unique market conditions that arise due to its supply management system, the greatest economic premiums were observed in regions characterized by below-average aggregated replacement prices and on-average farm-gate prices, such as Czechia, Spain, Poland, Russia, and Turkey. In these regions, the expected value of aggregated replacement prices ranged from CA$186 to CA$551 per animal purchased compared to the revenue-weighted average price of CA$784, while farm-gate prices ranged from CA$37 to CA$40 compared to the revenue-weighted average price of CA$40. Conversely, the smallest economic premiums were observed in regions characterized by on- or above-average replacement prices and below-average production per cow such as Australia, Ireland, and New Zealand. In these regions, replacement prices ranged from CA$738 to CA$1521 per animal, while annual production per cow ranged from 4437kg to 6017kg, compared to the weighted average of 7302kg.

While the general method used to estimate the premiums associated with MAP-negative replacement purchases is appropriate for most major dairy-producing regions, the Canadian dairy sector requires particular attention, as discussed in Chapters 2 and 3. Farm-gate milk prices in Canada are determined through a complex process requiring negotiation across regional milk pools and provincial milk boards, incorporating milk pool cost and revenue data, cost of production data from the Canadian Dairy Commission (CDC), production quotas, and harmonized pricing. These planned and controlled domestic production levels, cost-of-production-based pricing of fluid milk, and import controls are designed to insulate Canadian producers from competitive forces both domestic and foreign in an overarching supply management system. If the Canadian dairy sector is modelled as a strict annually-fixed production system, there are two consequences for this study: 1) production losses can no longer be quantified as the value of forgone milk sales since producers cannot be financially compensated for production in excess of their production quota; and 2) Canadian dairy producers receive an above-average farm-gate milk price, which is the highest among countries modelled (aside from Japan which subsidizes dairy production at particularly high rates) and much higher than the price received by dairy producer in the US, Canada’s most comparable counterpart. As detailed in Chapters 2 and 3, the higher farm-gate price in Canada results in a greater valuation of milk production losses associated with MAP-infection and therefore greater economic benefits associated with the purchase of MAP-negative replacements in Canada. While the differences in estimated benefits across the two neighbouring dairy sectors are partially attributable to differences in technical and allocative efficiencies, which are not addressed within this framework, the effects of supply management in Canadian dairy are addressed, at least in as much as Canadian market prices capture benefits from being part of a supply managed agricultural industry. To reflect the constraint of fixed annual production levels for Canadian producers, milk production losses were also quantified as the cost of having additional, less productive MAP-positive cows to maintain a fixed level of production over the 10-year horizon.

Under the fixed production assumption, the expected value of estimated benefits per MAP-negative replacement purchased in average Canadian dairy herds (**Table 5-6**) decreased from the variable production estimate of CA$175 per MAP-negative replacement purchased (a premium of 14%), to CA$101 (a premium of 8%). Although overall annual production and farm-gate prices in Canada are predetermined and producers are only compensated for the milk produced within their production quota, there is still competition among producers for additional quota (as well as other inputs including land and labour). Overall milk production generally increases year-on-year (CDIC, 2019a) and producers trade quota through a quota exchange market; more profitable producers purchase quota from less profitable ones to increase their production capacities. Partly as a result of this competition, the number of Canadian dairy herds has steadily decreased while the size of herds has increased (CDIC, 2019b); therefore, producers operate somewhere in between a fixed production and a variable production environment, and the true benefits associated with MAP-negative replacement purchases in Canadian dairy herds likely lie somewhere in between the two estimates, or between CA$101 and CA$175 per replacement purchased.

Capturing these economic premiums through increased domestic and international trade, whether in Canada or in other major dairy-producing regions, requires some understanding of the trade patterns in major dairy-producing regions. For Canada from an international trade perspective, it was determined that the largest and most consistent international export market for dairy cattle was the US. However, there have been several important events that impacted Canada-US dairy cattle trade flows, changing the market's structure and complicating any potential modelling efforts: the bovine spongiform encephalopathy (BSE) crisis and subsequent trade bans from 2003 to 2006, and to a lesser extent, the 2008 global financial crisis. Although over 95% of all BSE cases during the late 1990s and early 2000s occurred in the United Kingdom (Raude et al., 2004; Boyd et al., 2009), the crisis soon impacted Canadian cattle sectors. On May 20, 2003, BSE was confirmed in a cow in Alberta, Canada, and soon after, the US and most other major Canadian export markets announced import bans on live ruminants and many products made from ruminants, including beef (Le Roy et al., 2007). Prior to this BSE confirmation, Canada's cattle exports accounted for 25% to 40% of its total domestic slaughter, exporting over 40% of its beef production primarily to the US (Vandeveer, 2007). Although the US reopened to Canadian beef soon after the initial import bans (September 2003), Canadian cattle remained banned for over two years until July 2005. This dependence on US demand for cattle exports was not exclusive to the beef sector, and although the economic impact of the

Canadian BSE outbreak is typically discussed in terms of its impact on the beef producers, it had significant impact on Canadian dairy producers as well.

At the onset of the BSE crisis, Canadian dairy cattle exports were valued at an all-time high of CA$137 million exported almost entirely to the US (CDIC, 2020). Their value dropped to a few thousand CA$ in 2004 and reached zero in 2005. Canadian dairy cattle exports never fully recovered even after exports to the US resumed, despite a brief resurgence over the period of 2006 to 2008, at which point the global financial crisis severely impacted economies around the world, including the US. Interestingly, other dairy genetic export markets such as semen and embryos, which were largely left unscathed by the BSE outbreak, were also relatively unaffected by 2008's economic recession. Although the reason for the immunity of these other genetic export markets to the BSE outbreak is straightforward—these products were not considered vectors for the disease and therefore not subject to import bans—their immunity to the global financial crisis just a few years later is more curious. This may be attributable, at least in part, to the relatively more diversified set of import destinations observed in the Canadian semen and embryo export markets. In 2008, Canada was exporting over 50% of its dairy cattle to the US, with the remainder exported to nine other destinations, with only five of those destinations having export values exceeding CA$1 million: Croatia, Cuba, Kazakhstan, Russia, and Serbia (CDIC, 2020). Meanwhile, there were 75 export destinations for Canadian dairy semen and 42 for Canadian dairy embryos, with the US importing only 34% and 4% of Canadian exports of semen and embryos that year, respectively (CDIC, 2020). While Canadian dairy cattle exports nearly fell back to their 2006 levels from their 2008 high by 2009, embryo exports remained relatively stable, and semen exports continued to increase with total export values ranging from five to 10 times the value of annual dairy cattle exports since 2010. The risk mitigation benefits of geographical diversification have long been accepted among economists (Brainard and Cooper, 1968; Lessard, 1976; Rugman, 1976; Elton and Gruber, 1977; Smoluk et al., 2003; Deng and Elyasiani, 2008), and while the 2008 global financial crisis affected many economies, it is generally accepted that its impact on the US was more severe than its impact on Canada (Lynch, 2010; Haltom, 2013; Bank of Canada, 2014; Hossain and Nguyen, 2016; Rashid, 2020). This gap in impact across the two economies contributed to a fall in the value of US currency relative to Canadian currency in the years immediately following the onset of the financial crisis from 1.14 CA$/US$ in 2009 to 0.99 CA$/US$ in 2011 (FAOSTAT, 2020). This deterioration in the terms of trade faced by US importers of Canadian goods decreased the attractiveness of Canadian exports including dairy cattle. While the diversity of trading partners observed in other dairy genetics exports markets, particularly semen, likely helped to insulate Canadian exporters of those goods from this change in the terms of trade with the US, changing attitudes towards livestock trade likely also played a role.

Although the OIE has set animal health standards, most livestock trade is based on bilateral agreements between two countries (Abubakar et al., 2020). Intuitively, the additional complexity that these trade agreements must involve when drafted around live animal exports as opposed to frozen semen or embryo exports are obvious. There are growing concerns about the biosecurity implications associated with livestock movement and trade (Perry et al., 2013; Brooks-Pollock et al., 2015; Enticott, 2016; Hidano et al., 2016; Léger et al., 2017), with a focus on traceability and transparency among animals and along the food chain (Verbeke, 2001; Hernández-Jover et al., 2008; Clemens and Babcock, 2015). The costs of meeting these increasingly demanding trade requirements, whether incurred by the exporter or the importer, add to the already high handling, veterinary, and basic transportation costs associated with long-distance livestock trade. As is the case with most physical trade, transportation costs are positively related to the geographical distance between trading partners (Egger and Pfaffermayr, 2004; Feyrer, 2009; Kepaptsoglou et al., 2010; Shepherd, 2013); effectively, the geographic proximity of the US to Canada, and conversely the geographic distance between other export destinations and Canada, result in a natural reliance on US demand for Canadian exporters, particularly in the case of dairy cattle. Therefore, from an international trade perspective, it is reasonable to assume that the majority of international trade benefits derived from effective JD control in Canada in terms of Canadian dairy herds becoming a source of MAP-negative dairy replacements would result from increased export quantities at a premium price to the US. However, from a domestic trade perspective, the benefits for Canadian dairy producers that adopt JD control and subsequently become verifiable sources of MAP-negative dairy replacements would likely also be significant. At the same time, the domestic and international benefits associated with JD control and MAP-negative replacements could also be captured by dairy producers in other countries, likely through their geographically proximate export markets, and within their domestic markets through herd-level dairy replacement trade.

At the herd-level, for a single producer to become a reliable source of MAP-negative replacements and capture some of these potential trade benefits, there are several requirements: 1) more effective JD control practices must be developed; 2) more sensitive diagnostic tools must be developed, both for their complementary role within an effective control programme and also to provide confidence among prospective buyers; 3) the economic value of MAP-negative replacements must recognized; and 4) prospective buyers must be willing to pay a premium for a verified MAP-negative replacement. While research into new control practices and diagnostic tools is ongoing and the necessary components of an effective JD control programme are being developed, the latter two conditions are largely dependent on the information available to dairy producers. Studies such as this one, where the potential premiums associated with MAP-negative replacement purchases are estimated across major dairy-producing regions play an important role, but there is also a need to further incentivize producers to invest in JD control in an effort to guarantee access to the potential economic benefits associated with being recognized as a MAP-negative dairy herd.

One possibility is the creation of a futures market for MAP-negative replacement animals, not unlike the Intercontinental Exchange (ICE) used for canola, or the Minneapolis Grain Exchange (MGEX) used for wheat. As described by Carlton (1984), when an individual purchases a futures contract through an organized exchange like ICE or MGEX, they agree to pay the current futures price to receive a good at some predetermined future date. That individual satisfies their contractual obligation either by physically receiving the good at that later date and paying for it, or by selling the contract to another individual who in turn faces the same two options. These markets typically have a clearing organization attached to them, which acts as buyer to sellers and seller to buyers, providing confidence to market participants who can deal exclusively with a known and trusted entity. While futures markets provide flexibility for market participants, their main benefit, particularly for agricultural goods, come from their “risk-transfer” and “price-discovery” functions (Silber, 1985); they provide an efficient mechanism for hedging and a trusted forum for establishing and disseminating price information. In the case of a futures market for MAP-negative dairy replacements, registered and verified MAP-negative herds would sell replacements at an agreed upon price for some future delivery date to a clearing organization, which would then sell the replacements to dairy herds looking to either decrease the risk of MAP contagion within their herds, decrease MAP prevalence within their herds, or to expand their operations while remaining verified MAP-negative sellers within the futures market.

There are, however, incentives for dairy producers to invest in JD control aside from directly estimable economic benefits and potential access to domestic and international trade premiums. From a herd-health perspective, although JD control remains a minor priority for dairy producers relative to more easily addressable diseases and conditions such as mastitis, research into interactions between MAP and other pathogens affecting dairy cows is still developing. Higher incidences of and higher culling rates due to mastitis have been observed in MAP-positive herds (Diéguez et al., 2008; Arrazuría et al., 2014), and a higher incidence of clinical mastitis has been observed in MAP-positive cows (Rossi et al., 2017). It has also been suggested that JD control will likely reduce the incidence of similarly transmitted infections in calves such as rotavirus and coronavirus, *Escherichia coli*, *Cryptosporidium parvum*, *Cryptosporidium bovis*, and *Salmonella* spp. (Barkema et al., 2018). From a public health perspective, the zoonotic potential of MAP is still being investigated. An association between MAP and Crohn's disease in humans has been suggested (El-Zaatari et al., 2001; Harris and Lammerding, 2001; Hermon-Taylor, 2001; Chacon et al., 2004; Naser et al., 2004; Abubakar et al., 2007; Feller et al., 2007; Waddell et al., 2015). Furthermore, 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). Although MAP's zoonotic potential remains unclear, national control programmes have been established in several countries including Australia, Ireland, Japan, the Netherlands, and the US (Whittington et al., 2019) and JD is listed by the OIE as a priority disease for international trade. With the herd-level MAP infection prevalence in Canada exceeding 42% (Corbett et al., 2018), the severe economic consequences of a single BSE-positive cow being identified in Canada in 2003 should serve as a warning to dairy producers; markets are fragile. A proactive approach to JD control will not only benefit producers directly through reduced economic losses and potentially through access to trade premiums but may also prevent catastrophic losses in the event of a change in the perception of the risks associated with MAP.

5.6. Conclusions

Significant economic benefits were associated with the purchase of MAP-negative dairy replacements when compared to the purchase of replacements with unknown MAP infection status. Greater premiums were observed in MAP-negative herds relative to MAP-positive herds despite within-herd prevalence being positively related to the estimated premium. This suggests that although the benefits associated with the purchase of MAP-negative replacements increase with within-herd prevalence, the greatest benefits are captured by herds that avoid infection altogether. Assuming a regional cow-level MAP infection prevalence of 5% among replacement animals, a revenue-weighted average benefit of CA$96 per MAP-negative replacement was estimated, equivalent to a premium of 13% of average aggregated replacement prices across both infected and uninfected dairy herds in major dairy-producing regions. For Canadian dairy herds, it was estimated that the economic benefits range from CA$101 to CA$175 per MAP-negative replacement, or 8% to 14% of average aggregate replacement prices. Although the potential domestic and international trade benefits of JD control were not estimated, this research suggests that MAP-negative replacements have significant additional value, and that given the dissemination of accurate pricing information and an organized market, this value could be captured, at least in part, by herds that successfully control JD.

5.7. References

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Table 5-1. Changes in key indicators of economic losses (within-herd prevalence, premature culls, *Mycobacterium avium* subspecies *paratuberculosis* (MAP) -positive culls, and forgone production) due to MAP infection among both MAP-negative and MAP-positive herds when purchasing MAP-negative replacements and when purchasing replacements with unknown MAP infection status. A herd-level MAP infection prevalence of 50% in the region, a within-herd MAP infection prevalence on 10% within infected herds, and a resulting 5% cow-level MAP-infection prevalence among replacement animals were assumed. Based on 10,000 iteration Monte Carlo simulations.

	MAP-negative herds			MAP-positive herds		
	Baseline	MAP-negative replacements	Replacements with unknown MAP infection status	Baseline	MAP-negative replacements	Replacements with unknown MAP infection status
Indicator	Year 0	Year 10	Year 10 (90% CI)	Year 0 (90% CI)	Year 10 (90% CI)	Year 10 (90% CI)
Within-herd MAP prevalence (%)	-	-	5.32 (4.07 - 6.67)	9.99 (6.66 - 13.34)	16.53 (13.31 - 19.22)	19.57 (15.71 - 22.97)
Premature culls (% of total)	-	-	0.60 (0.20 - 1.26)	1.56 (0.39 - 3.21)	3.61 (2.23 - 5.02)	4.25 (2.64 - 5.97)
MAP-positive culls (% of total)	-	-	3.35 (2.47 - 4.11)	6.90 (4.45 - 9.20)	11.11 (9.05 - 12.84)	12.43 (10.10 - 14.42)
Forgone production (% of potential)	-	-	0.31 (0.23 - 0.41)	0.60 (0.37 - 0.84)	0.98 (0.74 - 1.21)	1.15 (0.87 - 1.45)

Table 5-2. 10-year aggregated replacement prices (average across mature cows, bred heifers, and open heifers in CA$), annual benefits per *Mycobacterium avium* subspecies *paratuberculosis* (MAP) -negative replacement, and economic premiums associated with MAP-negative replacements across major dairy-producing regions in both MAP-negative and MAP-positive herds. Initial within-herd MAP prevalence of 10% and a mean herd-level prevalence of 50% (initial mean prevalence of 5% among purchased replacements) were assumed. Regions ordered according to 2018 total milk production.

	MAP-negative herds			MAP-positive herds		
Region	Aggregated replacement price [1] (CA$/head)	Benefits per replacement (CA$/head/ year)	Economic premium (% replacement price)	Aggregated replacement price [1] (CA$/head)	Benefits per replacement (CA$/head/ year)	Economic premium (% replacement price)
European Union (28)	767.03	100.00	13.03	814.33	91.77	11.16
Germany	921.45	113.79	12.34	978.27	105.18	10.65
France	790.47	97.92	12.38	839.21	90.47	10.68
Great Britain	801.28	108.60	13.54	850.69	99.16	11.55
Poland	277.75	70.88	25.50	294.87	60.91	20.47
Netherlands	1,076.26	133.90	12.43	1,142.63	123.64	10.72
Italy	725.95	105.95	14.58	770.71	95.88	12.33
Ireland	1,475.31	105.50	7.15	1,566.28	107.18	6.78
Spain	534.18	102.01	19.08	567.12	89.75	15.68
Denmark	1,242.50	147.49	11.86	1,319.11	137.08	10.29
Belgium	861.48	104.86	12.16	914.60	97.12	10.52
Austria	952.97	102.25	10.72	1,011.73	96.46	9.44
Czechia	433.48	102.86	23.71	460.20	88.86	19.13
Sweden	1,065.36	126.98	11.91	1,131.05	117.95	10.33
Finland	1,071.07	138.94	12.96	1,137.12	127.59	11.12
United States	1,075.47	131.91	12.26	1,141.79	122.05	10.59
California	1,033.76	130.79	12.64	1,097.50	120.50	10.88
Wisconsin	833.49	127.17	15.25	884.89	114.49	12.82
Idaho	624.12	123.98	19.85	662.60	108.69	16.25
New York	1,117.01	135.93	12.16	1,185.89	125.89	10.52
Texas	920.34	129.71	14.08	977.09	117.87	11.95
Michigan	757.02	134.42	17.74	803.70	119.09	14.68
Pennsylvania	887.87	114.55	12.89	942.62	105.26	11.06
Minnesota	938.63	121.35	12.92	996.51	111.48	11.08
New Mexico	712.80	127.83	17.92	756.75	113.15	14.81
Washington	1,016.18	134.43	13.22	1,078.84	123.13	11.31
Brazil	177.70	26.76	15.05	188.66	24.13	12.67
China	251.37	43.56	17.31	266.87	38.68	14.36
Russia	197.22	48.52	24.58	209.38	41.80	19.78
New Zealand	715.55	63.91	8.93	759.68	62.16	8.10
Turkey	180.01	38.44	21.34	191.11	33.49	17.36
Australia	931.64	82.76	8.88	989.09	80.56	8.07
Japan	1,747.89	262.31	15.00	1,855.67	236.61	12.63

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[1] Based on the average total number of replacements purchased over the 10-year horizon and regional aggregated replacement prices across all age groups Chapter 2.

Table 5-3. Expected values of 10-year aggregated replacement prices (average across mature cows, bred heifers, and open heifers in CA$), annual benefits per *Mycobacterium avium* subspecies *paratuberculosis* (MAP) -negative replacement, and economic premiums associated with MAP-negative replacements across major dairy-producing regions. An initial within-herd MAP prevalence of 10% and a mean herd-level prevalence of 50% (initial mean prevalence of 5% among purchased replacements) were assumed. Regions ordered according to 2018 total milk production.

Region	Aggregated replacement price (CA$/head) [1]	Benefits per MAP-negative replacement (CA$/head/year)	Economic premium (percentage of replacement price)
European Union (28)	790.68	95.88	12.10
Germany	949.86	109.48	11.50
France	814.84	94.20	11.53
Great Britain	825.98	103.88	12.55
Poland	286.31	65.90	22.99
Netherlands	1,109.44	128.77	11.58
Italy	748.33	100.92	13.46
Ireland	1,520.79	106.34	6.96
Spain	550.65	95.88	17.38
Denmark	1,280.81	142.28	11.08
Belgium	888.04	100.99	11.34
Austria	982.35	99.35	10.08
Czechia	446.84	95.86	21.42
Sweden	1,098.21	122.46	11.12
Finland	1,104.10	133.27	12.04
United States	1,108.63	126.98	11.42
California	1,065.63	125.65	11.76
Wisconsin	859.19	120.83	14.03
Idaho	643.36	116.34	18.05
New York	1,151.45	130.91	11.34
Texas	948.72	123.79	13.02
Michigan	780.36	126.75	16.21
Pennsylvania	915.24	109.91	11.98
Minnesota	967.57	116.41	12.00
New Mexico	734.78	120.49	16.37
Washington	1,047.51	128.78	12.26
Brazil	183.18	25.45	13.86
China	259.12	41.12	15.84
Russia	203.30	45.16	22.18
New Zealand	737.62	63.03	8.51
Turkey	185.56	35.96	19.35
Australia	960.36	81.66	8.47
Japan	1,801.78	249.46	13.82

[1] Based on the average total number of replacements purchased over the 10-year horizon and regional aggregated replacement prices across all age groups (Chapter 2).

Table 5-4. 10-year aggregated replacement prices (average across mature cows, bred heifers, and open heifers in CA$), benefits per *Mycobacterium avium* subspecies *paratuberculosis* (MAP) -negative replacement, and economic premiums associated with MAP-negative replacements across Canadian provinces for MAP-negative herds in both variable production and fixed production scenarios. In the fixed production scenario, production losses due to MAP infection are measured as the additional variable costs per cow due to a greater number of cows being required to maintain production levels. An initial within-herd MAP prevalence of 10% and a mean herd-level prevalence of 50% (initial mean prevalence of 5% among purchased replacements) were assumed.

			Variable production		Fixed production	
Region	Variable costs ($CA/cow/year) [1]	Aggregated replacement price (CA$/head) [2]	Benefits per MAP-negative replacement (CA$/head/year)	Economic premium (percentage of replacement price)	Benefits per MAP-negative replacement (CA$/head/year)	Economic premium (percentage of replacement price)
Canada	3,211.40	1,191.64	184.13	15.44	102.25	8.57
Québec	3,152.27	1,024.39	174.43	17.02	95.63	9.33
Ontario	2,925.52	1,162.52	178.77	15.37	95.65	8.22
British Columbia	4,155.39	1,279.15	204.43	15.97	123.74	9.67
Alberta	4,028.97	1,651.69	210.95	12.76	133.38	8.07
Manitoba	3,908.59	1,070.81	185.79	17.34	112.08	10.46
Saskatchewan	3,611.75	1,372.68	199.66	14.53	116.05	8.45
Nova Scotia	3,261.32	905.10	173.41	19.15	93.90	10.37
New Brunswick	3,196.17	946.13	167.88	17.73	93.95	9.92
Prince Edward Isl.	2,780.46	905.78	174.72	19.28	84.42	9.31
Nfld. and Labrador	5,333.46	1,641.13	248.03	15.10	158.80	9.67

[1] STATCAN - Table 32-10-0136-01 Farm operating revenues and expenses, annual (STATCAN, 2019). Sum of "Total livestock expenses" and "Total variable livestock expenditures added to 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, 2019). Number of cattle: STATCAN – Table 32-10-0130-01 – Number of cattle, by class and farm type (STATCAN, 2020).

[2] Based on the average total number of replacements purchased across all age groups and regional aggregated replacement prices (Chapter 2).

Table 5-5. 10-year aggregated replacement prices (average across mature cows, bred heifers, and open heifers in CA$), benefits per *Mycobacterium avium* subspecies *paratuberculosis* (MAP) -negative replacement, and economic premiums associated with MAP-negative replacements across Canadian provinces for MAP-positive herds in both variable production and fixed production scenarios. An initial within-herd MAP prevalence of 10% and a mean herd-level prevalence of 50% (initial mean prevalence of 5% among purchased replacements) were assumed. Regions ordered according to 2018 total milk production. In the fixed production scenario, production losses due to MAP infection are measured as the additional variable costs per cow due to a greater number of cows being required to maintain production levels.

			Variable production		Fixed production	
Region	Variable costs ($CA/cow/year) [1]	Aggregated replacement price (CA$/head) [2]	Benefits per MAP-negative replacement (CA$/head/year)	Economic premium (percentage of replacement price)	Benefits per MAP-negative replacement (CA$/head/year)	Economic premium (percentage of replacement price)
Canada	3,211.40	1,265.11	165.54	12.96	100.17	7.84
Québec	3,152.27	1,087.56	155.20	14.14	92.28	8.40
Ontario	2,925.52	1,234.20	160.81	12.91	94.45	7.58
British Columbia	4,155.39	1,358.02	183.11	13.36	118.69	8.66
Alberta	4,028.97	1,753.53	194.11	10.97	132.18	7.47
Manitoba	3,908.59	1,136.84	164.99	14.38	106.14	9.25
Saskatchewan	3,611.75	1,457.33	180.76	12.29	114.01	7.75
Nova Scotia	3,261.32	960.91	152.52	15.73	89.05	9.18
New Brunswick	3,196.17	1,004.47	148.75	14.67	89.72	8.85
Prince Edward Isl.	2,780.46	961.64	153.58	15.82	81.49	8.39
Nfld. and Labrador	5,333.46	1,742.32	223.55	12.71	152.31	8.66

[1] STATCAN - Table 32-10-0136-01 Farm operating revenues and expenses, annual (STATCAN, 2019). Sum of “Total livestock expenses” and “Total variable livestock expenditures added to 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, 2019). Number of cattle: STATCAN – Table 32-10-0130-01 – Number of cattle, by class and farm type (STATCAN, 2020).

[2] Based on the average total number of replacements purchased across all age groups and regional aggregated replacement prices (Chapter 2).

Table 5-6. Expected values for 10-year aggregated replacement prices (average across mature cows, bred heifers, and open heifers in CA$), benefits per *Mycobacterium avium* subspecies *paratuberculosis* (MAP) -negative replacement, and economic premiums associated with MAP-negative replacements across Canadian provinces in both variable production and fixed production scenarios. An initial within-herd MAP prevalence of 10% and a mean herd-level prevalence of 50% (initial mean prevalence of 5% among purchased replacements) were assumed. In the fixed production scenario, production losses due to MAP infection are measured as the additional variable costs per cow due to a greater number of cows being required to maintain production levels. Regions ordered according to 2019 total milk production.

			Variable production		Fixed production	
Region	Variable costs ($CA/cow/year) [1]	Aggregated replacement price (CA$/head) [2]	Benefits per MAP-negative replacement (CA$/head/year)	Economic premium (percentage of replacement price)	Benefits per MAP-negative replacement (CA$/head/year)	Economic premium (percentage of replacement price)
Canada	3,211.40	1,228.37	174.84	14.20	101.21	8.21
Québec	3,152.27	1,055.97	164.82	15.58	93.96	8.87
Ontario	2,925.52	1,198.36	169.79	14.14	95.05	7.90
British Columbia	4,155.39	1,318.58	193.77	14.66	121.22	9.16
Alberta	4,028.97	1,702.61	202.53	11.86	132.78	7.77
Manitoba	3,908.59	1,103.82	175.39	15.86	109.11	9.85
Saskatchewan	3,611.75	1,415.01	190.21	13.41	115.03	8.10
Nova Scotia	3,261.32	933.01	162.97	17.44	91.47	9.77
New Brunswick	3,196.17	975.30	158.32	16.20	91.84	9.39
Prince Edward Isl.	2,780.46	933.71	164.15	17.55	82.96	8.85
Nfld. and Labrador	5,333.46	1,691.72	235.79	13.91	155.56	9.16

[1] STATCAN - Table 32-10-0136-01 Farm operating revenues and expenses, annual (STATCAN, 2019). Sum of "Total livestock expenses" and "Total variable livestock expenditures added to 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, 2019). Number of cattle: STATCAN – Table 32-10-0130-01 – Number of cattle, by class and farm type (STATCAN, 2020).

[2] Based on the average total number of replacements purchased across all age groups and regional aggregated replacement prices (Chapter 2).

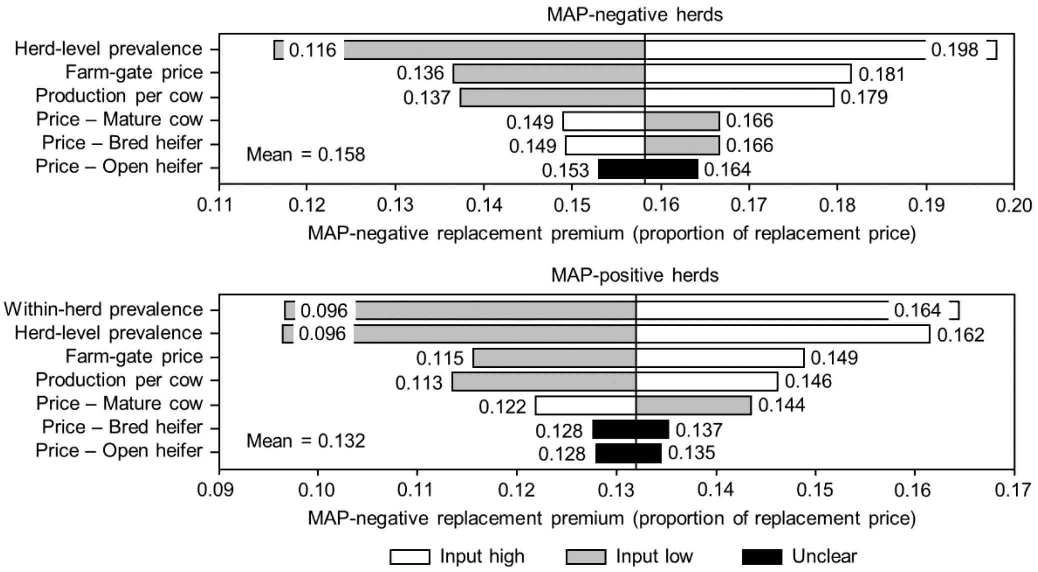

Figure 5-1. Sensitivity of estimated economic premiums associated with *Mycobacterium avium* subsp. *paratuberculosis* (MAP) -negative replacements in average Canadian dairy herds to a range of input variables (10,000 iterations) in both MAP-negative and MAP-positive herds. An initial mean value of 10% within-herd prevalence in MAP-positive herds, 50% herd-level prevalence, and a 5% MAP-infection prevalence among purchased replacements were assumed. The color of the sensitivity bars indicates the direction of the relationship between the variable and estimated losses (grey indicates the effect of variable values below their mean value, white indicates the effect of values above their mean, and back indicates that the effect is unclear).

CHAPTER 6: CONCLUSIONS

6.1. Introduction

The main objectives of this thesis were to estimate the economic impact of MAP infection in major dairy producing regions, evaluate the economic viability of potential JD control practices, estimate the value of controlling JD to Canadian dairy producers, and estimate the economic premiums associated with MAP-negative dairy replacement purchases. These objectives were met using a combination of Markov Chain Monte Carlo (MCMC) simulation methods and microeconomic and econometric approaches. The conclusions of the four manuscripts presented in this thesis will be briefly reiterated in this chapter, followed by discussions of the limitations of these studies and potential future research directions.

6.2. Economic losses due to JD in dairy herds

Although JD's economic impact in dairy herds has been estimated before, Chapter 2 is unique in two ways: firstly, it estimates economic losses due to JD across a comprehensive selection of major dairy-producing regions within one methodological framework, and secondly, 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. Under the assumptions of 10% within-herd prevalence, 50% herd-level prevalence, and a doubling of within-herd prevalence over 10 years in infected herds, it was estimated that approximately 1% of gross milk revenue is lost annually in MAP-positive dairy herds, equivalent to revenue-weighted average losses of US$33 per cow per year on infected farms. Greater losses were estimated in regions characterized by higher farm-gate prices and production per cow, with 24% of those losses are attributable to premature culling, 11% attributable to reduced salvage values, and 65% attributable to reduced production. These findings agree with the hypothesis that there are significant economic losses due to MAP infection in dairy herds, and that on a per-cow level, those losses are similar across dairy sectors sharing similar economic and production characteristics. It was estimated that each year, 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 modelled. 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-year dynamic prevalence models, but similar patterns emerged across regions and the magnitude of the losses were comparable.

6.3. Economic viability of potential JD control practices

Chapter 3 used an augmented version of the Markov Chain model developed in Chapter 2 to simulate the impact of various potential JD control practices on herd structure and to evaluate their economic merit. Vaccination was the most economically viable type of JD control practice modelled; dual-effect vaccines (reducing shedding and providing protective immunity) showed most promise. Even with modest 50% reductions in shedding and 50% protective immunity conferred by vaccination, BCRs for this type of vaccine were between 2.13 and 1.48 in Canada, with a break-even period of between 6.17 and 7.61 years. At this same level of efficacy, dual-effect vaccines were also estimated to be desirable with BCRs greater than one in almost all major-dairy producing regions, with a revenue-weighted average BCR of 1.24 and a revenue-weighted average break-even period of 7.88 years. Testing and culling was comparably effective to a dual-effect vaccine at test sensitivities greater than 70% but would remain economically unviable in almost all regions modelled, even at levels of testing sensitivity above 70%. These findings agree with the hypothesis that vaccination is an economically viable JD control practice.

6.4. The value of JD control to Canadian dairy producers

Chapter 4 used confidential cost of production data from the Canadian Dairy Commission (CDC) for the years 2014 to 2018 and a Cobb-Douglas approach to develop a production model of the Canadian dairy sector. Canadian producers were framed as expenditure minimizing consumers of feed, labour, and capital and using the results of a nationally distributed dairy production characteristics questionnaire, the value of JD control to Canadian dairy producers was estimated. Assuming an initial within-herd MAP prevalence of 10% and a 50% reduction in that prevalence over 10 years, the value of JD control to average Canadian dairy producers was estimated at CA$28 per cow per year. These findings agree with the hypothesis that there is value in controlling JD that can be appreciated by Canadian dairy producers given their production and consumption patterns.

6.5. Economic premiums associated with MAP-negative replacements

Chapter 5 once again used a variation of the Markov Chain model developed in Chapter 2, this time comparing two sets of herds: 1) MAP-negative herds purchasing MAP-negative replacements and MAP-negative herds purchasing replacements at the regional cow-level MAP prevalence; and 2) MAP-positive herds purchasing MAP-negative replacements and MAP-positive herds purchasing replacements at the regional cow-level MAP prevalence. It was estimated that there are significant economic benefits associated with the purchase of MAP-negative dairy replacements when compared to the purchase of replacements with an unknown MAP infection status, with greater premiums observed in MAP-negative herds relative to MAP-positive herds despite within-herd prevalence being positively related to the estimated premium. This suggests that the greatest benefits of MAP-negative replacement purchases are captured by herds that avoid infection altogether. Assuming a regional cow-level MAP infection prevalence of 5% among replacement animals, a revenue-weighted average benefit of CA$96 per MAP-negative replacement was estimated, equivalent to a premium of 13% of average aggregated replacement prices across both infected and uninfected dairy herds in major dairy-producing regions. For Canadian dairy herds, it was estimated that the economic benefits range from CA$101 to CA$175 per MAP-negative replacement, or 8% to 14% of average aggregate replacement prices. Although the potential domestic and international trade benefits of JD control were not estimated, these results agree with the hypothesis that MAP-negative replacement animals have greater economic value than replacements with an unknown MAP infection status, and that this value could be captured, at least in part, by herds that successfully control JD.

6.6. Limitations and future research

Sensitivity analyses throughout this thesis work revealed several key epidemiological areas where further research would benefit future economic modelling of JD in dairy herds. As described, Chapters 2, 3, and 5 assume that on average, within-herd MAP infection prevalence will double over a 10-year horizon. Although this assumption is the driver of all estimated economic losses because of its effect on within-herd prevalence, little is known about the rate of spread of MAP infection within infected herds over time. A robust study tracking within-herd prevalence across a representative group of MAP-positive dairy herds over an extended period is therefore needed. Other key areas of MAP-related epidemiological research that would benefit future economic models are how the risk of infection and disease progression differ across production systems, feed regimens, climates, and perhaps most importantly, breeds of cattle. In this thesis, it was assumed that these production characteristics were uniform across regions at the mean, with variations only implicitly captured through hypothesized deviations around the mean values used in the 10,000 iteration simulations. If more epidemiological studies of the relationship between these variables and MAP infection were available, perhaps future economic analyses could explicitly capture the impact of variations in these characteristics across regions. Lastly, the economic analyses presented here only briefly discuss interactions between MAP and other pathogens affecting dairy cattle and do not explicitly consider them in the economic impact estimates. As epidemiological research into these interactions continues to develop, the economic burdens associated with other health issues, such as mastitis, could potentially be incorporated into economic models of JD.

Despite these limitations, the models and estimates generated by this thesis work provide the opportunity for some interesting follow-up analyses. For example, the economic losses estimated in Chapter 2 and the benefit-cost ratios of various control practices estimated in Chapter 3 could be used to model other control practices and develop a comprehensive national JD control programme, even considering optimal testing (e.g., type, timing, pool size, etc.) and vaccination protocols. The simple yet robust Cobb-Douglas production model developed in Chapter 4 could be used as the production basis for modeling approaches to estimate optimal herd sizes, labour-to-land and labour-to-machinery ratios, the impacts of technological advances or climate changes that affect input prices or production levels, as well as the impact of various other dairy herd health threats and pathogens. Chapter 5 suggests that there are significant economic premiums associated with MAP-negative replacement purchases. It follows that if JD control were to become a widespread management practice, as the regional cow-level MAP infection prevalence among replacements decreased, there would be a growing incentive for producers to free-ride; a portion of these benefits could be captured by producers purchasing replacements without investing in JD control. The Markovian framework developed in this chapter could be included in economic impact assessment of this incentive. Scenarios of low to high regional MAP prevalence combined with low to high within-herd prevalence in the potentially free-riding herd could be analyzed within an experimental economics framework to estimate the willingness to engage in JD control among dairy producers. This chapter also suggested that there could be domestic and international trade benefits for producers that successfully control JD, given the dissemination of accurate pricing information and an organized market using, for example, a regulated futures market. Further analysis of the potential structure of a futures market for MAP-negative dairy replacements could lead to direct estimates of these potential trade benefits.

6.8. Conclusions

Significant economic losses due to MAP infection were estimated across major dairy producing regions, with greater losses in regions with higher levels of production per cow and farm-gate prices, such as Canada. The most economically viable control practice modelled was dual-effect vaccination, with benefits exceeding costs in almost all major dairy-producing regions, even at modest levels of protective immunity and shedding reduction. Although the most effective control practice in terms of reducing within-herd prevalence was a combination of vaccination and testing and culling, the main barrier to testing and culling is the impractical nature of the aggressive culling that would have to accompany highly sensitive tests. Without additional incentives for producers to strive for verifiably MAP-negative herds, a comprehensive control programme involving both vaccination and rigorous testing and culling would be economically unviable, despite there being substantial value in JD control to Canadian producers. One untapped source of potential additional incentives are the economic premiums associated with MAP-negative dairy replacement sales. If there were reliable pricing information and a regulated market structured around their sale, the trade benefits captured by MAP-negative producers could potentially incentivize a nationally adopted JD control programme.

APPENDIX

Table A-1. Key dairy sector characteristics for various dairy-producing regions in order of decreasing 2018 annual production.

Region	Annual production ('000 MT)[1]	Annual production (kg/cow)[2]	Dairy cattle ('000 head)[3]	Farm-gate price (US$/100kg)[4]
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	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

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[1] Canadian 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).

[2] Canadian 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).

[3] Canadian cattle values: STATCAN – Table 32-10-0130-01 – Number of cattle, by class and farm type (x 1,000) (STATCAN, 2020b). 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).

[4] Turkey: 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, 2019b). All other regions: CLAL.it – Dairy by Country (CLAL, 2019). Converted to 2018 US$ using IRS.gov – Yearly Average Currency Exchange Rates (IRS, 2020).

[5] 2017 values.

Table A-2. Region-specific aggregated input variables used in the Monte Carlo simulations of the *Mycobacterium avium* subsp. *paratuberculosis* -positive Markov herd model. All variables simulated with a normal distribution and standard deviation of 10% of the mean.

Region	gdppc[1] (US$)	wage[2] (US$/hr)	r-c[3] (US$/hd)	r-oh[3] (US$/hd)	r-bh[3] (US$/hd)	r-m[3] (US$/hd)	s-12[4] (US$/kg)	s-24[4] (US$/kg)	s-m[4] (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

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[1] Gross domestic product per capita (gdppc). US GDPPC by state (BEA, 2019) and Canadian GDP by province (STATCAN, 2019b). Converted to US$ (IRS, 2020). All other regions (World Bank, 2020).

[2] Estimated aggregate dairy wage rate (wage). US 2018 (USDA NASS, 2019). All other regions (*i* through *n*) calculated using the following formula: $wage_i = \frac{wage_{USA}*gdppc_i*farm-gate\ price_i}{farm-gate\ price_{USA}*gdppc_{USA}}$.

[3] 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: $r_i = \frac{r_{USA}*gdppc_i*farm-gate\ price_i}{farm-gate\ price_{USA}*gdppc_{USA}}$.

[4] 0-12-month animals (12), 12-24-month animals (24), and mature cow (m) salvage (s) prices. Canadian salvage prices (STATCAN, 2019a). Converted to kg at 50.8023 kg/CWT and converted to US$ (IRS, 2020). All other regions (*i* through *n*) calculated using the following formula: $s_i = \frac{s_{CAN}*gdppc_i*farm-gate\ price_i}{fram-gate\ price_{CAN}*gdppc_{CAN}}$.

Table A-3. Estimated mean-value 10-year average annual losses (US$ per cow in *Mycobacterium avium* subsp. *paratuberculosis* -positive herds and millions US$ per region) across a range of prevalence scenarios.

	Prevalence scenarios (Within-herd prevalence : Herd-level prevalence)							
	5% : 50%		15% : 50%		10% : 30%		10% : 70%	
Region	Per cow (US$)	Region (M US$)	Per cow (US$)	Region (M US$)	Per cow (US$)	Region (M US$)	Per cow (US$)	Region (M US$)
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

Table A-4. Estimated sources of losses per cow in various dairy-producing regions assuming a *Mycobacterium avium* subsp. *paratuberculosis* herd-level prevalence of 50% and a within-herd prevalence 10%.

Region	Premature culling (proportion of losses)	Reduced salvage value (proportion of losses)	Reduced production (proportion of losses)
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

Table A-5. Estimated mean-value annual losses (US$ per cow in *Mycobacterium avium* subsp. *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	Annual losses (US$ per cow)	Annual losses (% of milk revenue)	Annual losses (M 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

Table A-6. Estimated sources of losses per cow in Canadian regions assuming a *Mycobacterium avium* subsp. *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	Premature culling (proportion of losses)	Reduced salvage value (proportion of losses)	Reduced production (proportion of losses)
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

Table A-7. Estimated mean-value 10-year average annual losses (US$ per cow in *Mycobacterium avium* subsp. *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).

	Prevalence scenarios (Within-herd prevalence : Herd-level prevalence)							
	5%: 50%		15%: 50%		10%: 30%		10%: 70%	
Region	Per cow (US$)	Region (M US$)	Per cow (US$)	Region (M US$)	Per cow (US$)	Region (M US$)	Per cow (US$)	Region (M US$)
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

Table A-8. Pairwise correlation matrices for the regression results for the natural logarithm of milk output in hL (the outcome variable) on the natural logarithms of capital in Canadian dollars (CA$), total labour in hours, and feed in CA$ (the regressors), with all dollar amounts standardized to 2014 values. Data obtained from the annual Canadian Dairy Commission cost-of-production studies (2015 to 2018).

Year		*ln_output_hl* [1]	*ln_capital_$* [2]	*ln_labour_hr* [3]	*ln_feed_$* [4]
2015	*ln_output_hl*	1.000			
	ln_capital_$	0.7729	1.000		
	ln_labour_hr	0.6273	0.4915	1.000	
	ln_feed_$	0.7633	0.6658	0.5165	1.000
2016	*ln_output_hl*	1.000			
	ln_capital_$	0.7751	1.000		
	ln_labour_hr	0.7120	0.5336	1.000	
	ln_feed_$	0.8161	0.6949	0.5990	1.000
2017	*ln_output_hl*	1.000			
	ln_capital_$	0.7667	1.000		
	ln_labour_hr	0.7639	0.5526	1.000	
	ln_feed_$	0.8162	0.7175	0.6367	1.000
2018	*ln_output_hl*	1.000			
	ln_capital_$	0.7446	1.000		
	ln_labour_hr	0.7527	0.5554	1.000	
	ln_feed_$	0.7601	0.6567	0.5482	1.000

All dollar values standardized using Table 18-10-0005-01 Consumer Price Index, annual average, not seasonally adjusted (STATCAN, 2020a).

[1] Natural logarithm of milk output in hL of milk.

[2] Natural logarithm of feed expenditures in 2014 CA$.

[3] Natural logarithm of labour expenditures in hours.

[4] Natural logarithm of capital (sum of machinery and land) expenditures in 2014 CA$.

Table A-9. Estimated annual value of Johne's disease control per cow among Canadian dairy producers in 2019 CA$ across yearly production models. Estimates are adjusted to account for additional premature culling losses, reduced salvage value losses, and the time required to achieve a reduction in within-herd *Mycobacterium avium* subspecies *paratuberculosis* infection prevalence. Assumes an initial within-herd prevalence of 10% and a 50% reduction in within-herd prevalence over 10 years. Regions ordered from east to west across Canada.

Region	Adjusted WTP (2015)	Adjusted WTP (2016)	Adjusted WTP (2017)	Adjusted WTP (2018)
Prince Edward Island	26.28	25.62	24.68	23.14
Nova Scotia	24.96	24.45	23.66	22.30
New Brunswick	23.95	23.48	22.74	21.44
Québec	26.57	26.05	25.23	23.80
Ontario	28.47	27.98	27.15	25.69
Manitoba	25.91	25.43	24.65	23.28
Saskatchewan	29.10	28.50	27.58	25.99
Alberta	34.05	33.81	33.15	31.76
British Columbia	29.15	28.74	27.98	26.57
CANADA	29.13	28.63	27.79	26.29

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SUPPLEMENTARY FILE

Document S-1. UCVM Dairy Production Characteristics Questionnaire

Before we begin…

During the past 12 months, did your farm produce cow's milk?

Yes (continue)

No (end questionnaire)

Introduction

Thank you for participating in this research project. We are developing a model of Canadian dairy production that will be used to evaluate herd-level health threats to our dairy industry. By better understanding how Canadian dairy producers use their resources (e.g., equipment, labor, land, etc.) we will be better able to predict the impact of infectious diseases on production.

This project is funded by Genome Canada and involves dairy experts, microbiologists, immunologists, epidemiologists, and economists. However, without the participation of individual producers like you the model's predictive power and usefulness will be severely limited.

This **anonymous** questionnaire consists of 22 questions and should take less than 10 minutes to complete.

Thank you again for participating.

Section 1: Herd and Farm Characteristics (9 Questions)

This section will inform us about your herd and your farming operation.

Q1: How many lactating cows, dry cows, bred heifers (pregnant), and open heifers (mature but not pregnant) are in your herd?

___________ lactating cows

___________ dry cows

___________ bred heifers (pregnant)

___________ open heifers (mature but not pregnant)

Q2: On average, how many kilograms of milk are produced per cow on your farm per year?

___________ average kg per cow per year

Q3: How many cows (first lactation or older) do you sell in an average year?

___________ cows sold

Q4: How many bull calves do you sell in an average year?

___________ bull calves sold

Q5: What percentage of your total farm revenue comes from the sale of semen and embryos in an average year?

____________ percent

Q6: What percentage of your total farm revenue comes from cash crops in an average year?

___________ percent

Q7: What percentage of your total farm expenditures is paid for using revenue from off-farm work in an average year?

___________ percent

Q8: What is the total amount of labor (hours including your own) used on your farm in an average week? This includes both directly compensated labor (e.g., salaried employees) and indirectly compensated labor (e.g., family assistance).

________ total hours of labor per week

Section 2: Farming Equipment (8 Questions)

This section will inform us about your farming equipment.

Q1: How many tractors under 60 horsepower do you own?

________ tractors under 60hp

Q2: How many tractors between 60 horsepower and 149 horsepower do you own?

________ tractors between 60hp and 149hp

Q3: How many tractors over 149 horsepower do you own?

________ tractors over 149hp

Q4: How many total cars, pick-ups, cargo vans, and passenger vehicles (not farm trucks) do you own that are used in the farm business?

________ cars, pick-ups, cargo vans, and passenger vehicles

Q5: How many farm trucks do you own (not passenger vehicles)?

________ farm trucks

Q6: How many total grain combines and swathers do you own?

________ grain combines and swathers

Q7: How many total forage harvesters, balers, mower-conditioners, etc. do you own?

________ forage harvesters, balers, mower-conditioners, etc.

Q8: How many total pieces of tillage, cultivation, seeding and planting equipment do you own?

________ pieces of tillage, cultivation, seeding and planting equipment

Section 3: Demographics and Wrap-Up (5 questions)

In this section we are asking for some background information.

Q1: In what province is your dairy farm located?

BC AB SK MB ON QC NB NL NS PEI

Q2: What is your age range?

18-24 25-34 35-44 45-54 55-64 65-74 75+

Q3: How many years have you been dairy farming/working on farms?

________ years

Q4: Have you completed a post-secondary degree (i.e., college, university, trade school, etc.)?

Yes No

Q5: Would you consider adopting a competitively priced vaccine for:

Paratuberculosis (Johne’s disease or JD)

Yes No Uncertain

Bovine tuberculosis (BTB)

Yes No Uncertain

Please let us know if you have any comments or suggestions. Thank you!