Economics of Johne's Disease control decisions

in western Canadian cow-calf herds

by

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ABSTRACT

Johne's is a chronic and untreatable contagious disease of cattle leading to severe diarrhea, emaciation and eventually death. Nursing calves are susceptible to infection if exposed to shedding cattle or a contaminated environment. The prevalence of Johne's disease in western Canadian beef herds is currently low, but rising, leaving the industry with a closing opportunity to develop strategies to control this costly disease.

The expected returns from consistently applied test and control strategies were evaluated by applying a net present value (NPV) model to outputs from a dynamic disease simulation model. A total of fourteen scenarios were considered with combinations of the initial disease prevalence (0%, 1.5%, and 7%), breeding cow replacement strategy (internal heifer retention or external mature cow purchases) and testing choices (no testing, annual testing with a fictious perfectly sensitive and specific test, and annual testing with a commercially available ELISA blood test). Each scenario was simulated 1000 times for ten years. All models assumed clinical cows were culled. Livestock sales and operating input expenses were used to calculate annual revenues and expenses using a partial budget approach. Year end cash positions were discounted by 7.5% to estimate a NPV for each herd. The distributions of NPVs within scenarios were compared to identify preferred control strategies.

Regardless of the initial prevalence of Johne's disease, the most profitable strategy in infected herds was to purchase external mature replacement cows and conduct no testing. All scenarios with internal replacement heifers had substantially lower NPVs than

the comparable strategy with external mature replacements. Scenarios exploring internal heifer replacement strategies led to rising rates of Johne's infection with those with external breeding stock purchases were able to decrease the disease pressure to a low rate.

The most important outcome from this study is that cow-calf operations in western Canada can economically control Johne's disease through early, consistent culling of clinical animals provided these animals are replaced with cows that have a low rate of Johne's infection. This project was undertaken because the prevalence of Johne's positive herds is rising in Saskatchewan and the disease is present in both commercial and seedstock operations. The Saskatchewan Stock Growers Association has managed a surveillance and control program with funding from the Saskatchewan Ministry of Agriculture. This research will help to ensure this surveillance investment has maximum effect.

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DEDICATION

I would like to dedicate this thesis to Dr. Cheryl Waldner. Cheryl, you are a joy to work with and I am deeply humbled to have had another opportunity to learn from you. Your curiosity about how disease and production interact has led you to meaningful research questions and your unwavering demand for excellence has translated into research that has made deep improvements in our industry. Working with you is always a pleasure that leaves me humbled. Thank you for your investment of time, teaching, and collaboration in me.

I also dedicate this thesis to my husband and family. Colin, I could not have done this without your support. Thank you for all of the times you chose to support my work, to cover my other responsibilities, and encouraged me to continue. I could never have achieved this goal without your love and continual belief in me. Tim, Brette and Nate, thank you for your patience and support as I have undertaken this challenge. I hope that living with a grad-school parent has instilled in you a belief that we are never done learning.

CHAPTER I: INTRODUCTION

Beef cattle are Saskatchewan's dominant livestock industry. The province has over one million cattle, 30% of Canada's beef herd, and over $1.5 billion in annual cash receipts (Statistics Canada 2020b, 2021). The provincial cattle population has been stable over the previous five years (Statistics Canada 2020a). Saskatchewan has a growth plan to increase livestock cash receipts from $2.3 to $3 billion by 2030 (Government of Saskatchewan 2019). To achieve this, the government has identified removal of barriers to intensive livestock growth and investing in a provincial disease surveillance systems as priorities (Canfax Research Services 2012; Government of Saskatchewan 2019; Statistics Canada 2021). Profitable beef industry growth is premised on a healthy provincial herd.

Johne's disease or bovine paratuberculosis is a chronic and untreatable contagious disease in cattle. Infected cattle are clinically undetectable until middle age when they develop debilitating diarrhea and weight loss. By this point, the value and the welfare of the affected animal has been compromised and it has provided an ongoing source of infection to neonatal calves for years. Canada's dairy industry ranked Johne's among its most costly contagious diseases two decades ago (Barkema 2018; Barker 2016; Chi 2002). Since then, most provinces have developed control programs in which over 35% of Canadian producers have participated. A Canadian National Dairy Study was also initiated in which 11% of Canadian farms participated (Barkema 2018). Lessons learned from these efforts have included the need for a national strategy with standardization in risk assessment, testing strategies, and industry policy on the management of test positive cows.

The specific management recommendation for Johne's control in dairies are not feasible for beef as they generally focus on separation of the calf from cow early in life and hygiene of barns (Dorshorst 2006; Groenendaal 2002). However, there are opportunities to learn from dairy industry experience in other areas including the need for structured testing programs, ongoing research to maintain producer engagement, and veterinary involvement in a control program as these activities may be more validly extrapolated between industries. The purpose of this thesis to provide a pro-active examination of the financial incentive to control Johne's in Canadian beef herds in respect to testing and replacement female decisions. It seeks to provide producers and industry level decision makers with a financial perspective on control decisions for use in conjunction with epidemiological findings.

The objective of this thesis is to utilize a dynamic disease transmission model for Johne's disease to inform a financial analysis of Johne's control. Specifically, a partial budget approach was used to estimate annual revenues and expenses affected by Johne's disease testing and replacement breeding female decisions. Annual profits were summarized over a ten-year time horizon using a net present value model.

The organization of the thesis will be as follows: Chapter 2 will provide a review of the epidemiology of Johne's disease and the economics of control options in beef cattle along with a review of approaches to evaluating endemic, infectious, disease control economics in beef and dairy herds. Chapter 3 will describe the Johne's disease agent-based model, along with the scenarios tested, and the economic modeling methods employed in this thesis. Chapter 4 will report on the simulated population effects of Johne's disease over a ten-year horizon along with the effect on annual revenues and expenses, overall net present value, and a sensitivity analysis exploring the factors. Finally, Chapter 5 will discuss the conclusions, including implications, limitations, and areas for future study.

CHAPTER II: LITERATURE REVIEW

This chapter will begin by discussing the epidemiology of Johne's disease with a focus on the challenge posed to control programs from the delayed ability to detect infected animals. Then publications describing the economics of control programs in beef cattle are reviewed followed by publications specific to control in dairy cattle. Finally, the strengths and weaknesses of modeling approaches to evaluate the economics of endemic infectious disease control in beef cattle are considered. The chapter will conclude with a discussion on how this study will contribute to the previous literature.

2.1 Epidemiology of Johne's Disease

Johne's disease or bovine paratuberculosis is a chronic and untreatable contagious disease in cattle. Oral transmission occurs when young cattle are exposed to the infectious agent, *Mycobacterium avium* ssp. *paratuberculosis* (MAP), commonly through contaminated feces, milk, or colostrum. Animals are most susceptible as neonates and susceptibility declines with age. Resistance emerges between 6 to 12 months of age (Tiwari 2006). Infected cattle transition through a latent, also known as silent, phase into a pre-clinical phase where shedding may be low and intermittent. During the early clinical phase, cattle have decreased milk production, decreased feed efficiency, potentially decreased fertility, and weight loss. The clinical phases can begin anywhere between 2 to 10 years. Clinically affected cattle develop increasingly severe diarrhea and eventually die of emaciation and malnutrition. The infection is untreatable (Bhattarai 2013; Tiwari 2006).

Diagnostic test options include fecal culture, serum ELISA, milk ELISA, or fecal PCR testing. Testing of milk samples is common in dairy cattle, but considered impractical in beef cattle. No available test can detect latently infected animals. Even in clinical cattle, no test has perfect sensitivity (i.e., the probability of a positive test result from a true positive animal) and the performance of all tests improves with clinical disease progression. Imperfect test performance creates challenges in control programs. Imperfect sensitivity means true positive cattle testing negative remain in the herd as a source of infection. Test specificity is not perfect and can vary depending on the region where cattle are located (Böttcher 2004; Martinez Covarrubias 2012) but there is low concern about false positives in western Canada (personal communication, Wendy Wilkins, Disease Surveillance Veterinarian, Saskatchewan Agriculture and Food 2021).

The prevalence of Johne's disease in western Canadian beef herds is currently low but rising. In 1999, a Saskatchewan sero-survey of cows on community pasture found an apparent sample prevalence of 0.8% (95% CI, 0.04% to 1.5%). Classifying herds with one or more test positive animals as positive, the apparent herd prevalence was 15.2% (95% CI, 7.1% to 28.6%) (Waldner 2002). Although the participating herds are not directly comparable, provincial surveillance in high risk herds found at least one positive in 8 of 9 herds in 2014 and 16 of 25 in 2015; with 3 to 6% of animals testing positive annually (Wilkins 2019a, 2019b).

Purchased breeding stock may introduce infectious animals into a Johne's negative herd, as purchasing animals has been identified as a risk factor for increasing within-herd seroprevalence in dairies (Tiwari 2009; Wells 2000). The western Canadian beef industry is consolidating. While herds can slowly expand through internal female retention, rapid growth requires external breeding stock. Since 2000, the total number of beef cows on cow-calf operations in Saskatchewan remained largely unchanged (1.1M in 2000 vs 1.08M in 2020), but the number of operations reporting cattle decreased by 40% (22,290 vs 13,160 operations) and the average number of cattle per operation increased by over 60% (101 vs. 168 head) (Statistics Canada 2020c). This suggests a substantial number of breeding cattle have been transferred between herds. Beyond animal introduction, the biosecurity standards of the industry are lower than typical standards of pork, poultry, or dairy (Canadian Food Inspection Agency 2021). In western Canada, comingling of breeding herds at summer pastures is still a common grazing practice. The timing of this practice coincides with the period of calf susceptibility to Johne's disease. Over the last few years, many federal and provincial pastures have been privatized and handed to patrons for management. Anecdotally, this has increased the turnover of herds bringing cattle for summer management and has created more diversity in the disease control standards between pastures. Finally, unlike pork and poultry, beef cattle in western Canada spend virtually their entire lives outside, which makes limiting contact with cattle from other herds, wildlife, or people virtually impossible.

The structure of the beef industry means that many recommended control approaches from dairy cattle are not feasible. In Danish dairies, a risk-based management approach is promoted over a test-and-cull strategy as it has been shown that intense management of high-risk females is more cost effective. However, this approach requires calves be removed from high-risk cows within 1-hour of birth as opposed to the standard 24 hours (Kudahl 2008). An American decision analysis identified herd hygiene practices including feeding milk replacer or pasteurized milk as influential in the ability to control the disease (Dorshorst 2006). Unlike dairy calves, beef calves nurse for several months and are managed in groups with exposure to many mature cows. These production differences drastically increase the potential for exposure and infection in beef versus dairy cattle and illustrate the need for beef-specific control strategies.

2.2 Estimated costs of control strategies for Johne's disease in beef cattle

Two studies were identified reporting on the financial consequences of Johne's disease and comparison of control strategies in beef cattle. Johne's control decisions for beef herds in Great Britain have been studied using a decision tree approach (Bennett 2012). A deterministic and dynamic model incorporated the probability of cattle transitioning through six disease states ranging from latent through clinical. Users could compare no action to the following four actions: (1) annual testing and culling high shedders and clinical animals, (2) annual testing and culling low and high shedders and clinical cases, (3) improved management, or (4) options 2 & 3 combined. The management actions included a "designated clean calving area, rearing calves in separate age groups, washing machinery and other feed/water/waste equipment between young animals and older cows and careful waste and slurry spreading and pastures management, which includes not allowing young stock on recently spread fields" (2012, p. 153). At model initiation, 10% of animals were assumed to be in a low-shedding state. Losses include a reduction in sales (both head and weight), cow replacement costs, deadstock costs, additional veterinary and labor costs, and control costs. Total disease cost was estimated as losses plus expenditures and reported as a 10-yr discounted cash flow. The model was reported across a range of test sensitivities for cows in the shedding or clinical state. Cumulative costs over ten years were greatest for no action (49,019£), followed by test and cull options (44,729 – 47,977£), improved management without testing (34,351£), and least for strict management improvements with testing and culling (26,023 – 27,752£). A sensitivity analysis using a hypothetical test with a 90% sensitivity did not change the ranking or interpretation of results.

Bennett's research demonstrates the value of a customizable model to simulate the effect of multi-year decisions for an individual producer's herd (Bennett 2012). A limitation was modeling management as a set of practices. Collectively these actions were assumed to reduce the risk of infection by 50%, an assumption that would be very challenging for a producer to implement consistently for the assumed 10 pence per animal per week equating to approximately $0.10 in Canadian dollars (CAD).

Johne's control decisions for beef herds in Australia have been studied using a deterministic spreadsheet model (Webb Ware 2012). Survey results of average revenues and expenses, excluding taxes, were used to estimate monthly cash flows for four control options; (1) no action, (2) test and cull, (3) partial cull of young stock presumed exposed, and (4) total destocking and restocking. The initial prevalence of Johne's was not reported, but the model assumed it was eradicated after three years with total depopulation, after five years with a partial depopulation, and not eradicated with a test and cull program. Cash flows were discounted over a ten-year period and a sensitivity analysis examined a 10% decrease and increase in livestock sales prices. In commercial herds, taking no action was preferred to test and cull, both of which were profitable, while both a partial or total destock had a negative NPV. The livestock sales price affected the NPV estimates, but did not change the interpretation of the optimal strategy. At baseline prices, a herd would need to experience a 5% death loss before a partial depopulation would be economical. Australian producers contemplating how to address Johne's disease in their herd require a long-term plan before making a significant financial investment. The results of this study suggest that commercial producers in Australia are best served by taking no action.

2.3 Methodological review of economic studies evaluating control strategies for Johne's disease in dairy cattle

The research methods used to the improve the decision-making process to address Johne's in dairy cattle are relevant despite some of the control interventions not being applicable to beef cattle in western Canada. The most simplistic, yet costly, research approach identified was an observational case-control study collecting cow level data from two infected dairies (Raizman 2009). The time and effort required to collect the data, paired with the limited relevance of results to other herds, regions, or time frames demonstrates the value in developing estimates from disease simulation models rather than collecting field data.

A partial budget model was used to estimate direct losses and treatment costs in the only Canadian publication identified (Chi 2002). The same methods and input costs were applied to the top four production limiting endemic diseases; thus, the findings provided context for allocating resources. The sensitivity analysis for losses associated with Bovine Viral Diarrhea (BVD), which under an epidemic had the largest cost of the diseases considered, provided insight to the robustness of the estimates and concerns in extrapolating results beyond small (50 head) herds in Maritime Canada. The primary limitation of this partial budget model was the epidemiological data informing the model; general assumptions were used which may mask significant, but subtle effects of the disease on the population.

Three studies created analytical models of Johne's disease to compare the profitability of various control choices. An economic decision tree model was used to optimize the net cost-benefit value per-cow-per year (Dorshorst 2006). The control scenario was taking no action, which was associated with an NPV of zero. Alternatives were ranked by comparing the estimated NPV to this baseline. Two strengths of this publication are worth highlighting. First, opportunity costs arising from increased cull rates in Johne's positive herds were included. This incorporated the costs arising from retaining more replacement females, the increased health costs, but also included the decreased revenues due to lower production in the remaining cow herd. This production decline was attributed to a decreased rate of culling for conditions other than Johne's disease and slowed genetic improvement due to culling genetically valuable animals. Second, the variables to which the outcome was sensitive were reported as a tornado chart, a one-way sensitivity analyses and as two-way strategy region graphs. The published sensitivity analysis allows readers to ask what-if questions without re-running the model and provides great insight into the complex interactions that influence the optimal decision. Reporting outcomes as deterministic point estimates for a single year, based on a cross sectional study, limits the application of these results given Johne's control strategies are necessarily multi-year and involve uncertainty. This limitation could theoretically be addressed by using one year's outputs as inputs for the next in a multi-year analysis, but the complexity of the tree (the three decision nodes and two chance nodes resulted in 960 branches in a single year) limited the feasibility of this approach.

The remaining two studies were related research and both used a dynamic simulation model to estimate NPV for Johne's control decisions (Groenendaal 2003; Groenendaal 2002). The proportion of dairy cattle in each disease state was estimated using probability distributions at six-month intervals over a 20-year period. Results were reported as disease prevalence and time-adjusted losses. Outcomes were reported as distributions, which allowed readers to evaluate variability and thus implicitly consider risk. They reported distributional extremes, which provided insight into the best- and worst-case scenarios for the control choices considered.

The methods described to this point have utilized analytic models in which the epidemiology of Johne's disease was described using formulas, with or without distributional assumptions. Diseases transmission is complex, rather than complicated, and dynamic interactions that are difficult to fully capture in an analytic model may be better suited to simulation modeling (Grigoryex 2018). Dynamic disease modeling also incorporates the effects of randomness or chance in disease transmission. When such models are paired with financial analysis this approach allows for the risk preference of the decision maker to be taken into consideration. An agent-based model (ABM) can simulate situations where it is possible to observe *how* agents behave even if you do not know *why* (Grigoryex 2018*)*. Once modeled, the "agents" are allowed to interact and the effect on the system are evaluated. An ABM is well suited for modeling Johne's disease because of the complex feedback loops between the animal population and the disease transmission and expression.

An agent-based simulation model has been used to consider the net benefits of interventions in a simulated 1,000-cow milking herd (Verteramo Chiu 2018). Verterama Chiu (2018) refers to analytic models as compartment models where the herd, or a homogeneous proportion of the herd, is subject to each decision. In contrast, an ABM allows for individual animal level decisions, thus, more closely mirroring on-farm reality. The 20-year NPV for scenarios of uninfected, infected but no action, and infected with four intervention strategies were reported. Fixed and variable costs per cow per day were summed and discounted to the year incurred. The NPV for the control options were compared based on the cost per cow per year. The robustness of the recommendations was examined by comparing the NPV of the model initiated with a set or range of assumptions to the baseline scenario.

2.4 Whole herd economics as an approach to making livestock health decisions

The research described previously reported NPV as the outcome. This does not take into account the effects of the decision on other scarce resources, most notably overall firm profitability. Beef operations involve complex interactions among land, animals, people, facilities and equipment, and may have constraints accessing financing or capital. NPV cannot account for interrelated aspects of the farm (Turner 2013). The effect of decisions on other scarce resources requires a whole-herd economic analysis, while the interaction with other complex aspects of the operation is best evaluated using simulation modeling. These approaches are beyond the scope of this work, but provide interesting avenues to pursue to understand the full economic scope of Johne's disease control decisions.

2.5 Concluding Remarks

There is a lack of consensus on the optimal test and control approach between the two available studies exploring the Johne's control decisions in beef cattle (Bennett 2012; Webb Ware 2012). The discrepancy may arise from the researchers asking a similar question in distinct industries and populations, but the discrepancy in recommendations clearly establishes a need for additional research specific to Canada. While an evaluation of methods, rather than results, was the focus of the review for papers studying dairy cattle, several studies also concluded that no action was the optimal economic outcome (Al-Mamun 2018; Groenendaal 2003; Groenendaal 2002; Verteramo Chiu 2018). This should give producers pause before embarking on a costly and uncertain plan to control an elusive disease. The volume of research on testing options and control strategies without a clear application demonstrates the need for economics research and business tools to be paired with epidemiology research.

There is a lack of information on the economics of Johne's control in beef cattle and no information available specific to Canada. There are a wide range of methods available to determine the most effective testing and control strategy with the majority reporting a comparison of the NPV over a multi-year horizon. The inconsistency in optimal control approaches demonstrate both a need for more research and the importance of distinguishing between different economic research approaches, which should aim to be broadly generalizable and customized through business decision tools. The latter are clearly required by producers operating in an increasingly volatile and uncertain market.

CHAPTER III: METHODS

3.1 Conceptual Framework

The optimal Johne's disease control approach will vary with epidemiological factors, including the initial herd prevalence, ability to correctly identify infected animals, and the transmission rate; production factors including the effect of the disease on conception rates, calf growth rates, and cow longevity; and economic factors such as breeding female replacement costs and market values. The financial incentive depends on the net difference between disease losses and control cost. These can be described using net present value (NPV) analysis.

An NPV analysis is limited to the revenues and expenditures associated with the decision. It is not a whole-firm profitability analysis nor does it consider cash flow. The only incorporation of project risk is through the discount or hurdle rate; the riskier the project the higher the rate a decision maker should use. A foundational assumption is that money is worth more in the present than in the future so cash flows must be discounted back to the point in time when the cost in incurred (Brealey 2017, p. 19). Investment decisions should only be made when an NPV is positive. When alternate scenarios are considered, the option with the highest NPV is the most desirable from a purely economic viewpoint.

Beef cattle have a long generation interval so disease control decisions can affect pathogen and host populations for many years. This delay must be considered when evaluating the financial implications of interventions in livestock breeding populations. The approach should allow for interventions to be applied at the herd, cohort or animal level; to change over time; and to track the associated revenues and expenses. These objectives can be achieved by pairing a NPV model with a dynamic epidemiological model.

An NPV includes only financial effects related to the decision in question. This limited scope means that the analysis can be approached within the framework of a partial budget. A partial budget compares the marginal change in costs and revenues arising from each of two choices being considered (Dalsted ; Dhoubhadel 2010). A partial budget provides a structured approach to quantifying the net short run effects of a single change or the difference between two-states. The partial budget assumes the business is profitable and able to implement either choice being considered. The analysis does not consider risk, cash flow, or enterprise profitability. Although, partial budgets have been criticized as having limited usefulness for long-run or multi-factorial decisions, pairing their fundamentals with an NPV analysis populated by an epidemiological model largely overcomes these limitations (Dalsted 2004; Dhoubhadel 2010).

An NPV model was not the only approach considered. Whole farm profitability could be examined, as has been done in two studies evaluating control practices for bovine viral diarrhea (BVD) (Cozzens 2015; Stott 2003). These studies used a TARGET MOTAD (minimization of total absolute deviations) mathematical programming model, which sought the most profitable decision, while constraining the model to a target minimum income (Tauer 1983). This approach was not pursued due to the lack of data to inform a model using whole-herd profitability and the concern that beef herds are highly variable in both physical and financial structure, which would not lend itself to generating a result that was relevant to many herds in Saskatchewan's beef industry. However, in recognition that cow-calf firms in Saskatchewan are primarily owner/operator enterprises, and that access to financing and cash flow can create real constraints to implementing decisions, the thesis includes annual net cash positions for revenues and expenses related to the Johne's control decision.

3.2 Overview

The expected returns from a consistently applied test and control strategy for Johne's disease were evaluated by applying a net present value model (NPV) to outputs from an agent-based model (ABM). The ABM simulated disease transmission dynamics in a typical Saskatchewan beef herd accounting for changes in animal inventories, including births, deaths, purchases, and sales, disease transmission, and disease effects.

Scenarios with a low (1.5%) and high (7%) initial prevalence of Johne's disease, along with a Johne's free situation, were tested to represent the prevalence range observed in Saskatchewan beef herds. Two replacement options were considered in this study: internal heifer retention or external mature cow replacements. Mature cows, rather than heifers, were considered as the preferred external source of breeding females because they could theoretically be tested for Johne's disease before or soon after the time of purchase. As cattle cannot be reliably tested until two years of age, external replacement heifers would pose an unmeasurable risk as replacements. The following three test and cull strategies were considered: No testing with culling of all animals showing clinical signs; Testing all mature cows (>2 years) and all bulls annually with the commercially available individual animal ELISA and culling all test positive animals as well as any clinical animals; Testing all mature cows (>2 years) and all bulls annually with a fictitious test with perfect sensitivity and specificity and culling all test positive animals as well as any clinical animal

A partial budget approach was used to evaluate the revenues and expenses under a set of scenarios considering disease prevalence, management, and disease testing strategies. Revenues were limited to livestock sales of weaned calves and culled breeding stock. Expenses included purchase of replacement cows and bulls, operating costs, and testing costs. The financial outcome for each scenario was described by the expected NPV over ten years.

3.3 Agent Based Model of Beef Herd Population Dynamics

An ABM developed by Waldner et al. (unpublished) was used to simulate the effects of Johne's disease test and control decisions on population dynamics. The agents, hereafter referred to using common industry terminology including stock, cattle, cows, heifers, bulls and calves represented animals in a spring calving beef herd. The herd was managed to attempt to maintain approximately 300 breeding females at calving and managed as two cohorts; breeding bulls and breeding females with or without calves at side. The populations in each livestock class were captured at six-month intervals while all other data were captured annually.

Females were either born into the herd or purchased as mature breeding females. Breeding cows were culled when older than 12 years, not pregnant, a positive Johne's test result, or clinical signs of Johne's disease arose. Yearling heifers were culled if they were not pregnant. Breeding males entered the herd only through purchase as yearling bulls. Breeding bulls were culled when any of the following conditions occurred: older than six years, a positive Johne's test result, or clinical signs of Johne's disease arose.

Calves entered the herd only through births. Preweaning mortality rates were based on Western Canadian research and was higher for calves born to first calf heifers (5%) than to mature cows (3%), but did not differ between bull and heifer calves (Elghafghuf 2014). All male calves were considered to be steers and exited either through death or weaning. In scenarios replacing breeding stock by external mature cow purchases, all heifer calves also exited the herd through death or sale at weaning. Scenarios replacing breeding females internally sold the heifer calves not required to maintain breeding herd size. The number retained was based on a prediction that incorporated the rates of cow culls and the lower predicted pregnancy rates in heifers (90%) than in cows (95%).

Susceptibility to Johne's infection was highest from birth to weaning (7 mo.), decreased by 1/3 from weaning until one year, and was zero in animals older than one year. Exposure from dam to calf occurred at a rate of 0.594 exposures per month which is equivalent to an expected cumulative incidence of dam to calf transmission of 0.3 over the first 6 months of life. The risk of infection from the environment at any time was based on a dynamic combination of the current herd prevalence of cows that were infectious but preclinical, the current prevalence of cows with clinical Johne's disease, and a parameter that represented a combination of contact rate and risk of infection given contacts. The infection parameter was calibrated based on long term prevalence data collected from herds participating in the Saskatchewan control program. The probability of purchased breeding stock being sub-clinically infected with Johne's was 1.5% based on baseline prevalence data reported for western Canada. The rate of transition through the state chart from infected to infectious to clinical were each modeled using triangular distributions. The mean latency period was seven months, or equal to the preweaning duration, while the mean infected duration was seventeen months. Animals less than 18 months of age were not infectious.

Bulls were eligible for testing at one year of age and cows were eligible if over 24 months. In scenarios where testing was performed, all eligible cows and bulls were tested each fall at pregnancy testing. The performance of the blood test was based on values reported in the literature for the commercially available ELISA test when applied to cattle that are infected but not yet infectious (pert (0.246, .0476, .262)), infectious but not clinical (pert (0.15, 0.793, 0.697)), and showing clinical signs (pert (0.8, 0.87, 0.825)) Scenarios considering a fictious perfect test assumed all animals that were infectious for Johne's disease were correctly identified. Clinical cattle were culled within a week of detection while subclinical cattle were culled two weeks after sample collection that resulted in a positive test.

The characteristics of the population were captured at six-month intervals as this timing corresponding to herd management practices that most dramatically affect the population structure. The late spring observation corresponded to the turn out to summer pasture when calves were one month old. The breeding season began one month after summer turn out; although the bulls remained with the cows for ninety days, all cows were bred simultaneously on a single day at the start of the breeding season. The fall observation immediately followed weaning, Johne's disease testing, pregnancy testing, and purchase of replacements and corresponded to the beginning of winter feeding. Winter feeding lasted six months. All cows calved simultaneously on a single day one month prior to summer pasture turn out.

The average weight of calves at weaning and sale was reported by gender. Cows sold were reported by age, body condition, and reason, while bull sales were reported by reason. It was assumed that cows in good body condition weighed 100 lbs. less the herd average of 1350 lbs. when sold due to old age (i.e., having reached 12 years). Cows sold in poor body condition were assumed to weigh 200 lbs. less. The model varied body condition for cows both seasonally and by clinical Johne's status based on data from western Canada. Bulls sold due to clinical signs of Johne's disease were assumed to have lost 15% of the body weight of an average mature bull (2100 lbs.). Yearling heifers sold for being not pregnant were assumed to weigh 950 lbs.

The term "scenario" is used loosely to describe each unique combination of initial Johne's disease prevalence, decision to test, test performance, and replacement female strategy. Fourteen scenarios were considered (Table 3.1). Six considered the combinations of management decisions under low Johne's pressure, six under high disease pressure, and two considered the effect of female replacement strategy in a known Johne's negative herd without testing. The initial Johne's prevalence describes the true subclinical infection rate at the initiation of the model; this is different from the test positive rate because of imperfect in test performance in latent and subclinical animals. The scenarios without Johne's were included as a proxy for a negative control and served to ensure outcomes were reflective of current industry expectations and experiences. The testing strategy described annual testing of all eligible cattle with either the fictious test that has perfect performance in infectious animals or the commercial ELISA test. The replacement strategy describes herds either purchasing mature bred females to replace culled cows in the fall or retaining sufficient heifers to offset the predicted number of cows to be culled in the next year. Each scenario was simulated in the ABM for 1000 iterations over a ten-year time horizon to provide distributional data about herd outcomes for the economic model.

Table 3.1: Scenarios tested in Johne's disease simulation

Scenario	Johne's prevalence [a]	Testing frequency [b]	Test sensitivity [c]	Replacement female strategy [d]
1	1.5	no testing	n/a	external mature cows
2	1.5	no testing	n/a	internal yearling heifers
3	1.5	annual	perfect	external mature cows
4	1.5	annual	perfect	internal yearling heifers
5	1.5	annual	commercial ELISA	external mature cows
6	1.5	annual	commercial ELISA	internal yearling heifers
7	7	no testing	n/a	external mature cows
8	7	no testing	n/a	internal yearling heifers
9	7	annual	perfect	external mature cows
10	7	annual	perfect	internal yearling heifers
11	7	annual	commercial ELISA	external mature cows
12	7	annual	commercial ELISA	internal yearling heifers
13	0	no testing	n/a	external mature cows
14	0	no testing	n/a	internal yearling heifers

[a:] initial true prevalence of Johne's infected cattle model initiation; [b] frequency of testing of cows >2 years and all bulls; [c] model assumption of test sensitivity; [d] source and age of replacement females

3.4 Economic model

A partial budget approach was used to identify the revenues and expenses that differ between control scenarios in a production year (Dalsted 2004). All prices are reported in CAD throughout. All livestock sales were included as revenues. Prices reported by Canfax through the Saskatchewan Agriculture and Food Weekly Cattle Market Updates for the five market weeks in October of 2020 were averaged to obtain initial market values for 500-600 lbs. steers and heifers, 800+ lbs. yearling heifers, as well as D2 and D3 cows (Saskatchewan 2020) (Table 3.2). October was used as the reference market for several reasons: First, this is reflective of the start of the fall run in western Canada when many producers market cattle. Second, this timing approximately matches the timing of weaning when calves are sold and cows were Johne's tested, pregnancy tested, and sold if greater than 12 years of age, open, or Johne's positive in the ABM. A comparison of reported values from 2016 – 2020 revealed that 2020 was a moderately weaker market than normal for cull cows and an average market for weaned calves (Table 3.3). Future livestock prices were forecast based on the USDA Agriculture Projections Outlook (United States Department of Agriculture 2020). The percentage year over year forecast change in 5-area steer values were from 2020 to 2029 were applied to the current market values for all classes of cattle.

Table 3.2: Livestock values in Saskatchewan, October 2020

Gender	Age	CWT	Grading Class	Value ($/cwt)
Female	Mature	n/a	D2	$ 78.99
Female	n/a	9	n/a	$ 163.56
Female		5.5	n/a	$ 180.05
Bull	Mature	n/a	E	$ 100.00
Steer		5.5	n/a	$ 206.88

[a] Canfax prices reported Fridays as prices in Canadian dollars per hundred weight ($/cwt) and determined from Saskatchewan auction market reports of sale from Thursday of the previous week to Wednesday of the current week.

Table 3.3: Average livestock values per CWT in Saskatchewan for the five-week period[a] following the first weekly October report from 2016 -2020 ($CAD).

Livestock class	2016	2017	2018	2019	2020
D2 slaughter cows	$87.48	$88.79	$83.02	$85.11	$78.99
D3 slaughter cows	$77.52	$78.96	$72.45	$74.49	$69.03
Heifers (500 - 600 lbs.)	$149.28	$201.46	$189.37	$187.36	$180.05
Steers (500 - 600 lbs.)	$174.20	$229.30	$220.32	$217.54	$212.66

[a] Canfax prices reported Fridays as prices in Canadian dollars per hundred weight ($/cwt) and determined from Saskatchewan auction market reports of sale from Thursday of the previous week to Wednesday of the current week.

The Canadian beef grading system for mature cows is based on muscling and fat. There are four categories with D2 and D3 the predominant classes for cull cows. Carcasses grading D2 require medium to excellent muscling and white to yellow fat less than 15mm, while D3 carcasses have deficient muscling. In practice, buyers attempt to predict the grade when bidding on live cull cattle with underconditioned and old cows typically valued as D3. Market values for mature bulls were reported by Canfax (Canfax Research Services 2020). Canada uses a five-point body condition score (BCS) ranking 0 - 2.5 as underconditioned, 3.0 in good condition, and 3.5 to 5.0 as over-conditioned (Beef Cattle Research Council). Cows 12 years or older when sold or with a body condition score <2.5 were assumed to trade at D3 value, while remaining culls were assumed to sell at D2 value (Beef Cattle Research Council 2020). The D2 price was subject to the UDSA trend and a D3 discount of $10/cwt, as observed in Oct. 2020, which was held constant over time. All mature bulls were assumed to be grade E regardless of age or condition. The price for both cows and bulls was discounted 20% when sold at < 2.5 BCS.

Revenues were calculated by livestock class as the product of head sold, average weight and market price. Yearling heifers were assumed to be in good body condition due to being sold for non-pregnancy and receive the full 9-CWT yearling heifer price. Calf price, by gender, was adjusted using a $0.10/CWT slide applied to the average weight reported from the population model.

Variable expenses included all breeding stock purchases, winter feed costs, summer grazing costs, veterinary costs, labor, yardage and Johne's testing costs. Fixed overhead expenses including accounting, insurance, licenses, taxes, capital investments, depreciation and opportunity cost were excluded from the partial budget model as they were not considered to be influenced by the Johnes' disease prevalence or control decision. All costs were adjusted annually for inflation at a rate of 2%.

Winter feed was set as a ration of mixed alfalfa/tame hay, barley, mineral, and salt. Feed barley was $168/mt as reported by Saskatchewan Agristability average values for July through October 2020 (Saskatchewan Crop Insurance Corporation 2020). The average fall forage price for alfalfa-grass hay ($144/mt) was reported by the Saskatchewan Forage Association Winter Forage Market Price Discovery report (Saskatchewan Forage Council 2020). Mineral cost was based on local market prices of $1.00/kg.

A winter ration of hay, barley, salt, and mineral was balanced using commercial ration software (CowBytes5 v5.32m Alberta Agriculture and Rural Development). The ration was designed to be appropriate for cattle raised in a winter environment with an ambient temperature of -10°C. The amount fed per day was adjusted according to the gender, growth rate, weight and reproductive status of the animals in each class so as to meet the requirements of each of the following: 2100 lbs. mature bulls, 1350 lbs. dry cows, 1350 lbs. lactating cows, and 600 lbs. breeding heifers targeting growth of 1.4 lbs. per day in order to reach 65% of mature body weight at breeding (850 lbs.). These average animal weights were based on aggregate responses collected from Western Canadian Cow-Calf survey respondents (Western Beef Development Centre 2015). The daily diet cost per animal unit per day (AUD) was $2.00.

Summer grazing rates were based on the published rate by the Association of Manitoba Community Pastures, which included management, but not breeding fees (Association of Manitoba Community Pastures 2020). As per the Manitoba grazing rates, calves sent to pasture nursing a breeding cow were charged $45/season. Labor was set at $1.00/head/day and yardage at $1.00/head/day with both pro-rated by livestock class.

Summer labor was not charged based on the grazing rates used. Winter labor demands were assumed as follows: breeding cows, 1 hour/day; bred heifers, 1.1 hours/day; retained open heifers, 0.75 hours/day; bulls 0.5 hours/day. Yardage was approximated to cover the variable costs incurred to maintain and provide for animals outside of those previously listed including bedding, equipment operation and maintenance, fuel, and facility maintenance. Winter yardage was set at $2/day for bulls, $1.50/day for replacement heifers and $1/day for breeding cows. Yardage was not charged in summer.

Herd health costs included an annual parasiticide, 5-way modified live BVD vaccination, and clostridial vaccination for all animals (Table 3.4). Breeding cows received a scour vaccine and pregnancy test. Calves received vitamin A, vitamin E, a management tag, and a Canadian Cattle Identification Agency (CCIA) RFID tag. All pharmaceuticals were assumed to be used at label rate. Veterinary costs for dystocia, semen evaluation and pregnancy testing were established using the Canadian Veterinary Medical Association fee guide and pharmaceuticals were based on local rates. The cost of Johne's testing was set at $22.00 per head tested which is the average rate for herds participating in the Saskatchewan Johne's surveillance project (personal communication, Wendy Wilkins Saskatchewan Agriculture and Food). This cost included the professional fees for veterinarian sample collection, consumables, courier fees, and laboratory testing. It did not include professional time to interpret test results. The fictious perfect test was priced equivalent to the commercial ELISA. Inflation of all expenses was set at 2% annually.

Veterinary exposures occurred once per season. The percent of animals in each class assumed to receive an antibiotic and anti-inflammatory to treat health issues was as follows: mature cows 1%, yearling replacement heifers 2%, retained heifer calves 2.5%, pre-weaned calves 5%, and mature bulls 2%, with exposure distributed by season. Veterinary care for dystocia or individual animal treatment was assumed to be required for 0.5% of mature cows and 1% of yearling heifers. All bulls received a breeding soundness exam and a trichomoniasis test.

Expenses were calculated by applying each cost to the proportion of the animals in a livestock class exposed and the population present at exposure. The proportion exposed was either 0 or 100% for all costs, except antibiotics, anti-inflammatory, and veterinary interventions for dystocia. The population exposed to each cost was determined by the frequency and timing of when costs were incurred. Costs incurred at a single point per season were multiplied by the population at the beginning of the season. Costs incurred repetitively over a season were applied to the average of the population at the start and end of the season. Feed and grazing costs were adjusted based on average animal weights converted to animal units present over the season (Table 3.5) (Manske 1998). To eliminate the effect of different herd sizes and structures, direct operating costs were described as the cost per animal unit day by dividing operating costs by total animal days in each year as seen in equation (1)

$$Animal\ Unit\ Equivalents\ (AUE) = \frac{(lbs.live\ animal\ weight)^{0.75}}{1000^{0.75}}. \qquad (1)$$

Table 3.4: Cost of direct operating inputs in Saskatchewan, October 2020 ($CAD)

Category	Item	Unit Cost	Unit
Feed			
	Winter feed	$ 2.00	Animal unit day [a]
	Summer grazing	$ 0.80	Animal unit day [a]
	Pasture fee (calf)	$ 45.00	Head
Health			
	Parasiticide	$ 0.03	ml
	5-way MLV	$ 1.58	ml
	Clostridial	$ 0.20	ml
	Scour	$ 1.50	ml
	Vitamin E	$ 0.38	ml
	Vitamin A	$ 0.24	ml
	Antibiotic	$ 1.13	ml
	Metacam	$ 0.38	ml
	CCIA	$ 2.50	Tag
	Ear Tags	$ 1.00	Tag
	Pregnancy Detection	$ 2.00	Test
	Veterinary Intervention Dystocia	$ 400.00	Test
	Breeding Soundness Exam	$ 120.00	Test
Other			
	Labor	$ 1.00	Day
	Yardage	$ 1.00	Day
	Johne's sample collection and testing	$ 22.00	Head

[a] Animal Unit Day: Cost per animal unit equivalent per day (Equation 1)

Table 3.5: Age range and animal weights in each livestock class used to calculate exposures to direct inputs

		Age Range			Weight
Cohort	**Class**	Min.	Max.	Units	(lbs.)
Breeding Female	**Mature cows**	2	12	years	1,350
	Yearling heifers	1	2	years	950
	Open replacement heifers	8	12	months	850
Breeding Males	**Mature bulls**	2	6	years	550
	Yearling bulls	1	2	years	2,100
Calves	**Heifers**	0	8	months	550
	Steers	0	8	months	600

Estimated cash flows were calculated for each simulated herd by subtracting the sum of annual operating expenses, breeding stock purchases, and testing costs from the sum of all livestock sales. Future cash flows were discounted using a constant discount rate of 7.5% and summed over the simulated ten years (Brealey 2017). The annual cash flow was equivalent to year-end earnings before interest, tax, depreciation, or amortization. For each scenario, NPVs were reported as median, 5th percentile, and 95th percentile.

3.5 Statistical analysis and sensitivity testing

Population changes and changes in Johne's disease prevalence between scenarios were reported according to the central tendency (median) and distribution (5th and 95th percentiles) of the 1000 iterations run for each scenario. Scenarios were ranked for preference as a control method by ranking the median estimated NPVs within each initial Johne's prevalence. The NPV estimates had left skew and were not normally distributed so were not compared using parametric tests or regression analysis.

The sensitivity of recommendations was explored by comparing the rank of scenarios by median NPV for the following four assumptions. First, the effect of cattle market strength was examined by increasing and decreasing the initial livestock prices by 10% and 25% and comparing the rank of estimated NPVs to the baseline scenario. Second, the effect of livestock prices following the USDA Agricultural Projections was examined by comparing the ranks of median estimated NPVs for each scenario with trending versus constant livestock price over time. Third, the effect of variation in direct input costs was examined for the scenarios with external mature replacements. From each of these scenarios, 100 iterations were retained. Each of these iterations was expanded 100 times and subject to a variable input price for winter feed, summer grazing, veterinary costs, labor and yardage. Each input varied according to a normal distribution with a mean equal to the baseline price and a standard deviation equivalent to 20% of the price. The rank of scenario by median NPV and the distributional variation were compared to the baseline scenarios. Finally, the effect of Johne's test price was examined by comparing the rankings of median NPVs when testing was free compared to the baseline test cost.

CHAPTER IV: RESULTS

4.1 Population dynamics

Herds purchasing external mature cows for replacement had a median initial population of 275 mature cows and 26 yearling replacement heifers in the fall of the first year. After the initial year, herds in these scenarios reported no yearling heifers. Scenarios retaining internal heifers for replacements had a median of 249 mature cows, 26 yearling heifers and 27 retained heifer calves. In all scenarios, herds had a median of 10 mature bulls and 6 yearling bulls in the fall of the first year. Minimal differences occurred between scenarios with respect to bull sales while interesting patterns emerged for both cow and calf sales.

The median cumulative culled females sold per herd was 444 with differences observed between simulations comparing the initial Johne's prevalence and the female replacement strategy (Table 4.1). Simulations of herds without Johne's disease had the fewest cull females (median 387; 5th to 95th percentile, 364 to 409), simulations of herds with a low (1.5%) initial prevalence of Johne's disease reported 454 females sold (5th to 95th percentile, 388 to 665) and simulations of herds with a high (7%) initial Johne's prevalence resulted in a median of 546 females sold (5th to 95th percentile, 401 to 945) indicating rising Johne's prevalence is associated with a rising and increasingly variable rate of cow culling. Some of the variation was explained by the female replacement strategy. While the same trend in cumulative culled females was observed for both female replacement strategies, the difference was more pronounced when heifers were retained as internal replacements (Median values: 0% Johnes, 382; 1.5% Johnes, 547; 7% Johnes, 802) compared to when external cows were purchased (Median values: 0% Johnes, 390; 1.5% Johnes, 410; 7% Johnes, 425).

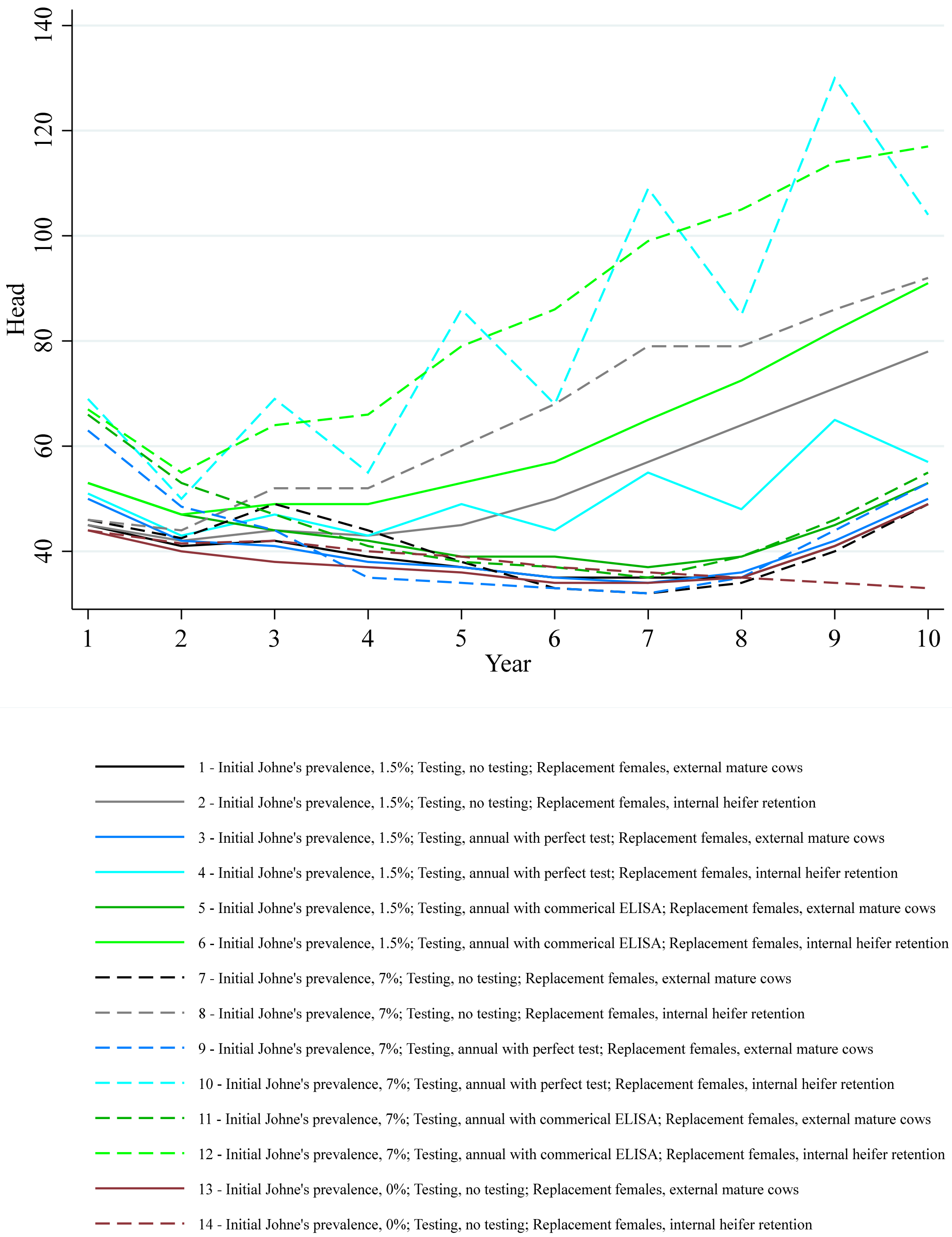
Over time, the annual number of cows culled slowly declined for the first eight years in simulations of herds with external mature replacements (Figure 4.1). Incoming bred cows were modeled as having a subclinical infection rate of 1.5% at purchase which may have contributed to a slow rise in the culling rate again after year eight for all testing strategies. This rise was delayed and insubstantial compared to the trend of increased culled females in simulations utilizing internal heifer replacement. In some iterations of these scenarios the rising demand for replacements outpaced the ability to produce sufficient heifers to maintain a breeding herd size of 300. This trend was due to the positive feedback loop that arose from retaining an increasing number of females from an increasingly infected herd (Figure 4.2). By the tenth year, herds with a low initial prevalence of Johne's and internal replacements had a median of 233 breeding cows (5^{th} to 95^{th} percentile, 206 to 266) of which 28% were first calf heifers. Herds with a high initial prevalence and internal heifer retention had a median of 210 breeding cows (5^{th} to 95^{th} percentile, 195 to 255) of which 44% were first calf heifers (Figure 4.2). In scenarios with Johne's infection and using internal heifer replacements a lower proportionately of the cows were old (>10 years) (median 36.4%; 5^{th} to 95^{th} percentile, 24.2 to 53.3) when sold than herds sourcing external mature bred cows as replacements (median 64.9%, 5^{th} to 95^{th} percentile 55.2 to 70.1) (Figure 4.3).

Table 4.1: Cumulative number of cull breeding females and weaned calves sold per herd over 10-years by initial Johne's prevalence, testing strategy, and replacement female source

Scenario	Johne's prevalence [a]	Testing frequency [b]	Test sensitivity [c]	Replacement female strategy [d]	Cull cows sold [e]
1	1.5	no testing	n/a	external mature cows	399 (379-420)
2	1.5	no testing	n/a	internal yearling heifers	540 (475-612)
3	1.5	annual	perfect	external mature cows	406 (384-427)
4	1.5	annual	perfect	internal yearling heifers	499 (413-633)
5	1.5	annual	commercial ELISA	external mature cows	437 (404-486)
6	1.5	annual	commercial ELISA	internal yearling heifers	619 (489-750)
7	7	no testing	n/a	external mature cows	408 (388-430)
8	7	no testing	n/a	internal yearling heifers	661 (582-744)
9	7	annual	perfect	external mature cows	424 (404-447)
10	7	annual	perfect	internal yearling heifers	829 (706-924)
11	7	annual	commercial ELISA	external mature cows	456 (422-502)
12	7	annual	commercial ELISA	internal yearling heifers	855 (766-938)
13	0	no testing	n/a	external mature cows	390 (370-410)
14	0	no testing	n/a	internal yearling heifers	382 (360-406)

[a:] initial true prevalence of Johne's infected cattle at model initiation (%); [b] frequency of testing of cows >2 years and all bulls; [c] Test performance on samples from infectious, subclinical cattle; [d] source and age of replacement females; [e] median of 1000 iterations with 5th and 95th percentile in parenthesis.

Figure 4.1: Median number of cows sold per herd annually for scenarios examining initial Johne's prevalence, testing strategy, and replacement female strategy



The age and condition of cows sold was explored as it affected the price difference between a cull and reproductively fit replacement. Across all scenarios, the vast majority of cows sold were in good condition as described by having a body condition score of >2.5 on a 5-point scale (Figure 4.4). The age, and to a lesser extent the body condition, of cows culled and the timing of sales and purchases over the scenario affected the price spread between a culled cow and the purchased mature bred replacement cow (Median price difference \$814 per head (5^{th} to 95^{th} percentile, \$777 to \$859)). In herds retaining heifers, the median bred to cull value difference was lower and more variable (median \$778; 5^{th} to 95^{th} percentile, \$686 to \$855) but did not directly affect expenses as breeding stock were internally transferred rather than purchased.

Total calves weaned is a key driver on revenues in cow-calf operations. Even without Johne's disease, herds with internal replacement heifers weaned fewer calves over the ten-years (median, 2,565; 5^{th} to 95^{th} percentile, 2,539 to 2,589) compared to herds with purchases of external mature cows (median, 2,843; 5^{th} to 95^{th} percentile, 2,822 to 2,865) which is equivalent to one entire calf crop lost over the ten years. This difference arose in part because of the assumption of lower conception rates in heifers (90%) than in cows (95%) and higher calf mortality rates in calves born to first calf heifers (5%) than to mature cows (3%), but it also occurred because the open replacements were included in targeted 300 head breeding herd count. This modeling approach was based on the premise that many ranches have a fixed land base and the retention of heifer calves must be offset by carrying fewer pairs. The declining breeding herd size observed in scenarios with internal heifer replacements and Johne's disease exacerbated the trend of weaning fewer calves. Over the ten-year model, herds in scenarios with purchases of external mature cows weaned more calves (median 2,844, 5^{th} to 95^{th} percentile, 2,820 to 2,867) than in herds with internal heifer retention (median 2,356, 5^{th} to 95^{th} percentile, 2,207 to 2,521) (Table 4.2).

Figure 4.2: Median number of breeding cows per herd for scenarios examining initial Johne's prevalence, testing strategy, and replacement female strategy

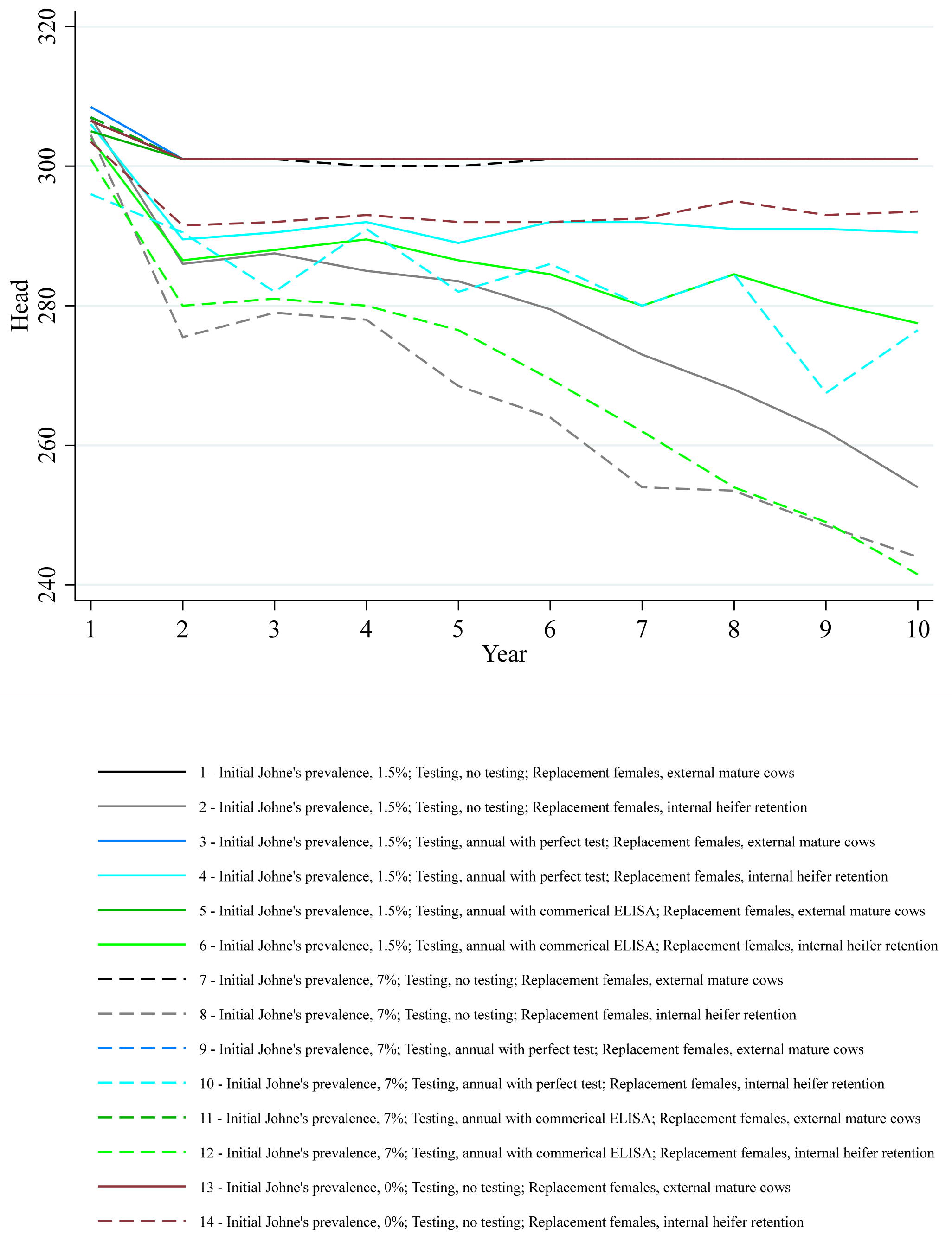
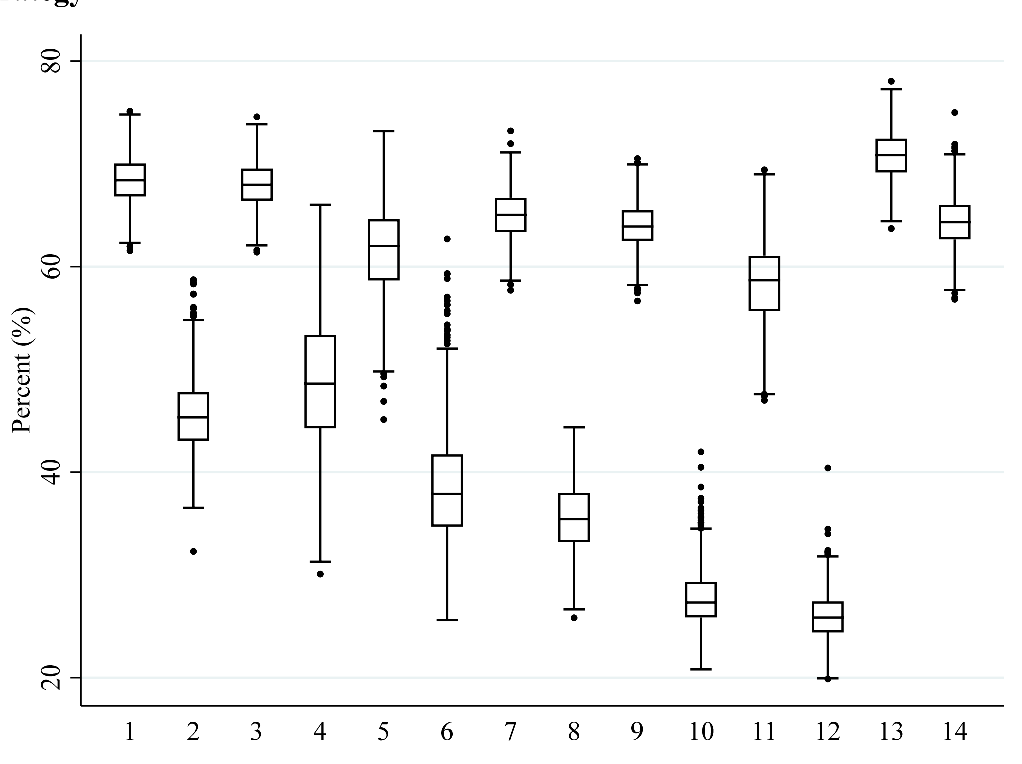


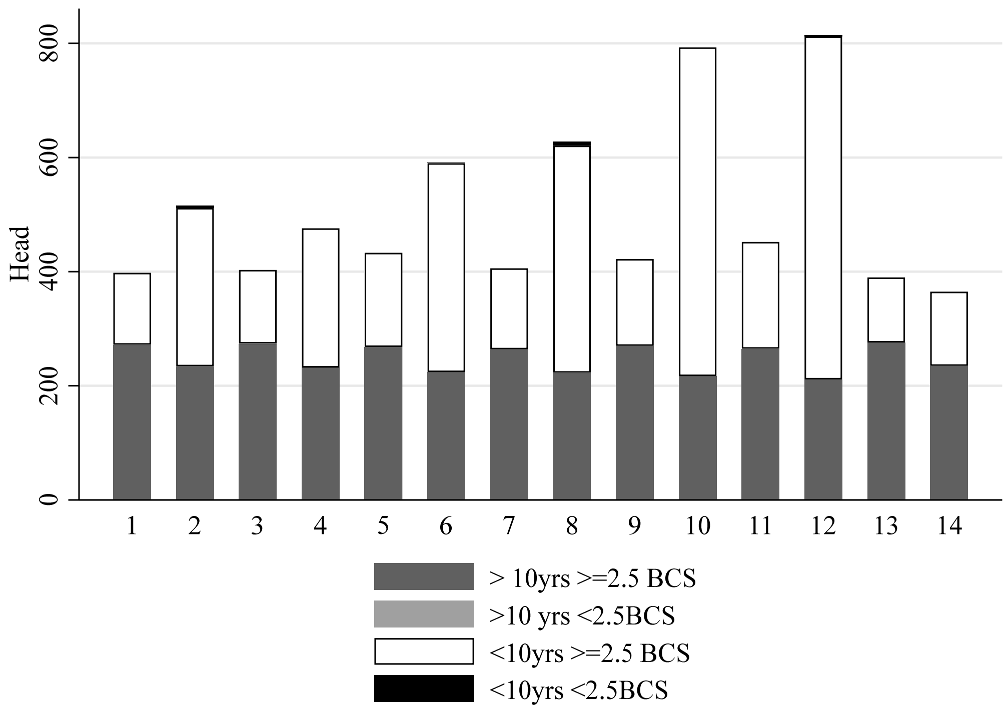
Figure 4.3: Percent of cows sold when younger than 10 years of age for scenarios examining initial Johne's prevalence, testing strategy, and replacement female strategy



Scenario	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Prevalence [a]	1.5	1.5	1.5	1.5	1.5	1.5	7	7	7	7	7	7	0	0
Testing [b]	no	no	yes	yes	yes	yes	no	no	yes	yes	yes	yes	no	no
Test performance. [c]	-	-	P	P	C	C	-	-	P	P	C	C	-	-
Replacements [d]	EC	IH	EC	IH	EC	IH	EC	IH	EC	IH	EC	IH	EC	IH

[a] initial true prevalence of Johne's infected cattle at model initiation (%); [b] Annual testing of cows >2 years and all bulls; [c] Test performance on samples from infectious, subclinical cattle; P = perfect test sensitivity, C = commercial ELISA sensitivity; [d] Female replacement source; EC = external mature cows. IH = internal heifer retention

Figure 4.4: Median cumulative cows sold per herd by age and body condition score (BCS) for scenarios examining initial Johne's prevalence, testing strategy, and replacement female strategy



Scenario	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Prevalence [a]	1.5	1.5	1.5	1.5	1.5	1.5	7	7	7	7	7	7	0	0
Testing [b]	no	no	yes	yes	yes	yes	no	no	yes	yes	yes	yes	no	no
Test performance. [c]	-	-	P	P	C	C	-	-	P	P	C	C	-	-
Replacements [d]	EC	IH	EC	IH	EC	IH	EC	IH	EC	IH	EC	IH	EC	IH

[a] Initial Johne's prevalence; [b] Annual testing of mature cattle; [c] Test performance on samples from infectious, subclinical cattle; P = perfect test sensitivity, C = commercial ELISA; [d] Female replacement source; EC = external mature cows. IH = internal heifer retention

Table 4.2: Cumulative number of calves weaned, sold, and heifer calves retained per herd over 10- years by initial Johne's prevalence, testing strategy, and replacement female source

Scenario	Johne's prevalence [a]	Testing frequency [b]	Test sensitivity [c]	Replacement female strategy [d]	Calves weaned [e]	Calves sold [e]	Heifer calves retained [e]
1	1.5	no testing	n/a	external mature cows	2,843 (2,820-2,865)	2,843 (2,820-2,865)	490 (429-559)
2	1.5	no testing	n/a	internal yearling heifers	2,434 (2,366-2495)	1,942 (1,816-2,066)	0
3	1.5	annual	perfect	external mature cows	2,848 (2,824-2871)	2,848 (2,824-2,871)	453 (369-583)
4	1.5	annual	perfect	internal yearling heifers	2,492 (2,398-2556)	2,036 (1,818-2,185)	0
5	1.5	annual	commercial ELISA	external mature cows	2,844 (2,822-2866)	2,844 (2,822-2,866)	568 (440-686)
6	1.5	annual	commercial ELISA	internal yearling heifers	2,419 (2,319-2510)	1,850 (1,634-2,059)	0
7	7	no testing	n/a	external mature cows	2,837 (2,812-2861)	2,837 (2,812-2,861)	602 (523-675)
8	7	no testing	n/a	internal yearling heifers	2,310 (2,186-2392)	1,711 (1,533-1,857)	0
9	7	annual	perfect	external mature cows	2,847 (2,825-2871)	2,847 (2,825-2,871)	743 (648-811)
10	7	annual	perfect	internal yearling heifers	2,269 (2,199-2356)	1,525 (1,394-1,705)	0
11	7	annual	commercial ELISA	external mature cows	2,845 (2,822-2867)	2,845 (2,822-2,867)	762 (700-821)
12	7	annual	commercial ELISA	internal yearling heifers	2,244 (2,176-2307)	1,480 (1,365-1,605)	0
13	0	no testing	n/a	external mature cows	2,843 (2,822-2865)	2,843 (2,822-2,865)	344 (326-363)
14	0	no testing	n/a	internal yearling heifers	2,565 (2,539-2589)	2,221 (2,181-2,256)	0

[a]: initial true prevalence of Johne's infected cattle at model initiation (%); [b] frequency of testing of cows >2 years and all bulls; [c] Test performance on samples from infectious, subclinical cattle; [d] source and age of replacement females; [e] median of 1000 iterations with 5th and 95th percentile in brackets.

4.2 Johne's Disease

In scenarios where testing was performed, the median number of cows tested per year was 267. The true prevalence of calves infected with Johne's was reported in late fall of the first, fifth and final year immediately before weaning, but after testing and culling occurred for the year. Given the current diagnostic testing limitations, this prevalence rate would not be known by a producer, but modeling provides insight into the degree of success that the control protocol is having on disease control and elimination. The proportion of infected calves remained below a median prevalence of 1%, and 95th percentile of 2% in calves at weaning for herds in scenarios purchasing external mature cows. In contrast, infection rates rose sharply in scenarios using internal heifer retention (Table 4.3, Figure 4.5). This was most pronounced when heifer retention was combined with no testing or an imperfect blood test.

Figure 4.5: True prevalence of Johne's disease infection in fall in pre-weaned calves by initial Johne's prevalence, testing strategy, and replacement female source

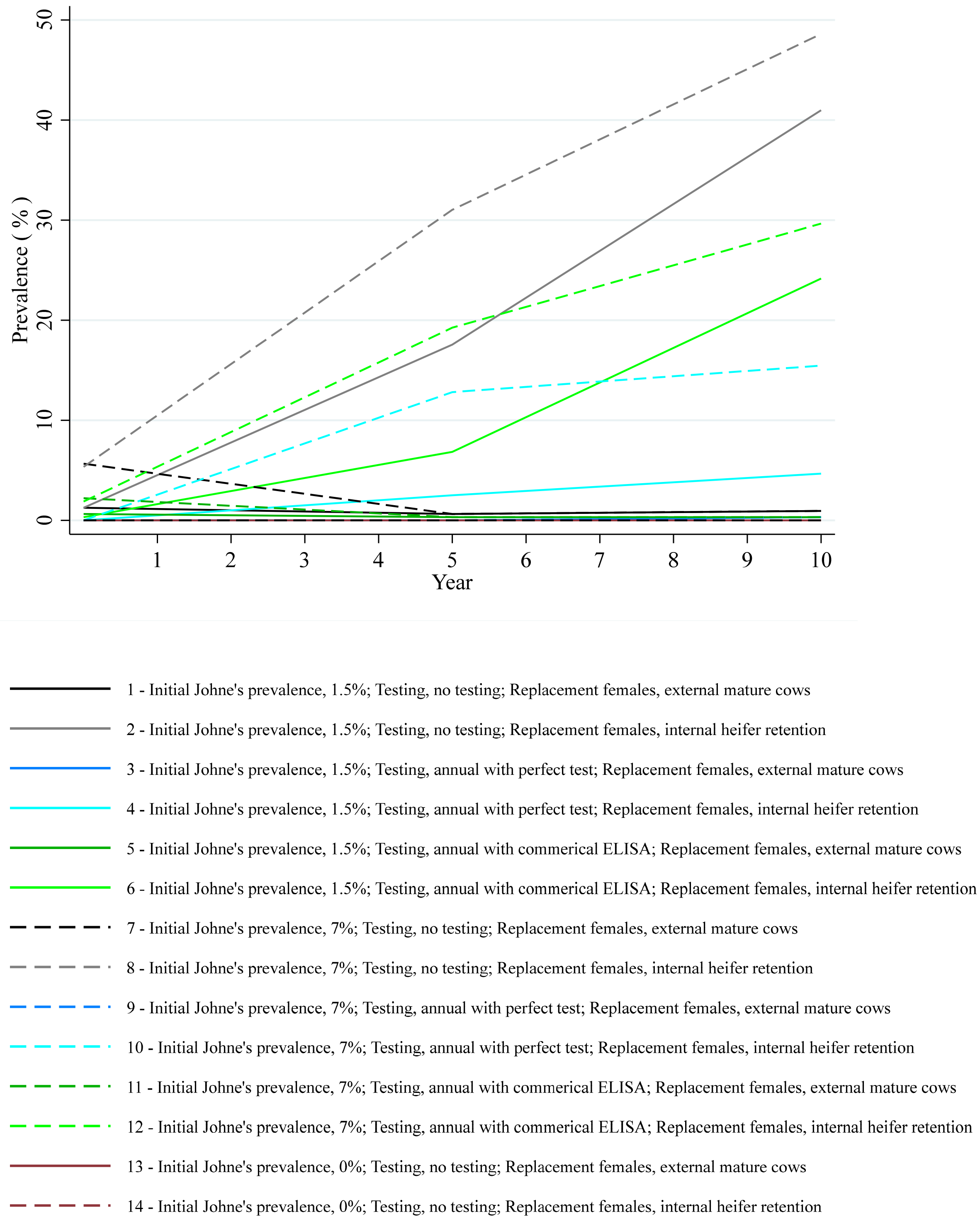


Table 4.3: True prevalence of Johne's disease infection in fall of years 1, 5, and 10 in pre-weaned calves by initial Johne's prevalence, testing strategy, and replacement female source

Scenario	Johne's prevalence [a]	Testing frequency [b]	Test sensitivity [c]	Replacement female strategy [d]	Year 1 (%)	Year 5 (%)	Year 10 (%)
1	1.5	no testing	n/a	external mature cows	1.3 (0.3-2.5)	0.6 (0-1.6)	0.9 (0-1.9)
2	1.5	no testing	n/a	internal yearling heifers	1.3 (0.3-2.2)	41 (31.2-49.3)	41 (31.2-49.3)
3	1.5	annual	perfect	external mature cows	0 (0-0.3)	0.3 (0-0.9)	0.3 (0-0.9)
4	1.5	annual	perfect	internal yearling heifers	0 (0-0)	4.7 (0.3-11.9)	4.7 (0.3-11.9)
5	1.5	annual	commercial ELISA	external mature cows	0.6 (0-1.3)	0.3 (0-1.3)	0.3 (0-1.3)
6	1.5	annual	commercial ELISA	internal yearling heifers	0.3 (0-1.3)	24.2 (11.9-33.8)	24.2 (11.9-33.8)
7	7	no testing	n/a	external mature cows	5.7 (3.8-7.9)	0.9 (0-1.9)	0.9 (0-1.9)
8	7	no testing	n/a	internal yearling heifers	5.3 (3.5-7.6)	48.6 (37.8-55.7)	48.6 (37.8-55.7)
9	7	annual	perfect	external mature cows	0 (0-0.6)	0.3 (0-0.9)	0.3 (0-0.9)
10	7	annual	perfect	internal yearling heifers	0 (0-0)	15.5 (10.9-19.8)	15.5 (10.9-19.8)
11	7	annual	commercial ELISA	external mature cows	2.2 (0.9-4.4)	0.3 (0-1.3)	0.3 (0-1.3)
12	7	annual	commercial ELISA	internal yearling heifers	1.9 (0.6-3.8)	29.7 (23-39)	29.7 (23-39)
13	0	no testing	n/a	external mature cows	0 (0-0)	0 (0-0)	0 (0-0)
14	0	no testing	n/a	internal yearling heifers	0 (0-0)	0 (0-0)	0 (0-0)

[a]: initial true prevalence of Johne's infected cattle at model initiation (%); [b] frequency of testing of cows >2 years and all bulls; [c] Test performance on samples from infectious, subclinical cattle; [d] source and age of replacement females; [e] median of 1000 iterations with 5th and 95th percentile in parenthesis.

4.3 Revenues and Expenses

Excluding herds negative for Johne's, the median cumulative revenues in herds with purchases of external mature cows was $3,584,603 (5th to 95th percentile, $3,361,722 to $3,561,404) compared to $2,736,192 (5th to 95th percentile, $2,668,447to $2,848,979) in herd with internal heifer retention. The scenario with the highest median revenues had an initial Johne's prevalence of 7%, mature external replacements, and used the commercial test.

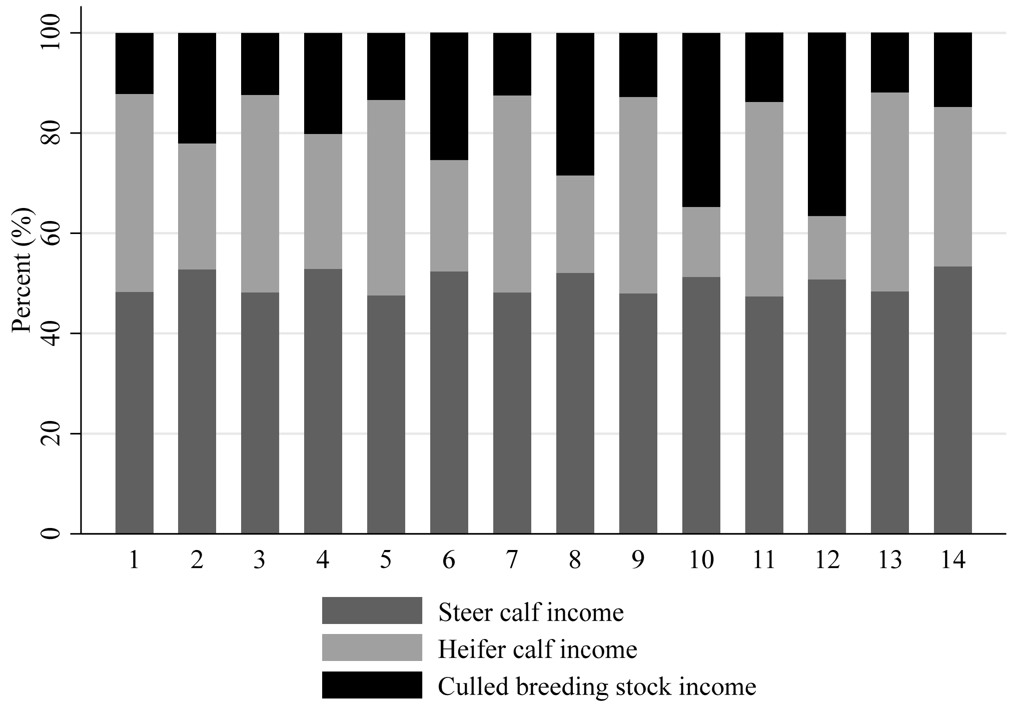
Cumulative revenues were higher when external mature replacements were purchased than when internal heifer retention not only because the entire weaned calf crop was sold, but also because more calves were weaned (Table 4.4). Within scenarios with herds purchasing mature external replacements, the pattern from highest to lowest median gross revenues were associated with the testing strategy. Cumulative revenues were greatest for scenarios with the imperfect commercial test, followed by the fictious perfect test, followed by no testing for both low and high initial Johne's prevalence rates. In contrast, within simulations using internal herd replacements, the primary differentiating factor for gross revenues were the initial Johne's prevalence; herds with a lower initial prevalence had a higher gross revenues than those with a high initial prevalence regardless of testing strategy. Further examination of the scenarios with internal heifer retention found revenues were highest when the perfect fictious test was used, followed by no testing, followed by the imperfect test for both low and high initial Johne's prevalence. In scenarios with internal heifer retention, revenues declined over time due to a decrease in the breeding herd size, decline in the number of calves born and weaned, and a decreasing proportion of heifer calves sold due to a growing demand for replacement females. Culled breeding stock provided a higher proportion of the revenues in these scenarios than in those using external mature replacements (Figure 4.6).

Table 4.4: Cumulative revenues over 10-years by initial Johne's prevalence, testing strategy, and replacement female source

Scenario	Johne's prevalence [a]	Testing frequency [b]	Test sensitivity [c]	Replacement female strategy [d]	Cumulative revenues (Thousands $) [e]	
1	1.5	no testing	n/a	external mature cows	$ 3,561	(3,527-3,594)
2	1.5	no testing	n/a	internal yearling heifers	$ 2,794	(2,728-2856)
3	1.5	annual	perfect	external mature cows	$ 3,574	(3,537-3,607)
4	1.5	annual	perfect	internal yearling heifers	$ 2,849	(2,765-2,912)
5	1.5	annual	commercial ELISA	external mature cows	$ 3,608	(3,559-3,671)
6	1.5	annual	commercial ELISA	internal yearling heifers	$ 2,790	(2,712-2,873)
7	7	no testing	n/a	external mature cows	$ 3,568	(3,529-3,606)
8	7	no testing	n/a	internal yearling heifers	$ 2,678	(2,572-2,774)
9	7	annual	perfect	external mature cows	$ 3,595	(3,558-3,632)
10	7	annual	perfect	internal yearling heifers	$ 2,682	(2,634-2,737)
11	7	annual	commercial ELISA	external mature cows	$ 3,632	(3,579-3,694)
12	7	annual	commercial ELISA	internal yearling heifers	$ 2,668	(2,613-2,716)
13	0	no testing	n/a	external mature cows	$ 3,550	(3,514-3,583)
14	0	no testing	n/a	internal yearling heifers	$ 2,910	(2,883-2,935)

[a]: initial true prevalence of Johne's infected cattle at model initiation (%); [b] frequency of testing of cows >2 years and all bulls; [c] Test performance on samples from infectious, subclinical cattle; [d] source and age of replacement females; [e] median of 1000 iterations with 5th and 95th percentile in parenthesis.

Figure 4.6: Proportion of cummulative 10-year gross revenues derived from sales of steer calves, heifer calves, and culled breeding stock by initial Johne's prevalence, testing strategy, and replacement female source



Scenario	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Prevalence [a]	1.5	1.5	1.5	1.5	1.5	1.5	7	7	7	7	7	7	0	0
Testing [b]	no	no	yes	yes	yes	yes	no	no	yes	yes	yes	yes	no	no
Test performance [c]	-	-	P	P	C	C	-	-	P	P	C	C	-	-
Replacements [d]	EC	IH	EC	IH	EC	IH	EC	IH	EC	IH	EC	IH	EC	IH

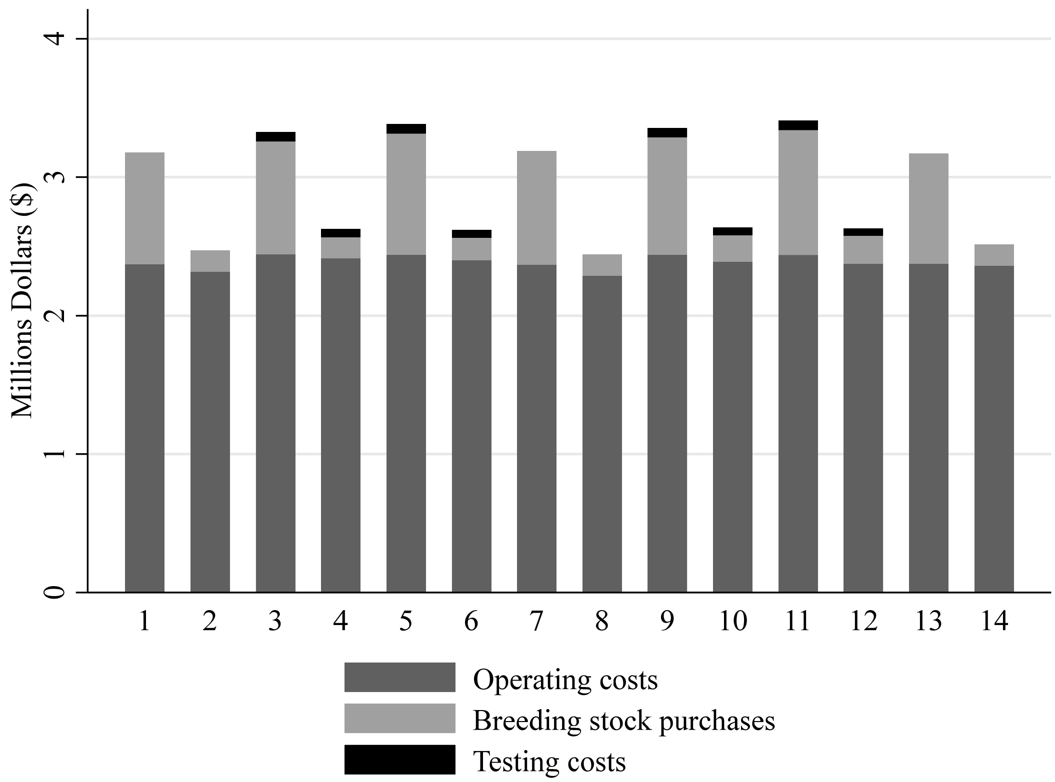
[a] initial true prevalence of Johne's infected cattle at model initiation (%); [b] Annual testing of cows >2 years and all bulls; [c] Test performance on samples from infectious, subclinical cattle; P = perfect test sensitivity, C = commercial ELISA sensitivity; [d] Female replacement source; EC = external mature cows. IH = internal heifer retention

As with revenues, total expenses were not directly comparable between herds purchasing external replacements and those using internal heifer retention so expenses are separated into breeding stock and operating expenses (Figure 4.7). Breeding stock expenses were lower in herds with internal heifer replacement compared to purchase of external mature cows. Within herd buying cows, breeding stock expenses were highest when the imperfect commercial ELISA test was used (Table 4.5).

Median cumulative operating expenses differed by \$154,977 between the scenarios with the highest and lowest expenses (Table 4.5). Testing accounted for an average of 2.6% of operating expenses in herds that conducted testing. Operating expenses were more variable in scenarios with internal heifer replacement and particularly variable in the scenario with no testing (Figure 4.8).

The cost per animal day was calculated to account for differences in herd size and population structure; the median operating cost per AUD was \$1.32 (5^{th} to 95^{th} percentile, \$1.28 to \$1.36) in the first year and differed by \$0.05 from the most to least costly scenarios. By the tenth year, the median cost per AUD had increased to \$1.59 (5^{th} to 95^{th} percentile, \$1.55 to \$1.65) and the difference between the scenario with the highest and lowest daily costs had spread to \$0.10. For both initial prevalence levels considered the scenarios with no testing and external mature replacements had both the lowest cost per AUD every year, which is relevant for producers who seek to manage risk by minimizing expenses.

Figure 4.7: Median cumulative expenses from operating costs, breeding stock purchases and Johne's disease testing for scenarios examining initial Johne's prevalence, testing strategy, and replacement female strategy



Scenario	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Prevalence [a]	1.5	1.5	1.5	1.5	1.5	1.5	7	7	7	7	7	7	0	0
Testing [b]	no	no	yes	yes	yes	yes	no	no	yes	yes	yes	yes	no	no
Test performance [c]	-	-	P	P	C	C	-	-	P	P	C	C	-	-
Replacements [d]	EC	IH	EC	IH	EC	IH	EC	IH	EC	IH	EC	IH	EC	IH

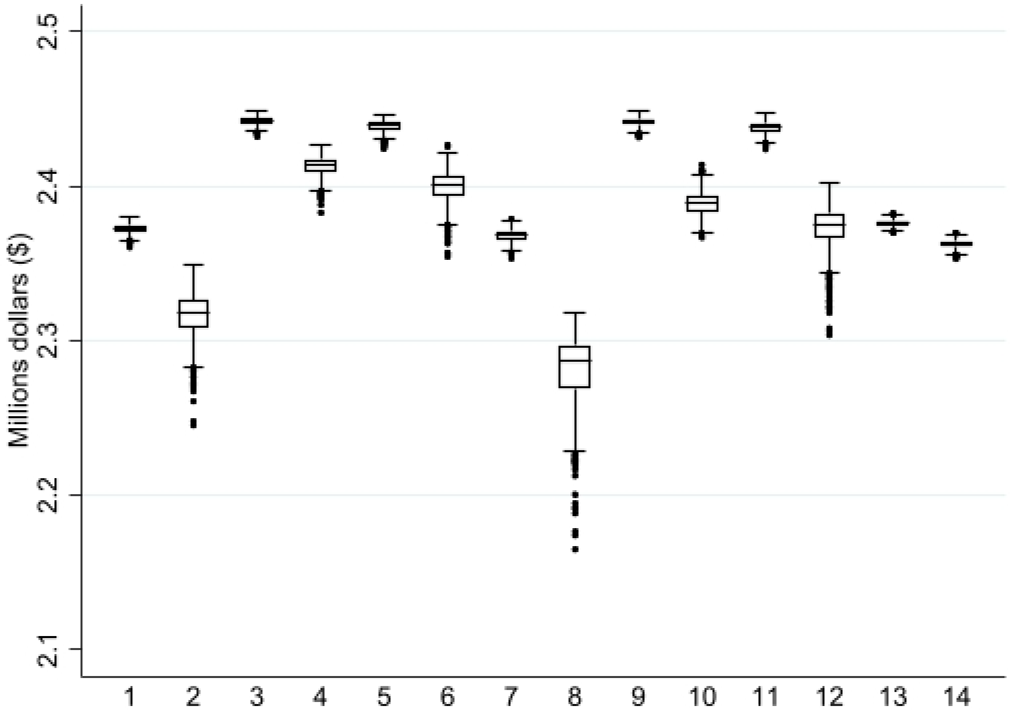
[a] initial true prevalence of Johne's infected cattle at model initiation (%); [b] Annual testing of cows >2 years and all bulls; [c] Test performance on samples from infectious, subclinical cattle; P = perfect test sensitivity, C = commercial ELISA sensitivity; [d] Female replacement source; EC = external mature cows. IH = internal heifer retention

Table 4.5: Cumulative total expenses, operating expenses and breeding stock purchases over 10-years by initial Johne's prevalence, testing strategy, and replacement female source

					Thousands of Dollars ($)		
Sce-nario	**Johne's prevalence [a]**	**Testing frequency [b]**	**Test sensitivity [c]**	**Replacement female strategy [d]**	**Total expenses**	**Operating expenses[e]**	**Breeding stock purchases[e]**
1	1.5	no testing	n/a	external mature cows	$3,176 (3,141-3,214)	$3,141 (3,214-2,373)	$3,214 (2,373-2,368)
2	1.5	no testing	n/a	internal yearling heifers	$2,473 (2,445-2,494)	$2,445 (2,494-2,318)	$2,494 (2,318-2,290)
3	1.5	annual	perfect	external mature cows	$3,258 (3,220-3,295)	$3,220 (3,295-2,442)	$3,295 (2,442-2,438)
4	1.5	annual	perfect	internal yearling heifers	$2,569 (2,557-2,580)	$2,557 (2,580-2,414)	$2,580 (2,414-2,403)
5	1.5	annual	commercial ELISA	external mature cows	$3,315 (3,259-3,395)	$3,259 (3,395-2,439)	$3,395 (2,439-2,433)
6	1.5	annual	commercial ELISA	internal yearling heifers	$2,563 (2,545-2,579)	$2,545 (2,579-2,401)	$2,579 (2,401-2,380)
7	7	no testing	n/a	external mature cows	$3,189 (3,151-3,225)	$3,151 (3,225-2,368)	$3,225 (2,368-2,361)
8	7	no testing	n/a	internal yearling heifers	$2,445 (2,395-2,471)	$2,395 (2,471-2,287)	$2,471 (2,287-2,238)
9	7	annual	perfect	external mature cows	$3,288 (3,251-3,328)	$3,251 (3,328-2,442)	$3,328 (2,442-2,437)
10	7	annual	perfect	internal yearling heifers	$2,582 (2,549-2,630)	$2,549 (2,630-2,389)	$2,630 (2,389-2,377)
11	7	annual	commercial ELISA	external mature cows	$3,340 (3,284-3,418)	$3,284 (3,418-2,438)	$3,418 (2,438-2,432)
12	7	annual	commercial ELISA	internal yearling heifers	$2,576 (2,536-2,625)	$2,536 (2,625-2,375)	$2,625 (2,375-2,345)
13	0	no testing	n/a	external mature cows	$3,170 (3,134-3,205)	$3,134 (3,205-2,376)	$3,205 (2,376-2,373)
14	0	no testing	n/a	internal yearling heifers	$2,514 (2,510-2,519)	$2,510 (2,519-2,362)	$2,519 (2,362-2,358)

[a:] initial true prevalence of Johne's infected cattle at model initiation (%); [b] frequency of testing of cows >2 years and all bulls; [c] Test performance on samples from infectious, subclinical cattle; [d] source and age of replacement females; [e] median of 1000 iterations with 5th and 95th percentile in parenthesis.

Figure 4.8: Cumulative operating expenses over 10-years by initial Johne's prevalence, testing strategy, and replacement female source



Scenario	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Prevalence [a]	1.5	1.5	1.5	1.5	1.5	1.5	7	7	7	7	7	7	0	0
Testing [b]	no	no	yes	yes	yes	yes	no	no	yes	yes	yes	yes	no	no
Test performance [c]	-	-	P	P	C	C	-	-	P	P	C	C	-	-
Replacements [d]	EC	IH	EC	IH	EC	IH	EC	IH	EC	IH	EC	IH	EC	IH

[a] initial true prevalence of Johne's infected cattle at model initiation (%); [b] Annual testing of cows >2 years and all bulls; [c] Test performance on samples from infectious, subclinical cattle; P = perfect test sensitivity, C = commercial ELISA sensitivity; [d] Female replacement source; EC = external mature cows. IH = internal heifer retention

The only scenario with a positive median annual net cash position every year described herds free of Johne's disease with internal replacement heifers (Table 4.6, Figure 4.9). The median annual net cash position was positive for the first nine years in the scenarios with no testing and mature external replacements regardless of initial Johne's prevalence. In contrast, for a high initial Johne's prevalence, an imperfect test and internal heifer replacements the projected annual net cash position became negative in year five and remained negative. Across all scenarios, the annual net cash position declined over time with a more variable decline in scenarios with the perfectly performing test combined with internal heifer retention (Figure 4.9). The overall trend towards lower year end cash position over time was expected; input costs were inflated 2% annually while livestock prices decreased in every year except year two, where prices increased by 10%, and year five when prices remained essentially unchanged as per the trend in the USDA price forecast. No increase in production or efficiency was modeled to offset this trend.

Figure 4.9: Annual net cash position by initial Johne's prevalence, testing strategy, and replacement female source

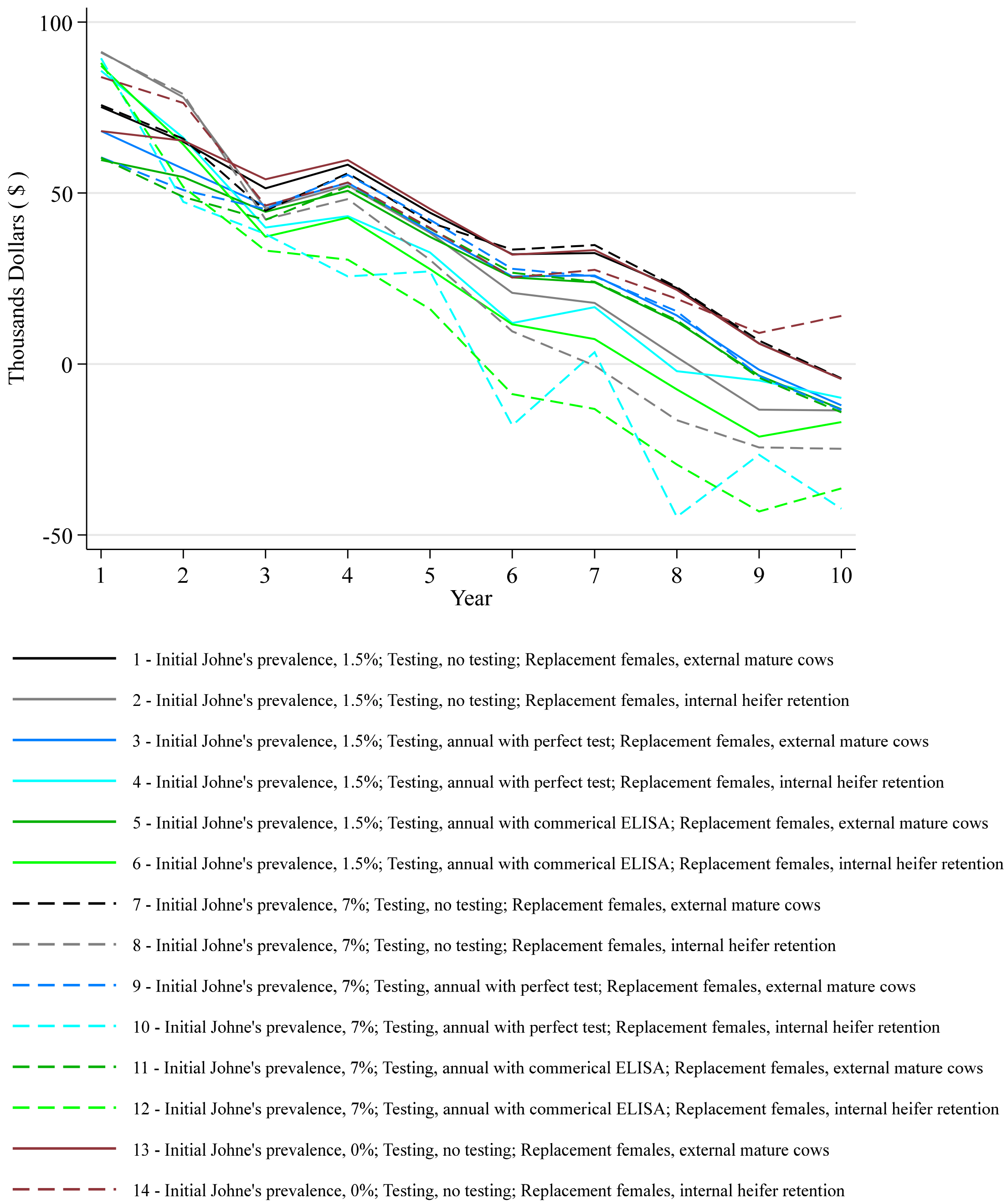


Table 4.6: Net cash position for years one, five and ten and number of years with positive net cash flow by initial Johne's prevalence, testing strategy, and replacement female source

Scenario	Johne's prevalence [a]	Testing frequency [b]	Test sensitivity [c]	Replacement female strategy [d]	Net Cash Position[e] Year 1	Year 5	Year 10	Years of positive net cash
1	1.5	no testing	n/a	external mature cows	$ 75,178	$ 32,103	$ (4,348)	9
2	1.5	no testing	n/a	internal yearling heifers	$ 91,296	$ 20,791	$ (13,584)	8
3	1.5	annual	perfect	external mature cows	$ 68,140	$ 25,606	$ (12,069)	8
4	1.5	annual	perfect	internal yearling heifers	$ 85,726	$ 11,958	$ (9,914)	8
5	1.5	annual	commercial ELISA	external mature cows	$ 59,648	$ 25,306	$ (13,225)	8
6	1.5	annual	commercial ELISA	internal yearling heifers	$ 87,200	$ 11,599	$ (17,000)	7
7	7	no testing	n/a	external mature cows	$ 75,747	$ 33,440	$ (4,183)	9
8	7	no testing	n/a	internal yearling heifers	$ 91,071	$ 9,528	$ (24,785)	6
9	7	annual	perfect	external mature cows	$ 60,431	$ 27,821	$ (13,413)	8
10	7	annual	perfect	internal yearling heifers	$ 89,409	$ (17,967)	$ (42,317)	6
11	7	annual	commercial ELISA	external mature cows	$ 60,340	$ 26,694	$ (14,130)	8
12	7	annual	commercial ELISA	internal yearling heifers	$ 88,034	$ (8,813)	$ (36,389)	5
13	0	no testing	n/a	external mature cows	$ 68,086	$ 31,962	$ (4,342)	9
14	0	no testing	n/a	internal yearling heifers	$ 83,913	$ 25,278	$ 14,074	10

[a]: initial true prevalence of Johne's infected cattle at model initiation (%); [b] frequency of testing of cows >2 years and all bulls; [c] Test performance on samples from infectious, subclinical cattle; [d] source and age of replacement females; [e] median of 1000 iterations with 5th and 95th percentile in parenthesis.

4.4 Net Present Value

Johne's is a costly disease; the 10-year median NPV decreased with rising initial Johne's infection rates (Table 4.7) which was most profitably addressed by sourcing external replacement breeding stock (Table 4.8) and culling cows at the onset of clinical signs rather than annual testing (Table 4.9).

All scenarios with internal heifer retention had lower NPVs than those with external mature replacements due to rising Johne's prevalence and associated losses from decreased cow longevity. The most profitable scenario modeled was a Johne's free herd with internal heifer retention (Median NPV $327,295; Table 4.7). The second highest NPV was in the scenario with external mature replacements in a low prevalence Johne's herd (NPV $319,394) which was even slightly higher than a Johne's free herd with mature replacements (median $315,909; Table 4.10, Figure 4.10). The median difference in NPV between these scenarios was only $7,901, indicating solutions exist for those who are proactive in ensuring replacement females are not contributing to the problem. In contrast, even in herds with a low-grade infection (1.5% prevalence) the median NPV was $107,528 lower for the least profitable approach of testing and retaining heifers compared to being Johne's free.

Table 4.7: Net present value for 10-years by initial Johne's prevalence

Johne's prevalence [a] (%)	NPV ($) [b, c]		
0	$	322,120	(296,603-344,854)
1.5	$	265,188	(201,735-327,311)
7	$	239,656	(99,747-320,744)

[a]: initial true prevalence of Johne's infected cattle at model initiation b median of 1000 iterations with 5th and 95th percentile in parenthesis; [c] discount rate of 7.5%

Table 4.8: Net present value for 10-years by source of replacement breeding females

Source of female replacements	NPV ($) [a, b]		
External mature cows	$	276,570	(231,629-332,825)
Internal heifer retention	$	235,941	(102,685-332,818)

[a] median of 1000 iterations with 5th and 95th percentile in parenthesis; [b] discount rate of 7.5%

Table 4.9: Net present value for 10-years by testing freqency and performance

Testing frequency and performance	NPV ($) [a, b]		
No testing	$	310,786	(220,636-340,355)
Annual testing with perfect test sensitivity	$	253,418	(108,808-287,206)
Annual testing with commercial ELISA test	$	232,172	(102,685-270,668)

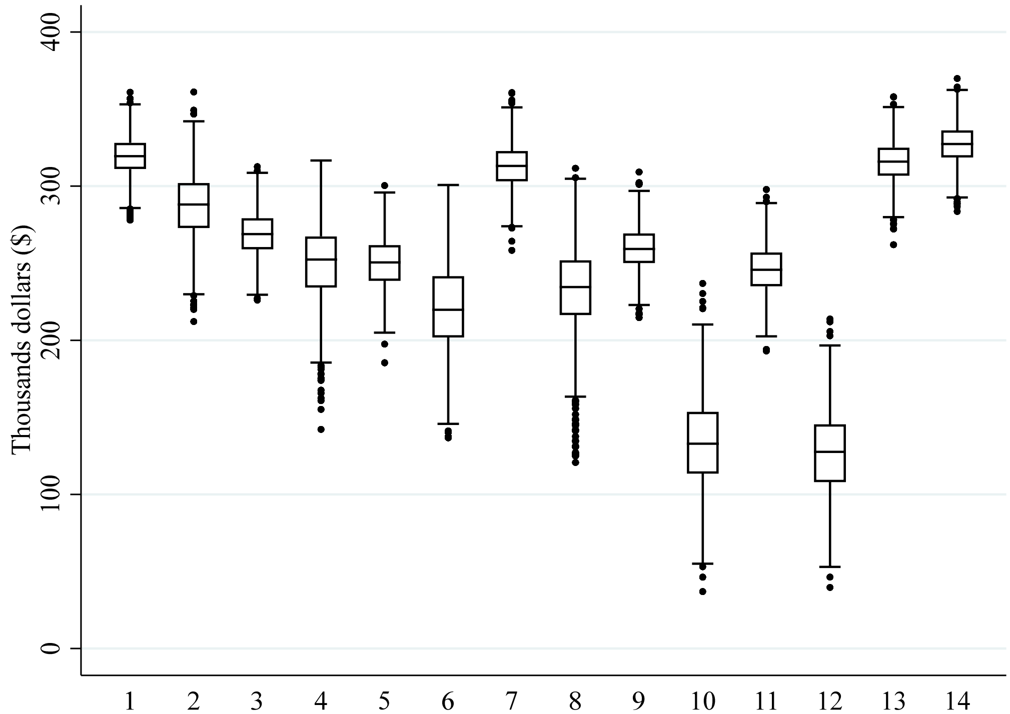
[a] median of 1000 iterations with 5th and 95th percentile in parenthesis; b discount rate of 7.5%

Table 4.10: Net present value for 10-years by initial Johne's prevalence, testing strategy, and replacement female source

Sce-nario	Johne's prevalence [a] (%)	Testing frequency [b]	Test sensitivity [c]	Replacement female strategy [d]	NPV ($) [e,f]	
1	1.5	no testing	n/a	external mature cows	$ 319,394	(295,513-342,441)
2	1.5	no testing	n/a	internal yearling heifers	$ 288,079	(249,010-323,954)
3	1.5	annual	perfect	external mature cows	$ 268,866	(246,039-293,604)
4	1.5	annual	perfect	internal yearling heifers	$ 252,400	(202,790-290,283)
5	1.5	annual	commercial ELISA	external mature cows	$ 250,455	(221,609-277,056)
6	1.5	annual	commercial ELISA	internal yearling heifers	$ 219,767	(173,379-268,277)
7	7	no testing	n/a	external mature cows	$ 313,130	(288,213-337,163)
8	7	no testing	n/a	internal yearling heifers	$ 234,504	(175,407-280,833)
9	7	annual	perfect	external mature cows	$ 259,204	(236,322-283,644)
10	7	annual	perfect	internal yearling heifers	$ 132,876	(84,409-184,850)
11	7	annual	commercial ELISA	external mature cows	$ 245,752	(220,562-271,898)
12	7	annual	commercial ELISA	internal yearling heifers	$ 127,644	(81,811-170,935)
13	0	no testing	n/a	external mature cows	$ 315,909	(293,789-336,973)
14	0	no testing	n/a	internal yearling heifers	$ 327,295	(305,903-348,689)

[a:] initial true prevalence of Johne's infected cattle at model initiation (%); [b] frequency of testing of cows >2 years and all bulls; [c] Test performance on samples from infectious, subclinical cattle; [d] source and age of replacement females; [e] median of 1000 iterations with 5th and 95th percentile in parenthesis; f discount rate of 7.5%

Figure 4.10: Distribution of estimated net present values over 10-years by initial Johne's prevalence, testing strategy, and replacement female source



Scenario	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Prevalence [a]	1.5	1.5	1.5	1.5	1.5	1.5	7	7	7	7	7	7	0	0
Testing [b]	no	no	yes	yes	yes	yes	no	no	yes	yes	yes	yes	no	no
Test performance [c]	-	-	P	P	C	C	-	-	P	P	C	C	-	-
Replacements [d]	EC	IH	EC	IH	EC	IH	EC	IH	EC	IH	EC	IH	EC	IH

[a] initial true prevalence of Johne's infected cattle at model initiation (%); [b] Annual testing of cows >2 years and all bulls; [c] Test performance on samples from infectious, subclinical cattle; P = perfect test sensitivity, C = commercial ELISA sensitivity; [d] Female replacement source; EC = external mature cows. IH = internal heifer retention

To help illustrate the factors affecting profitability median annual revenues and expenses were presented graphically for the two scenarios with the highest and lowest NPV, respectively, when Johne's was present (Figures 4.11 & 4.12). The highest median NPV was found when a low initial prevalence of Johne's occurred with no testing and mature replacements. These herds maintained annual calf sales above $300,000 and had relatively consistent cull breeding stock sales and breeding stock purchases over the years

(Figure 4.10). Expenses climbed annually due to inflation in operating expenses. In comparison, the lowest median NPV was found when a high initial prevalence of Johne's disease occurred with use of the commercial test and internal heifer retention. In these herds, median revenues from calf sales declined by over $100,000, while breeding stock sales rose to equal calf sales (Figure 4.11). Herds in this scenario were eroding their productive base and causing losses to increase. Total expenses were held relatively stable due to the decline in the breeding herd size. Testing cost was included to demonstrate the insignificance of this line item, despite it being cited as a barrier to monitoring.

Figure 4.11: Net cash position, gross revenues, and expenses for herds in a scenario considering a 1.5% initial prevalence of Johne's disease, mature external breeding stock retention, and no testing (scenario 1)

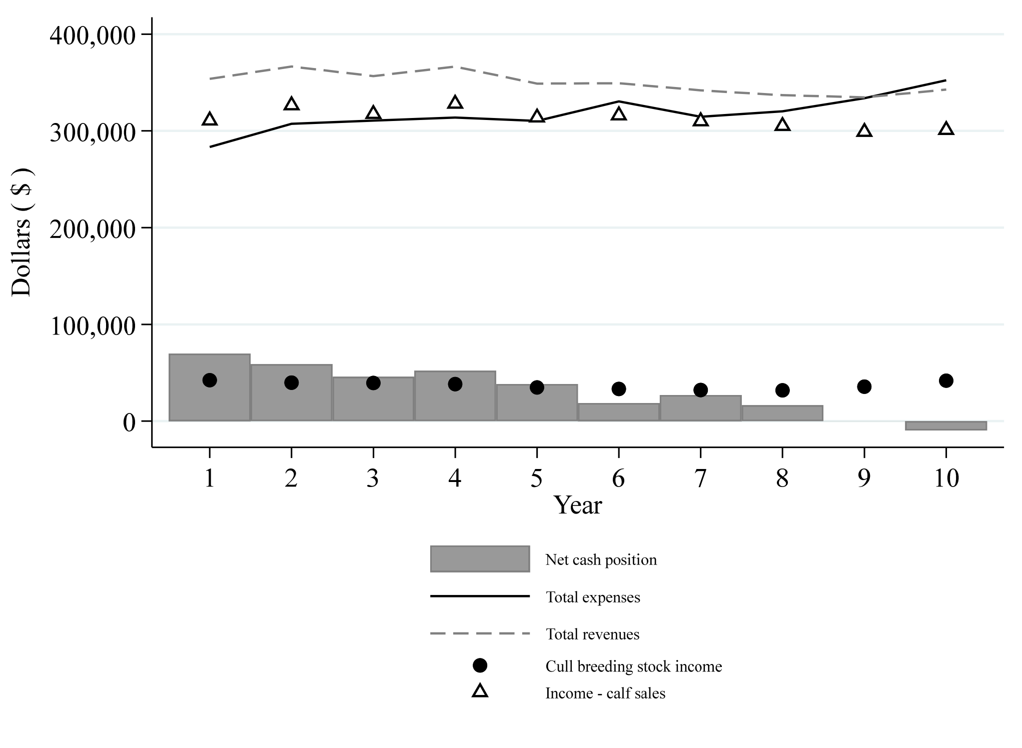
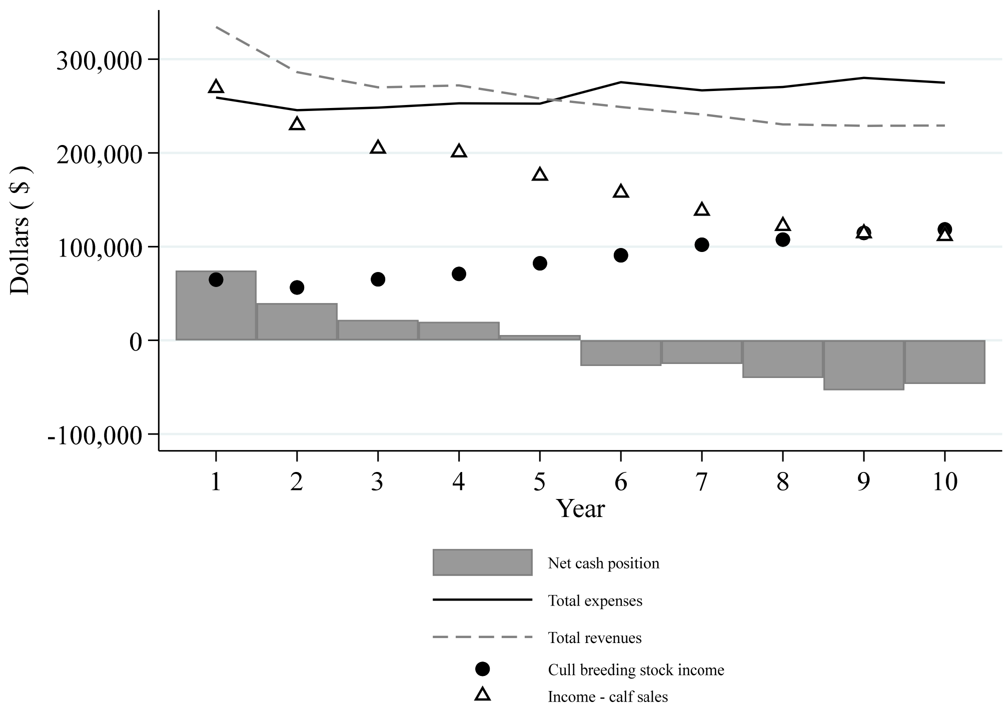


Figure 4.12: Net cash position, gross revenues and expenses for herds in scenarios considering a 7% initial prevalence of Johne's disease, internal heifer retention, and annual testing of mature cattle with commerical ELISA test (scenario 12)



4.5 Sensitivity Analysis

The dynamic ABM provided insight into the complexity of disease control decisions given testing uncertainty and random variation in disease transmission. In addition to addressing biological risk, producers seek to minimize financial risk. For this reason, the sensitivity analysis considered the effect on disease control recommendations with changing livestock markets and operating costs.

The estimated NPVs changed in the same direction as livestock prices, but the effect of changing livestock prices was not proportionate for all scenarios. The spread between the highest and lowest NPVs within each scenario widened when livestock prices rose from baseline and narrowed when livestock prices decreased from baseline. The NPV estimates were not normally distributed; all were skewed to the left. Using the median to rank the scenarios from highest NPV (1) to lowest NPV (14), seven scenarios switched rank when the livestock price changed (Table 4.11, Figure 4.13). While most scenarios changed by a single rank a single time, the scenario examining 7% initial Johne's prevalence with no testing and internal heifer retention was very sensitive to the livestock price, ranking 6/14 when livestock prices were decreased by 25%, but 12/14 when livestock prices increased by 10%. None of the top five most profitable choices changed rank over the prices considered.

Table 4.11: Rank[a] from hightest to lowest median NPV with adjustement to initial livestock market prices in year 1 and livestock markets in years 2 to 10 trendig according to USDA forecast and input prices increase at 2% annual inflation

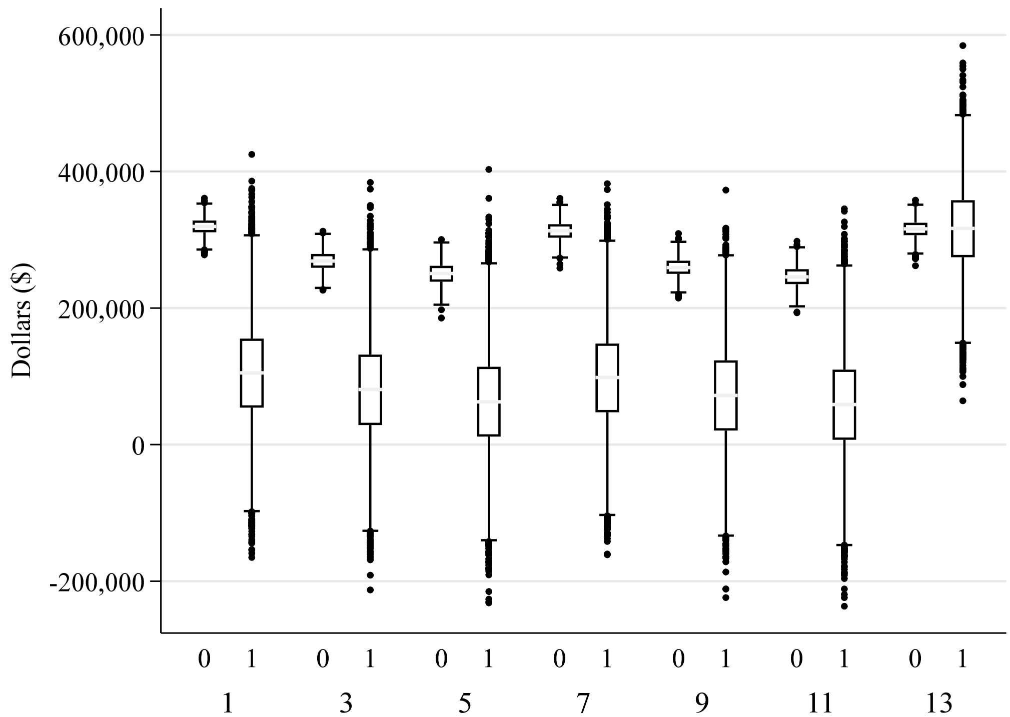
Sce-nario	Johne's prevalence [b]	Testing frequency [c]	Test sensitivity [d]	Replacement female strategy [e]	Rank [a]					
					-25%	-10%	0	+10%	+25%	Rank Change
1	1.5	no testing	n/a	external mature cows	2	2	2	2	2	no
2	1.5	no testing	n/a	internal yearling heifers	5	5	5	5	5	no
3	1.5	annual	perfect	external mature cows	7	6	6	6	6	yes
4	1.5	annual	perfect	internal yearling heifers	8	8	8	9	9	yes
5	1.5	annual	commercial ELISA	external mature cows	10	9	9	8	8	yes
6	1.5	annual	commercial ELISA	internal yearling heifers	12	12	12	12	11	yes
7	7	no testing	n/a	external mature cows	4	4	4	4	4	no
8	7	no testing	n/a	internal yearling heifers	6	10	11	11	12	yes
9	7	annual	perfect	external mature cows	9	7	7	7	7	yes
10	7	annual	perfect	internal yearling heifers	13	13	13	13	13	no
11	7	annual	commercial ELISA	external mature cows	11	11	10	10	10	yes
12	7	annual	commercial ELISA	internal yearling heifers	14	14	14	14	14	no
13	0	no testing	n/a	external mature cows	3	3	3	3	3	no
14	0	no testing	n/a	internal yearling heifers	1	1	1	1	1	no

[a:] Rank from highest NPV (1) to lowest NPV (14), [b] initial true prevalence of Johne's infected cattle at model initiation; [c] frequency of testing of cows >2 years and all bulls; [d] Test performance on samples from infectious, subclinical cattle; [e] source and age of replacement females;

The effect of variation in operating input costs on NPV was explored only for scenarios using external mature replacements because this replacement strategy was clearly superior to internal heifer retention in the presence of Johne's disease. Allowing the per unit cost of each input to vary by 20% independent of the other put prices resulted in a wider distribution of estimated NPV and a lower median estimate within each scenario but did not change the ranking by median NPV for most profitable testing strategy. While this sensitivity analysis did not alter the recommended strategy for Johne's control it highlighted the threat Johne's poses to economic viability. The scenario without Johne's performed as expected with a very similar median NPV to the baseline scenario and a balanced increased upside potential and downside risk with fluctuating input prices. In contrast, all scenarios with Johne's disease saw a marked decrease in the median NPV resulting in increased variance in NPV with minimal upside potential when input costs fluctuated (Figure 4.13). There was no notable change in ranking by median NPV when variable input prices were combined with variable livestock values.

Two of the most common objections made by producers and veterinarians with respect to Johne's monitoring are test cost and test performance. The NPVs for scenarios with mature replacement females were estimated using a perfectly sensitive and cost-free Johne's test. Under this assumption, herds with a low initial prevalence of Johne's, the NPV was almost equivalent (median \$318,807, 5^{th} to 95^{th} percentile, \$294,982 to \$342,792) to the NPV with no testing (median \$319,394, 5^{th} to 95^{th} percentile \$295,513 to \$342,441). The NPV of a free and perfectly sensitive test in herds with a high initial prevalence of Johne's was slightly lower (median \$308,266 to \$285,482 to 3330,66) compared to no testing (median \$313,230; 5^{th} to 95^{th} percentile, \$288,213 to \$337,163) when external mature replacements were used. This sensitivity analysis suggests that future research should consider the feasibility developing testing methods that could detect latently infected cattle rather than investing in improving the test sensitivity in subclinical cattle. In the meantime, future models could evaluate the feasibility of more frequent testing in younger animals to shorten the time to detection of subclinical shedding stock.

Figure 4.13: Distribution of estimated net present values with baseline input costs (0) and variable input costs (1) over 10-years by initial Johne's prevalence, testing strategy, with external mature bred cows purchased as replacements



Scenario	**1**	**3**	**5**	**7**	**9**	**11**	**12**	**13**
Prevalence [a]	1.5	1.5	1.5	7	7	7	7	0
Testing [b]	no	yes	yes	no	yes	yes	yes	no
Test performance [c]	-	P	C	-	P	C	C	-
Replacements [d]	EC	EC	EC	EC	EC	EC	IH	EC

[a] initial true prevalence of Johne's infected cattle at model initiation (%); [b] Annual testing of cows >2 years and all bulls; [c] Test performance on samples from infectious, subclinical cattle; P = perfect test sensitivity, C = commercial ELISA sensitivity; [d] Female replacement source; EC = external mature cows. IH = internal heifer retention

CHAPTER V: DISCUSSION

Johne's disease can insidiously establish and spread in a beef herd due to the prolonged contact between cow and calf and the long infectious, but subclinical phase of the disease with negative economic consequences. In order to proactively limit the spread of Johne's disease in western Canadian beef herds, industry awareness of clinical signs, risk factors for spread, and optimal control strategies are needed. Therefore, most pressing outcome to communicate from this research is that Johne's can be controlled at a very low economic cost through proactive culling and minimizing ongoing transmission from high-risk replacement stock.

The two initial infection levels tested represent the range of within herd prevalence rates observed in the Saskatchewan Stock Growers Association surveillance project (Wilkins 2019a). Consistency in the recommended test and replacement strategies, regardless of initial prevalence, suggest these recommendations hold for most Johne's positive herds in Saskatchewan. Producers with infection rates above these levels or with substantially different management practices than described in the agent-based model should be cautious in applying these recommendations. The main value from comparing a low and high initial prevalence of Johne's disease was determining that the most profitable control strategy was consistent, but amplified with increasing prevalence of Johne's disease.

Under these research assumptions, the most profitable approach to Johne's control in a cow-calf operation was through consistent culling of clinical animals without testing provided the replacement breeding stock have a low rate of Johne's infection. Although it is not commonly practiced, producers could purchase bred cows conditional on negative Johne's test results. This risk mitigation strategy only applies to mature females as infected bred heifers would likely still be in a latent infective stage and undetectable with current diagnostic tests. This option was the reason why strict purchase of mature bred cows was considered in these scenarios.

Producers with positive cows in the herd should be aware of the high risk posed by retaining heifers as replacements. Internal retention in an infected herd created a positive feedback loop: infected heifers caused increasing rates of Johne's infection in the cow herd which subsequently increased the infection rates in the heifer calves available as replacements. Positive herds with internal heifer retention faced growing losses due to culling Johne's positive cows and eventually insufficient heifer calves to maintain the breeding herd.

Improvements to cow longevity, productivity, and efficient use of inputs are fundamentally important for profitability in cow-calf production. The cost to replace prematurely culled Johne's positive cows, which were predominantly young and in good body condition, negatively affected profitability. A typical beef cow produces five calves and cows can remain productive well into their mid-teens (Damiran 2018). Prior to analysis, we hypothesized testing would lead to increased profitability because the herd would become progressively healthier with resultant improvements in cow longevity. Following analysis, it appears that a blanket approach to culling sub-clinical infective cows it too costly. Instead, weaning as many calves as possible before culling is necessary to recoup the purchase or replacement heifer investment which were either directly incurred through the purchase of mature bred cow or indirectly incurred by foregoing the profits from weaning heifers and incurring the cost of heifer rearing.

Under the market assumptions the replacement to cull price spread averaged ~$800 per cow. Test positive cows were culled and replaced on a set schedule that did not account for within year livestock price variation. Most producers seek to maximize returns by manipulating this timing, but the effect of capturing seasonal market fluctuation was not included as it was considered imprudent to develop a strategy in which producers would not immediately cull known positive cows. Further, the bred to cull price spread was conservative given the assumption that the replacement stock were "good quality" as indicated both by the low Johne's infection rate and an equivalent ongoing probability of culling existing cows in the herd. It seems likely that any gains made in modeling the cull market cycle could easily be offset by accounting for quality differences between purchased and in-herd stock. Although not specifically tested, the results suggest the profitability difference between testing and no testing widens with the bred to cull spread, but narrows with superior performance or longevity in the replacement stock.

Herd performance can be improved through a genetic program. The retained heifers were selected randomly from the available weaned female calves and the genetic potential and productivity of the cattle did not change over time. In practice, producers use selection to retain the best heifers which represents an intangible investment in genetic improvement that cannot be cost effectively replicated when buying mature bred cows. Genetic improvement, and its subsequent effect on livestock value and/or performance, could be incorporated via expected progeny difference (EPD) parameters linked to agents. Both the probability of transmitting a trait and the degree of expression could be incorporated to value herd improvement programs concurrently targeting genetics and health.

Herd improvement can also occur through improved efficiency of input use. The per-unit use of inputs was held constant across time and between scenarios, but the quantity consumed changed with the population present over time. Describing input efficiency as the cost per AUD accounted for differences in the population structure. The total operating expenses were higher for herds with external mature replacement because herds in these scenarios had larger populations consuming resources. Thus, the cost per AUD was lower which contributed to improved profitability. All of the scenarios ended the ten-year model in a negative annual net cash position because the USDA forecast is premised on continued productivity improvements in the industry. It is assumed that the beef industry will remain viable in ten-years, emphasizing the importance of including improved performance in future iterations of the model. Unlike gains in performance, this would primarily be achieved through adjustments to the economic assumptions.

The recommendation to not test for Johne's was consistent with previous research in beef cattle in Australia, but contradicted research from Great Britain (Bennett 2012; Webb Ware 2012). The Canadian and Australian industries are more similar with respect to extensive animal management with export-focused markets. Further, the difference in recommendations from the British study may partially be attributed to including intensive on-farm management with testing. Our recommendations could plausibly change if the effect of improved calving-area hygiene or shifting to summer calving on grass were considered. While this could be an area for future research it was beyond the scope of the current study and was not prioritized on the assumption that factors other than Johne's control have more influence on major operational decisions.

This study highlighted many opportunities for veterinary intervention to improve the outcomes in a Johne's infected herd. Veterinarians have a role in advising clients on the relative risks associated with different replacement female sources. The scenarios exploring internal heifer retention illustrated that a risky replacement strategy can be highly impactful on profitability but it is concurrently important to remember there is no risk-free source of replacement stock. The Johne's disease model assumed mature cows had a 1.5% probability of infection when purchased. Producers who purchase mature bred cows can do so through direct farmgate sales, dispersal sales, or bred cow auction. The rate of Johne's disease infection could differ between these sources. It behooves producers to be discriminant about the source and health status of cows purchased. Vet-to-vet consultations regarding the health status of purchased cattle remains uncommon in the western Canadian beef industry, but personal experience indicates most producers and veterinarians are willing to engage in this practice. The industry should be encouraged to increase this practice while reducing purchases of cows of unknown source or health status as is common at bred cow auctions.

Purchasing external breeding stock can create other disease introduction risks which were beyond the scope of the model. It is possible that a risk-based heifer selection strategy designed to minimize the probability of retaining or purchasing positive heifers could alter the recommendation to only purchase external mature females. Alternatively, it would be worth examining the highest threshold of Johne's disease at which internal heifer retention was more profitable than purchasing external mature replacements and then comparing the year-ten prevalence in such a model to the 1.5% infection rate considered as the low-level initial prevalence in order to determine if this approach could be sustainable. This exercise would help determine if there are situations in which internal heifers could be most profitably retained with minimal risk without complete Johne's eradication.

The findings of this study were premised on consistent early culling of clinical cows. The low within herd prevalence of Johne's disease means that producers may lack confidence in making an early clinical diagnosis which could lead to delayed culling. Future models could consider the effect of delayed culling of clinical cases on the most profitable protocol. In the meantime, veterinarians can prioritize education about early detection in herds with high-risk practices and producers can develop a standard practice to minimize bias and emotion from their actions when a clinical case is suspected. Although not explored in this study, investing in an isolation area that could be feasibly maintained with good biosecurity would allow producers to concurrently mitigate the risk from early clinical cases and the possibility of unnecessarily culling a productive cow. Funding to offset 50% of the investment for an isolation area is currently available to Saskatchewan producers participating in the Verified Beef Production Plus program (Verified Beef Production Plus 2021).

This Johne's model was useful for informing strategic investment in research for improved diagnostic tests. The scenario of a test with perfect sensitivity and specificity helped quantify the losses attributable to the current inability to reliably detect subclinical and infectious cows. Perhaps surprisingly, profitability was not improved when a perfect test was used. The fictitious perfectly sensitive test did not have improved performance in identifying latently infected pre-clinical cows rather its ability to detect low-shedding subclinical cows was modeled as equivalent to the available commercial test. Exploring the effect of an improved test that could be used on young animals, ideally at selection of replacement breeding stock, would be insightful to indicate if research in this area would be worthwhile.

Combining agent-based models, epidemiology, and economics is a relatively new research approach in animal health research. The principles in this study brought and combined their experiences and expectations from diverse scientific disciplines which resulted in an untraditional approach to developing the test scenarios. Biological studies often include a control while simulation modeling is less likely to do so. Including the scenarios with no Johne's in the herd as a proxy for a negative control was valuable because it demonstrated the validity of the model. Without Johne's disease, the estimated NPV was higher when heifers were retained than when external breeding stock were purchased, even despite the slightly smaller breeding herd. This result reflects the common industry retention practice. This strategy was the most profitable because the operating costs to raise replacement stock were lower than the cost to purchase replacement cows. Herd improvement from retaining the best heifers from an intentional genetics program would have further emphasized this difference. To the author's knowledge this combination of an agent-based model with production economics was novel for considering control recommendations to the Canadian beef industry for any production limiting disease. Every model has limitations because it is a simplified representation of reality. Limitations were present in both the agent-based disease transmission model and the economic model used in this study, but the following is limited to a discussion of limitations in the economic models as the primary objective was the application of financial analysis through a NPV model to the dynamic disease model output.

Recommendations were based on NPV because it accounts for the timing of losses and profits in a long-term disease control program. However, not all producers are familiar with this approach and many make short term decisions based on annual net cash flow. It was for this audience that revenues, expenses, and annual net cash were reported. In an enterprise model, the retained heifer calves would have been valued at weaning and again at transfer into the breeding herd and the paired in and out transactions would balance between enterprises. In this project, the cattle herd was considered a single enterprise because the breeding herd demands dictated the number of heifers to retain. This limited the ability to directly compare annual revenues and expenses between the scenarios with different female retention strategies. This limitation was considered acceptable for three reasons. First, the partial budget model did not include all operational expenses nor did it include revenues from other profit-centers such as feed production or land rent because the model was not intended to be used for whole enterprise decision making. Second, the reported revenues and expenses served primarily to illustrate the net effect of Johne's on annual cash flow given changes to the population structure. Finally, the only effect of the revenues and expenses on the recommended strategy was as inputs into the NPV calculation.

Another limitation of the model was not directly accounting for cow depreciation. Brealey defines depreciation as "(1) Reduction in the book or market value of an asset; (2) portion of an investment that can be deducted from taxable income." (Brealey 2017, p. G-6). Livestock market values and replacement heifer development costs were included instead of cow depreciation because a deprecation rate would require assumptions about lifetime productivity which were the focus of the research question.

The general recommendations from this project held over a range of livestock prices. The spread in NPVs between scenarios increased as livestock markets rose meaning the magnitude of losses from sub-optimal disease management changed with livestock markets, but the optimal choice does not change. The recommendations also held when input prices for operating expenses, breeding stock, and testing costs fluctuated. The distribution of NPVs within scenarios with either variation in livestock prices or variation in input costs was much greater than the difference in NPV between control scenarios: Other herd management decisions including strategic marketing of livestock and managing operational costs have a far greater effect on profitability than Johne's control decisions. Ideally, future iterations of this model will allow producers to run customized scenarios to better reflect their operating practices, cost of production, and marketing strategy.

This study did not estimate the cost of Johne's disease in a Western Canadian herd and should not be interpreted as such. The partial budget approach limited the variables modeled to those involving herd management affected by the disease control decisions and is an under-estimation of the total costs associated with this disease. In a traditional NPV model, assets are sold at the end of the project. The cost of Johne's would be substantially higher than estimated here due to the opportunity cost of being unable to sell breeding stock from herds with a reputation of Johne's. This would be most impactful for a commercial operation at the time of herd dispersal.

CHAPTER VI: CONCLUSIONS

The most important take away from this study is that cow-calf operations in western Canada can economically control Johne's disease through aggressive, early, consistent culling of clinical animals provided these animals are replaced with breeding stock that have a low rate of Johne's infection. This project was undertaken because the prevalence of Johne's positive herds is rising in Saskatchewan and the disease is present in both commercial and seedstock operations. The Saskatchewan Stock Growers Association has managed a surveillance and control program with funding from the Saskatchewan Ministry of Agriculture. This research will help to ensure this surveillance investment has maximum effect.

While this study found that no testing and external replacements was the optimal control choice, the recommendation to not retain heifers will be unacceptable to many producers. Further investigation into more strategic approaches to minimize the risk from heifer calf management, selection and testing are required. Future research could explore risk-based testing, testing more frequently through the year, and segregating breeding animals by risk and selecting heifers from low-risk groups. All of these strategies can be easily tested by the agent based model and economic models developed. Given the majority of seedstock and commercial producers retain heifers, further research is warranted to identify control and testing practices that are economically and biologically optimal.

This study's findings are premised on continued ability to purchase replacement animals with a low probability of being infected with Johne's at market prices. To date, this has been the case, but uncontrolled spread in western Canada could create an industry situation analogous to the internal heifer retention problem. If Saskatchewan's beef industry is serious about controlling Johne’s disease, education is needed about the risks associated with retaining heifers in Johne’s positive herds and the need to aggressively cull or isolate suspicious cows.

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