

THE ECONOMIC IMPACT OF BOVINE LEUKEMIA VIRUS ON MICHIGAN DAIRIES

By

Drew Frommelt

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

Agricultural, Food and Resource Economics –Master of Science

2023

ABSTRACT

Bovine Leukemia Virus (BLV) is a zoonic virus that attacks the immune system of bovine (cows) and can lead to the development of bovine leukosis, lymphoma and lymphosarcoma. BLV can impact the productivity, longevity, and welfare of dairy cattle (Bartlett et al., 2014) and persists in over 94% of dairy operations in North America with an average herd prevalence of 46% (LaDronka et al. 2018). Our research project utilizes farm and cow level financial, production and biological data from four Michigan dairy farms over the span of five years to test for differences in partial profit across cows infected and not infected with BLV. Economic evaluations were based on a partial profit equation where we hold constant all revenues and costs not impacted by BLV. Each component of the partial profit equation is calculated using farm financial invoices and receipts, and production and biological data from each production year. Next, we used fixed effects regression analysis with the unbalanced panel dataset where we determined that BLV positive dairy cows had lower partial profit than BLV negative cows. Finally, through a sensitivity analysis on key partial profit input variables a range of partial profit loss for BLV positive cows was estimated to be between \$198.34 and \$496.76 per cow per lactation. The estimated loss in partial profit for BLV positive cows is greater when partial profit is calculated with energy corrected milk, which accounts for milk merit via fat and protein percentages, showing that BLV infection may have a greater negative impact on milk components such as fat and protein more so than total milk production. Given these estimates, for an average Michigan dairy herd of 550 cows and 46% herd BLV prevalence, we would expect an annual loss between \$50,180.02 and \$125,680.28 due to BLV infection.

ACKNOWLEDGEMENTS

First and foremost, I would like to thank my advisor and committee chair Dr. Melissa McKendree for all the support and guidance as a fantastic mentor throughout my master's program and vital co-collaborator on this thesis project. I would also like to thank fellow committee members Dr. Tasia Kendrick and Dr. Scott Swinton for the assistance and input on this project. This project would not have been possible without all the hard work and dedication Dr. Kendrick has shown to BLV research.

I would also like to thank MSU extension collaborators Phil Durst and Stanley Moore along with all the producers that participated in this study. Each one of you provided your passion and knowledge for dairy and BLV, and helped shaped what this research project has become, you all helped me gain a passion for dairy I hope is at least somewhat as strong as yours.

Finally, I would like to thank my family, mom, dad, and Maya for your endless emotional support throughout the last two years. It was certainly not easy, but you all gave me the unconditional love and support I needed to make it where I am today.

TABLE OF CONTENTS

1. INTRODUCTION.....	1
2. THEORETICAL MODEL	5
3. METHODS AND DATA.....	7
4. EMPIRICAL MODEL	29
5. RESULTS	32
6. IMPLICATIONS AND CONCLUSION	65
BIBLIOGRAPHY	68
APPENDIX A. LIST OF MEDICINES AND THEIR ASSOCIATED COSTS USED IN HEALTHCARE TREATMENT CALCULATIONS.....	71
APPENDIX B. DEPRECIATION TABLES	72
APPENDIX C. ONE-WAY ANOVA TESTS	79
APPENDIX D. REGRESSION OUTPUT TABLES.....	81

1. INTRODUCTION

Bovine Leukemia Virus (BLV) persists in over 94% of dairy operations in North America with an average herd prevalence of 46% (LaDronka et al. 2018). BLV is a retrovirus that attacks the bovine immune system and can lead to the development of harmful diseases such as lymphocytosis and lymphosarcoma. Up to 40% of all dairy cattle infected with BLV will develop lymphocytosis (Bartlett et al. 2014). BLV infection can have a negative impact on dairy cattle productivity, longevity, and welfare (Bartlett et al. 2014). Losses in productivity and shortening of herd longevity could lead to a decrease in the expected lifetime profitability of dairy cows. Another problematic aspect of subclinical BLV infection is that it can lead to an abnormal immune response by uninfected cells (Frie & Coussens 2015).¹ This can potentially make it more challenging for dairy cows to fight off other infections, leading to an increase in on-farm healthcare costs, breeding costs, and veterinarian costs.

Managing and mitigating BLV prevalence may be crucial for dairy farmers to produce milk at a level that creates sustainable profits, as well as deliver humane products to consumers. In the past 20 years, there have been tight margins and low profitability in the dairy industry (Salfer 2021), resulting in many small and medium sized farms exiting and industry consolidation. The total number of dairy farms have decreased from 650,000 in 1970 to 40,000 by 2017, and the average herd size increased from 100 to 900 head from 1980 to 2012 (Hennessy & Feng 2018). Potentially, BLV could be a contributing factor as to why profit levels are difficult to sustain given its link to increased breeding and healthcare costs as well as milk and carcass weight loss (Kuczewski et al. 2019). Our study will investigate whether BLV has any impact on profitability when considering costs such breeding and healthcare.

Utilizing farm level production, biological and financial data from four Michigan dairy farms from 2017 to 2022, this study aims to understand how BLV infection, and differing levels of BLV provirus loads (PVL) impact the profit of milking dairy cows, on a per cow basis. BLV infection status (positive, negative, or suspect) was collected using BLV enzyme-linked immunosorbent assay (ELISA) antibody status test, which tests for BLV antibodies in the milk

¹ Subclinical is defined as a disease that is not severe enough to present definite or observable symptoms (Merriam- Webster)

of individual cows. If a cow's ELISA test was positive or suspect, it was followed with a polymerase chain reaction (PCR) assay, collected through blood samples, to measure the level of PVL in infected cattle. We posit that ELISA BLV positive cows will have lower partial profit than ELISA BLV negative cows, on average, and that the magnitude of partial profit loss will be negatively correlated to the level of PVL of ELISA BLV positive cattle.

The literature on BLV has mainly focused on pathways for BLV infection, the implications of immune system deficiencies that result from infection, as well as options for controlling and mitigating the virus. An early study on BLV attempted to classify the virus biochemically to determine how it behaved in a host relative to other viruses of a similar biological makeup (Kettmann et al. 1976). Hopkins and DiGiacomo (1997) investigated the routes of transmission for bovine leukemia virus, finding that a small portion of transmission came vertically through cows *in utero*, and milk and colostrum, and a large portion of transmission of BLV came horizontally through blood contact that happens due to the living conditions of beef and dairy cattle. Studies such as Bartlett et al. (2014) explored options for BLV control and mitigation, finding that if producers decide to control and mitigate BLV, the options for control should be determined by the within herd prevalence of BLV, and that herd prevalence would inform how aggressive of a mitigation strategy should be used.

Economic estimates on the impacts of BLV have previously been made. Only one of these studies used individual cow level data, but consistently past studies have found negative economic impacts from BLV infection. Specifically, Pelzer (1997) theorized that costs such as increased feed, healthcare treatments and breeding costs, and reduced milk production, would need to be estimated before considering if and what BLV control strategy to implement on the farm. Rhodes et al. (2003) modeled the costs of both clinical (lymphosarcoma) and subclinical BLV infection at the farm level, using assumptions over what costs would be impacted most by BLV and estimating the distribution of these cost variables. Rhodes et al. (2003) found that it would be economically beneficial to implement BLV control measures on any farm with a BLV herd prevalence of 12.5% or greater, but noted this could vary given farm specific factors. Ott et al. (2003) modeled the effect of BLV infection on the annual value of production at the herd level of 112 Michigan dairy herds, by comparing herds that had any prevalence of BLV and BLV negative herds. The annual value of production considered milk revenue, value of calves at

birth and net replacement costs. This study found an average decrease of \$59 per cow in annual value of production on herds with BLV positive cows with the loss mainly due to reduced milk production. Kuczewski et al. (2019) created a partial net revenue equation based on assumed costs and revenues of dairy cattle in Canadian dairy herds to estimate the net benefits of four unique BLV control strategies. This study assumed that BLV infection decreased milk production, cow longevity, and increased carcass condemnation rates. Kuczewski et al. (2019) found that BLV positive cows generated Can\$635 less than BLV negative cows on a yearly basis. Furthermore, they found that any of the four suggested control strategies – colostrum management, test and cull, test and segregate, and all management strategies, when implemented on a farm with BLV present in the herd, yielded positive net benefits after a 10-year time period. Nakada et al. (2022) used historical cow level culling, carcass weight, and BLV testing data from Japan to estimate the economic losses attributed to carcass weight loss induced by BLV infection. This study found that high PVL infected cattle had an average carcass weight loss of 30.4 kg, when compared to BLV negative cattle. They also found that in 2017, in their study region of Hokkaido, Japan, the total economic losses from carcass weight loss from 73,650 cows, due to BLV infection, was \$1,391,649 USD. To our knowledge, Nakada et al. (2022) was the first published study to estimate the economic impact of BLV infection using cow level data.

Our study contributes to the literature in four ways. First, we estimate the economic impact of BLV by utilizing farm level **per cow data**, including BLV testing and biological data along with associated financial data. While both Rhodes et al. (2003) and Kuczewski et al. (2019) found increased on-farm costs associated with BLV infection, informing the hypothesis and research questions made in this study, both studies lack accuracy in their estimation by not including actual farm level and cow level data. Both studies rely on numerous assumptions to estimate the economic impacts of BLV such as assuming the loss in the milk production and culling revenue. Estimating the economic impact of BLV at the herd level as was done in Ott et al. (2003), rather than the cow level, which also leads to a loss in estimation accuracy as many determinate factors are not considered, especially the effect of BLV over multiple lactations in the milking herd. For instance, the profitability effects of a positive BLV infection on a single cow could change from the cow's first lactation to their fourth. As such, the second contribution of our study is analyzing trends in the effect of BLV on profitability

and longevity over time while controlling for time variant factors such as the production year (2017 to 2022) and the cows' parity (first lactation to greater than fifth lactation). Third, we test the effects of BLV infection on partial profit as a function of milk pounds, but also energy corrected milk, accounting for merit of the milk, via fat and protein percentage. No other study analyzing the economic impacts of BLV has investigated how BLV impacts energy corrected milk, yet milk merit is a key function of the milk revenue a farmer receives. A fourth contribution in our study is the use of ELISA and PCR testing to determine a potential link between BLV infection and economic losses. PCR testing allows us to test for differences in profit by the level of provirus copies in each infected cow.

The U.S. dairy industry has had ongoing discussions over whether to invest in BLV mitigation. Many point to a lack of substantial evidence that BLV impacts the bottom line of dairy production. However, other countries like those in western Europe and New Zealand have taken drastic measures to eradicate BLV such as implementing a testing and culling mitigation program (Kuczewski et al. 2019). Our study is germane to this industry debate as it will be the first to estimate the profitability impact of BLV using cow level data.

2. THEORETICAL MODEL

To measure the economic impact of BLV on a per cow level, we will use a partial profit equation where all revenues and costs assumed to not be impacted by BLV are fixed. Dairy production has many inputs and associated costs, which makes modeling the full profitability equation complex and unfeasible given data constraints. Using a partial profit allows us to simplify to the costs and revenues that previously studies have postulated are most impacted by BLV infection. Previous studies such as Rhodes et al. (2003), Kuczewski et al. (2019), and Bartlett et al. (2014), assumed that healthcare, breeding, feed, and veterinarian costs would all increase and milk production, carcass weight and herd longevity would decrease, because of BLV infection. Our study will build on the assumed impacts of BLV infection investigated in previous studies by including two novel opportunity costs for forgone milk production through both the cost of staying in a lactation longer than average and being culled earlier than average. We assume that BLV impacts one revenue source – milk revenue – and five costs – health care, breeding, depreciation, the opportunity cost of less productive days, and the opportunity cost of being culled earlier than average. Reduced longevity has been a well-documented impact of BLV infection (see Bartlett et al., 2014). We account for potential longevity differences in the partial profit equation through depreciation and the opportunity cost of early culling. We also run our own survival analysis, separate from the partial profit equation.

The partial profit for cow i on farm f in production year t is:

$$\begin{aligned}
 \textbf{Partial Profit}_{ift} &= \text{Milk revenue}_{ift} - \text{Healthcare costs}_{ift} - \text{Breeding costs}_{ift} \\
 &\quad - \text{Depreciation}_{it} \\
 &\quad - \text{Opportunity cost of fewer productive days}_{ift} \\
 &\quad - \text{Opportunity cost of early cull}_{ft}
 \end{aligned} \tag{1}$$

Following Rhodes et al. (2003), Ott et al. (2003), and Kuczewski et al. (2019), we hypothesize that cows which test ELISA positive for BLV will have a lower partial profit than cows that test negative for the virus. We will indicate BLV status as $V = \{0,1\}$ where 0 is BLV negative and 1 is BLV positive. Specifically, we test the hypothesis that the partial profit for cows that are infected with BLV (positive; subscript 1) is different than cows that are not infected with BLV

(negative; subscript 0):

$$\begin{aligned}H_0: & \textit{Partial Profit}_{1ift} = \textit{Partial Profit}_{0ift} \\H_a: & \textit{Partial Profit}_{1ift} \neq \textit{Partial Profit}_{0ift}\end{aligned}\tag{2}$$

3. METHODS AND DATA

Next, we will describe the farm and cow level data sources and the methods used to calculate each part of the partial profit equation. Data were available at different aggregation levels and for different time periods. In the sections below we will describe how the data was aggregated to create an unbalanced panel with a cow having one observation per lactation/production year.

3.1 Farm and herd descriptions

This study was considered exempt by the Human Research Protection Program at Michigan State University (STUDY00006291). There are four farms enrolled in this study. The farms will be referred to as farm A, B, C, and D. Each farm is in the state of Michigan and BLV has been detected in their milking herd.

Observations and BLV prevalence by farm and production year are in Table 1. Farm A currently operates a 550 head milking herd with roughly 600 replacement heifers. This farm's milking herd has a BLV prevalence of approximately 46% (meaning 46% of the cows in the herd tested positive for BLV). Farm B is a smaller farm with a milking herd of 260 head and 230 heifer replacements. The herd on farm B has a BLV prevalence of approximately 56%. Farm C has the largest milking herd of any farm participating in the study with over 1100 head in the milking herd and 1500 replacement heifers. Farm C has a BLV herd prevalence of 30%. Finally, Farm D has a milking herd of approximately 223 head with the highest BLV prevalence of the four farms in the study at 59%. Every farm in the study has implemented some BLV management practices. Every farm has implemented the practice of switching out gloves and needles during medical examinations and healthcare treatments. Farm D uses BLV-free colostrum to feed calves and heifers. Farm B feeds calves and heifers colostrum replacer.

There were 3,693 cows in this sample, with cows remaining in the panel for one to five years resulting in a total of 6,796 individual observations (per cow per lactation). Each cow in the study has a unique *COWID* that differentiates it from its herd-mates and cows from the other farms in the study. The lactation number varied where 31.34% were first lactation cows, 32.08% were second lactation cows, 18.92% were third lactation cows, and 17.66% of cows were in their fourth or higher lactation.

Table 1: Observations and herd BLV prevalence by farm and production year

Production year	Farm	A	B	C	D
2018	Cows	n=249	-	n=606	-
	BLV	49.8%		26.7%	
	Prevalence				
2019	Cows	n=391	-	n=1100	-
	BLV	49.6%		28.5%	
	Prevalence				
2020	Cows	n=461	-	n=801	n=153
	BLV	44.9%		28.5%	54.9%
	Prevalence				
2021	Cows	n=376	n=136	n=881	n=125
	BLV	38.8%	55.9%	19.5%	44.8%
	Prevalence				
2022	Cows	n=441	n=255	n=623	n=99
	BLV	36.1%	72.6%	16.9%	62.6%
	Prevalence				

Table 2: Observations and BLV herd prevalence by farm and lactation

Lactation	Farm	A	B	C	D
1	Cows	n=609	n=123	n=1,327	n=71
	BLV	26.6%	48%	12.9%	19.7%
	prevalence				
2	Cows	n=567	n=114	n=1,403	n=96
	BLV	39.7%	60.5%	22.6%	53.1%
	prevalence				
3	Cows	n=375	n=-57	n=791	n=63
	BLV	55.7%	75.4%	33%	73%
	prevalence				
4	Cows	n=210	n=43	n=374	n=64
	BLV	54.29%	79.07%	44.12%	70.31%
	prevalence				
5+	Cows	n=170	n=51	n=204	n=84
	BLV	67.06%	86.27%	47.06%	79.5%
	prevalence				
Total	Cows	N=1,931	N=388	n=4,099	n=377
	BLV	42.6%	64.2%	24.6%	58.9%
	prevalence				

3.2 BLV testing data

BLV testing data, as well as milk production data on a per cow per lactation basis was recorded and shared by Centralstar, a diagnostic and lab testing cooperative, for a concurrent biological study (USDA-AFRI Award #2020-67015-31562) and our study. Two different BLV tests were used in the study. The first test was an ELISA antibody assay taken from milk samples, which detects any level of BLV antibodies in a cow's milk from a given testing day. ELISA assays were then recorded as either "Positive", "Suspect" or "Negative." For the purposes of our study, animal scientist collaborators who are experts in BLV testing research stated we could use BLV "Suspect" results as "Positive" because a "Suspect" result still indicated that BLV antibodies were detected in the milk sample, just at a lower level than "Positive" test results. All dairy cows that had a "Positive" or "Suspect" ELISA antibody assay result were then subsequently tested with a qPRC blood sample test. The PCR test reveals the PVL of BLV, or in other words, how many copies of the BLV provirus exist in the cow's blood stream. The PCR test allows for the testing of potential differences in profit by PVL. For analysis, we transform PVL to a whole number by multiplying it by 1000 ($PVL \times 1000$), in its original state PVL observations are reported as decimals. Figure 1 below, is a histogram of the distribution of $PVL \times 1000$.

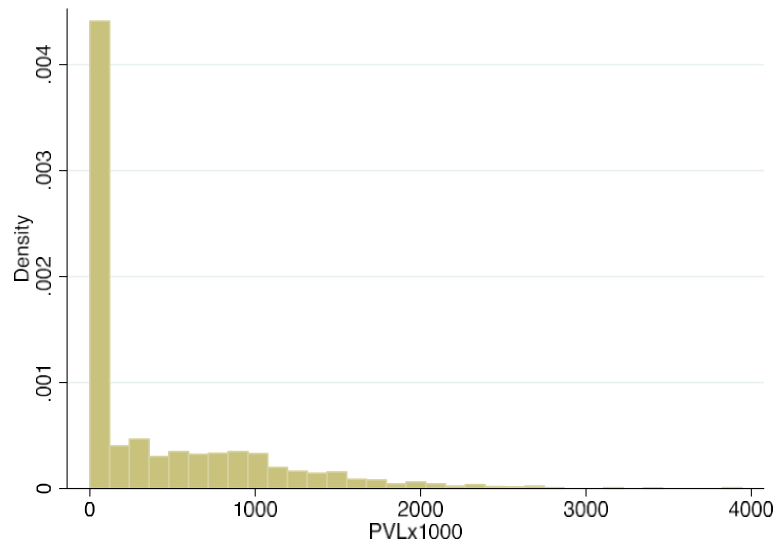


Figure 1: Histogram of the distribution of $PVL \times 1000$

One logistical issue we faced was missing BLV testing data for one lactation for small number of cows in the sample. ELISA milk testing was done on a yearly basis, but cows' lactate throughout the course of a year. Thus, there were instances where a cow would not have an ELISA test because she was in her dry period. For example, suppose BLV testing was completed in October 2020 and October 2021, but the cow in question started lactating in November 2020 and stopped milking in September 2021. In this case, the cow would not have an associated test for their 2021 lactation because they were not producing milk at the time of testing. Fortunately, we could use the biological fact that once a cow is infected with BLV, they will always have the virus –cows do not switch back from positive to negative. To remedy this issue, we would look at the prior and next lactations' test results for that cow to see if their BLV status changed. If a cow was negative (positive) in the prior and next lactation, we could be confident that we could assign that cow as negative (positive) in the lactation without a test. In only a handful of instances we had to drop a lactation entirely because the prior lactation was negative and next lactation was positive. In this case, we had no way of correctly assigning a BLV status for the missing test.

3.3 Financial and production data

Each farm shared their financial and production data. Two farms were enrolled in Telfarm, an agricultural financial record keeping system supported by the Department of Agricultural, Food, and Resource Economics at Michigan State University and MSU Extension program and used PcMars to share their financial data. Another farm used QuickBooks, and the final farm used their own organizational accounting system. The financial data was a set of monthly cash flows and receipts of different costs and revenues. Monthly cash flows and receipts that were used to calculate components of the partial profit equation were aggregated up to a per year basis to match availability of production and testing data.

Benchling data was shared by CentralStar for each farm. Benchling data includes data on annual milk production, milk merit, lactation longevity, and calving dates. Health, breeding, and culling records were collected through two different herd management software's, where three of the farms utilized PCDart and one of the farms utilized Bovi Sync.

We start the production year in September and end in August. This is done because cows start lactating at different dates over the course of a year. For example, a lactation that starts between September 2019 and August 2020 will be included in the 2020 production year. Starting the production year in September allows us to capture most of a lactation's revenues, and costs that occur during the same calendar year given that the typical time in milk is about 348 days in our sample.

3.4 Milk revenue

Each farm's financial records indicate the farm's monthly milk revenue (*milk revenue_{f_{mt}}*) and milk pounds sold (*milk pounds_{f_{mt}}*) where *m* is used to denote month. Using this we can calculate farm *f*'s average milk price over production year *t* as:

$$\text{average milk price per pound}_{ft} = \frac{1}{12} \sum_{m=1}^{12} \frac{\text{milk revenue}_{f_{mt}}}{\text{milk pounds}_{f_{mt}}} \quad (3)$$

Additionally, each cow's milk pounds (*milk pounds_{i_ft}*) over period year *t* were reported in Benchling. Thus, we can calculate cow *i*'s milk revenue during production year *t* as:

$$\text{milk revenue}_{i_{ft}} = \text{farm average milk price per pound}_{ft} * \text{milk pounds}_{i_{ft}} \quad (4)$$

Milk revenue was estimated in two different ways, one using milk pounds produced and the other using energy corrected milk. Both utilize the milk produced by each cow in each production year, but energy corrected milk accounts for the energy, or merit, of the milk.

Energy corrected milk is an important metric when analyzing the quality of the milk produced, as farmer's given milk revenue will be dependent on not only the quantity of the milk sold but also the merit of the milk via the fat and protein percentage of the milk. Instead of just noting the change in fat or protein percentage of milk between cows, energy corrected milk allows for an even comparison by setting a baseline level of fat and protein content expected for the average lactating cow, and adjusting total milk produced by how far over or under a cow is in their protein and fat levels compared to the baseline. The Benchling data reported how much milk, fat, and protein a cow produced each lactation. Thus, we were able to calculate their given fat and protein percentage each lactation to input into the energy corrected milk formula.

By correcting the total amount of milk produced by 3.5% fat and 3.2% protein we can estimate

cow i 's energy corrected milk for lactation t as:

$$\begin{aligned} \text{Energy Corrected Milk}_{ift} &= (.327 * \text{milk pounds}_{ift}) + (12.95 * \text{fat pounds}_{ift}) + (7.2 \\ &\quad * \text{protein pounds}_{ift}) \end{aligned} \quad (5)$$

Then we can substitute $\text{Energy Corrected Milk}_{ift}$ for milk pounds_{ift} in equation (4).

3.5 Healthcare costs

Healthcare costs for cow i in production year t involve two sub cost components, the on farm healthcare costs administered by the farm managers and the veterinarian costs. Not every health issue is treated solely on the farm or by the veterinarian, often it is some combination of both. Therefore, we must assign total healthcare cost per cow by the summation of all on farm healthcare treatments for cow i and the summation of all veterinarian treatments for cow i , over production year t .

3.5.1 Veterinarian expenses

Farms will utilize a veterinarian for healthcare treatments or breeding attempts and pregnancy checks. Veterinarian visit expenses are recorded in financial records on a monthly basis, while vet visits to the farm in the farm management software are recorded on a production year basis. Hence, we aggregate monthly vet expenses to find the total vet expenses for production year t , and assign the proportional amount of aggregated vet expenses ($\text{total vet expense}_{ft}$) to health care and breeding.

Total vet expense for farm f in production year t is found as follows:

$$\text{total vet expense}_{ft} = \sum_{m=1}^{12} \text{total vet expenses}_{fmt} \quad (6)$$

Since we do not know the visits on a per month (m) basis, only annually, we need to determine visits per cow for healthcare and breeding from the total vet visits in a production year

($\text{total vet visits}_{ft}$). The first step is to determine what proportion of vet visits in a production year were for breeding and which are for healthcare:

$$\text{proportion of vet visits for healthcare}_{ft} = \frac{\text{healthcare visits}_{ft}}{\text{total vet visits}_{ft}} \quad (7)$$

$$\text{proportion of vet visits for breeding}_{ft} = \frac{\text{breeding visits}_{ft}}{\text{total vet visits}_{ft}} \quad (8)$$

Now that we have the percentage of vet visits for breeding and healthcare, we can then use the percentage in equation (7) and multiply it by the total vet expenses for farm f in production year t to get the farm's healthcare veterinarian expense. Note, this is not at an individual treatment level yet.

$$\begin{aligned} \text{Healthcare Veterinarian Expenses}_{ft} \\ &= \text{total vet expense}_{ft} \\ &\quad * \text{portion of vet expenses for healthcare}_{ft} \end{aligned} \quad (9)$$

We can now take the total veterinarian expense for healthcare and allocate it across individual health treatments. Let $z=1 \dots Z$ be an individual treatment by the veterinarian. Then

$$\text{Vet cost per treatment}_{zft} = \frac{\text{Healthcare Veterinarian Expenses}_{ft}}{Z} \quad (10)$$

We will follow the same procedure to find veterinarian expenses for breeding for farm f in production year t :

$$\begin{aligned} \text{Breeding Veterinarian Expenses}_{ft} \\ &= \text{total vet expense}_{ft} * \text{portion of vet expenses for breeding}_{ft} \end{aligned} \quad (11)$$

Now we allocate the total veterinarian expenses for breeding across individual breeding attempts and pregnancy checks.

Let $k = 1 \dots K$ be breeding attempt, including insemination and pregnancy checks, such that:

$$\text{Vet cost per breeding attempt}_{kft} = \frac{\text{Breeding Veterinarian Expenses}_{ft}}{K} \quad (12)$$

3.5.2 Farm Administered Healthcare Costs

On farm healthcare treatment costs are assigned by the cost for each medicine, d , used for each treatment, plus the labor cost for each treatment.

Let $j = 1 \dots J$ be individual on farm treatments for a health issue:

$$\begin{aligned}
& \text{Healthcare costs per treatment}_{jdf} \\
&= \frac{\text{cost of medicine}_{jd}}{\text{doses per container}_{jd}} \\
&+ (\text{labor cost per hour}_f * \text{time per treatment in hours}_{jf})
\end{aligned} \tag{13}$$

A full list of the medicines, and their associated costs, used in the healthcare calculations can be found in appendix A.

3.5.3 Total Healthcare Costs Per Cow

Once all individual treatments j , are assigned a health care cost for medicine d , we can find the total healthcare cost per cow i over production year t :

$$\begin{aligned}
& \text{Healthcare cost}_{ift} = \sum_j (\text{on farm healthcare treatments}_{jift} * \\
& \text{Healthcare cost per treatment}_{jdf}) + \sum_z (\text{Vet visits for healthcare}_{zift} * \\
& \text{Vet cost per treatment}_{zft})
\end{aligned} \tag{1}$$

3.6 Breeding Costs

There are two components that make up breeding costs, semen costs and vet costs allotted to breeding over production year period t . Each cow i could have multiple breeding attempts in production year t , and so the semen and veterinarian costs are assigned on a per breeding attempt basis and summed across each individual cow.

Semen expenses were recorded monthly (semen_{fmt}) for each farm. Thus, they were aggregated and divided by total breeding attempts in production year t to find the semen cost per breeding attempt:

$$\text{semen cost per breeding attempt}_{ft} = \frac{\sum_{m=1}^{12} \text{semen}_{fmt}}{K} \tag{15}$$

Then we can sum together the semen and the vet costs in equations (12) & (15) to estimate a conservative total breeding cost for each cow ($\text{Breeding Costs}_{ift}$):

$$\begin{aligned}
& \text{Breeding Costs}_{ift} \\
&= [(\text{semen cost per breeding attempt}_{ft} \\
&+ \text{vet cost per breeding attempt}_{ft}) * \sum_k (\text{breeding attempts}_{kift})] \quad (16)
\end{aligned}$$

3.7 Depreciation

Depreciation is a way to allocate the fixed investment cost over an asset's expected useful life. Often, we think of depreciation for large equipment like combines, but it can also be applied to breeding animals. In the case of dairy cows, depreciation is a way to spread the upfront costs of raising a dairy heifer from birth until her first lactation across the years we expect the cow to be in the herd. Assigning an annual depreciation expense will allow us to account for differences in herd longevity and cull value, which could vary by BLV status. Straight-line depreciation uses the initial investment in the assets (*heifer replacement cost*), the anticipated value of the asset at the end of its useful life (*cull value*) and the expected years the asset will be used (*expected useful life*) to assign the same annual depreciation as:

$$\text{Depreciation} = \frac{\text{heifer replacement cost} - \text{cull value}}{\text{expected useful life}} \quad (2)$$

We use a three-year depreciation schedule as our baseline because the average useful life of all culled ELISA BLV negative milking cows in the sample was approximately three years. Then we update the depreciation schedule based on BLV status. Specifically, the assumed cull value will change once a cow tests positive for BLV. We did not find a large enough difference in the useful life of BLV positive cows to change the useful life of three years used in the depreciation equation. The depreciation schedule is therefore conditional on BLV status (V), denoted as 0 for ELISA negative cows and, 1 for ELISA positive cows.

Unfortunately, we did not have the ability to estimate heifer replacement costs or cull value with the data we had access too. This is because only some heifer replacement costs were given in farm financial records on a monthly basis, encompassing many subcomponents, making it impossible to attribute this cost to a single replacement heifer. As for cull values, dairy farms use ear tags for identification, however, when the cow is sold at an auction or to a meat processor, they use a separate identification system that does not include the farm ear tag. The forms of identification are not matched on receipts, so we were not able to test for differences in cull value

based on BLV status. We recommend other studies remedy this issue. We were not able to, given that we were collecting retroactive data.

To capture the most accurate estimate of both heifer replacement costs and cull cow sales, data were taken from regional data sets from the Livestock Marking Information Center (LMIC, 2022)². Heifer replacement costs were found by taking the average springing heifer costs for farms in the Midwest from 2017 to 2022 and implemented into the depreciation schedule. A springing heifer is in the final two weeks of her first pregnancy, and once they give birth, they are considered a milking cow in the herd. Given that cattle markets are considered competitive and long run economic profits should be zero, the price of a springing heifer should encompass almost all heifer replacement costs; thus, springing heifers should serve as a good proxy to estimate heifer replacement costs. A farmer could buy springing heifers instead of retaining heifer calves and raising them until milking. The heifer replacement price used in the depreciation schedule was \$1,106 per head.

To estimate the cull value in any given production year we used an LMIC dataset on weekly cull cow sales in Michigan from 2018-2020; the average cull-cow sales price was \$56.88/cwt. The average weight for 95% lean cutter cows of 1270.79 lbs. was used as the cull value. Therefore, the cull value used in the depreciation schedule for ELISA BLV negative cows was \$722.77.

We then use Nakada et al. (2022) to estimate the change in cull value based on BLV status. First, we estimated that BLV negative cows weighed 1270.78 lbs. Nakada et al. (2022) found that carcass weight for culled dairy cows is reduced by 7.4% when a cow tests positive for BLV. Therefore, we reduce the cull weight for BLV positive cows by 7.4%, making the cull weight of a cow with BLV 1177.14 lbs., and lowering the expected cull value to \$669.51. We investigate the robustness of this assumption in the sensitivity analysis.

Now, after estimating the assumed heifer replacement cost and cull values we can estimate the annual depreciation expense. The depreciation expense is assigned on a lactation basis, which we will denote as $l = \{1, 2, 3, \dots\}$. Up to this point the value assigned for each expense in the partial profit equation has been dependent on the production year (i.e., 2018, 2019...), but

² Michigan State University is a member of the LMIC. While these datasets are not publicly accessible, they were provided by LMIC staff for research purposes with regards to this project. (LMIC 2023)

depreciation is dependent on which lactation a cow is in, regardless of the production year that lactation falls under. The depreciation expense assigned to each cow is contingent on both what lactation a cow is in and the BLV status of the cow in that lactation. Again, based on our sample we expect a three year useful life for each cow in the study. If a cow lasts beyond their third lactation, they have exceeded their useful life and we have already fully expensed their upfront investment costs. Therefore, the depreciation expense in lactation four and above will be zero. Furthermore, the depreciation value assigned will be conditional on if and when a cow tests ELISA positive for BLV, via the given cull value. Given this information we can write the depreciation expense as follows:

$$Depreciation_{i,l} = \begin{cases} \frac{\text{heifer replacement cost} - \text{cull value}_v}{\text{usefull life}_i} & \text{if } l = 1, 2, \text{ or } 3 \\ 0 & \text{if } l \geq 4 \end{cases} \quad (18)$$

A full listing of depreciation schedules based on if and when a cow's tests positive for BLV can be found in appendix B.

3.8 Opportunity Cost of Fewer Productive Days

The lactation cycle and its stages inform how we create and assign the opportunity cost of less productive days. Two lactation examples are shown in Figure 2 and Figure 3, provided by Olthof (2023). Each lactation period for a cow starts once a cow births a calf, called calving, because this is when they will start producing milk (day 0). Milk production will increase over the course of lactation until reaching peak milk. At the beginning of each lactation there is a voluntary waiting period (VWP), often around 60 days, where a herd manager will not attempt to breed the cow again, allowing them to maximize milking potential in that lactation. After the VWP the herd manager will attempt to breed the cow, often in 21-day cycles, until they are pregnant.

Thus, the number of breeding attempts it takes for a cow to become pregnant influences how long it will take for a cow to reach their next lactation – this is key to the opportunity cost. For instance, we can see that the example cow in Figure 2 required two breeding attempts to become pregnant, whereas the cow in Figure 3 required four breeding attempts to become pregnant. As a result, the cow in Figure 2 has a total lactation length of 361 days, while the cow in Figure 3 has a total lactation length of 403 days. Finally, each lactation ends with a dry

period where the cow is not milked to encourage higher milking production in the next lactation. Each component of the lactation period can vary by farm, such as the VWP and dry period length. We assume that each farm manager in our study sets their VWP and dry period to optimal levels that maximizes milk production. Using our sample, the *Average Calving Interval*_{it} is 398 days, including 348 days in milk and an assumed 50-day dry period.

Lactation Period Example



Figure 2: Lactation period example from Olthof (2023)

Lactation Period Example, COW #2



Figure 3: Lactation period example from Olthof (2023)

Comparing the two figures above, the cow in Figure 3 required more breeding attempts to become pregnant, driving this cow to stay in their current lactation longer than the cow in Figure 2, as their VWP and dry period are the same. A cow will be producing less milk each day toward the end of their lactation, because daily milk production declines after reaching peak milk. Therefore, the cow in Figure 3, by staying in their current lactation longer than the cow in Figure 2 will be producing less daily milk over the same time period. These figures,

show the basis of what this opportunity cost is accounting for, as cows that stay in their current lactation longer than the average cow (like cow #2 when compared to cow #1 in this example) forgo producing more milk by moving into their next lactation.

Due to data constraints, the actual milk produced each day in lactation period l by cow i , was unknown. Given we had milk produced over the total lactation, a daily milk schedule was estimated. The *Opportunity Cost of Fewer Productive Days_{il}* was calculated using two different methods to estimate the milking schedule. The first method utilizes a discrete schedule that assigns the milk produced per day by five discrete periods of the lactation. The second method utilizes a continuous milking schedule formulated using the Wood function (Wood 1967). Having both a discrete and continuous milking schedule allows for the partial profit equations to be compared using each opportunity cost method.

One full lactation for a cow starts with an initial calving date and runs until their next calving date. Therefore, a full lactation will be the calving interval between the *Calving Date_{i, l+1}* and *Calving date_{il}*:

$$Calving Interval_{il} = Calving Date_{il+1} - Calving Date_{il} \quad (19)$$

Now, using each *Calving Interval_{il}* we can determine the *Average Calving Interval* for all BLV negative cows (we only use negative cows for this average as to not introduce bias into the calculation) to determine the *Difference from Average Calving Interval_{il}* for each cow in each production period. The average calving interval for the sample 348 days and is calculated as follows:

$$Average Calving Interval = \frac{1}{n} \sum_{l=1}^n Calving Interval_{il} \quad (3)$$

Therefore, the difference from average calving interval is:

$$\begin{aligned} & \textit{Difference from Average Calving Interval}_{idl} \\ &= \textit{Calving Interval}_{idl} - \textit{Average Calving Interval} \end{aligned} \tag{4}$$

Note, that d in equation (21) refers to the number of days in the calving interval and we assume days dry and VWP are the same for all cows. Thus, the difference in calving intervals is driven by extra days needed to breed the cow.

Next, we will determine the *Forgone Milk Production* using both the discrete and continuous methods. For the discrete method Table 3 depicts a typical milk schedule for a dairy cow in their first, second, and third lactations based on estimates from the Wood function (Wood 1967). For instance, in lactation one we assume a cow produces 61 lbs. of milk per day in the first 40 days of the lactation (interval A) and 73 lbs. per day in days 41 to 100 (interval B). However, after day 306 (interval E), a cow's average daily milk production decreases to around 58 lbs. per day. Therefore, if a cow takes longer to breed back, they will have a lower milk production than a cow that breeds back more quickly and begins the next lactation (in intervals A and B). We create an opportunity cost, *Opportunity Cost of Less Productive Days_{il}*, to account for the loss in milk revenue.

Table 3: Discrete milk production schedule over a lactation cycle using Wood (1967) function daily milk production estimates

Interval	Days in Lactation	Lactation 1 Milk per Day	Lactation 2 Milk per Day	Lactation 3+ Milk per Day	Difference Between Lactation 1 Interval E and Lactation 2 Interval	Difference Between Lactation 3 Interval E and Lactation 3 Interval	Difference Between Lactation 3+ Interval E and Lactation 3+ Interval
<i>A</i>	0-40	61	71	85	12	33	38
<i>B</i>	41-100	73	83	95	24	44	49
<i>C</i>	101-199	74	78	84	20	33	38
<i>D</i>	200-305	68	66	65	8	14	18
<i>E</i>	306+	58	52	47	-12	-5	0

The *Forgone Milk Production_{il}* using this discrete method is found by subtracting the expected milk pounds produced from the start of a new calving interval, or lactation (periods A-D in $l + 1$), from what they are actually producing by staying in the current lactation longer than the average BLV negative cow. This difference is found for each cow i , and each individual lactation period l , then multiplied by the number of days spent in each interval.

$$\begin{aligned}
\text{Forgone Milk Production}_{il} &= (\text{Days should be in Interval A} * (A_{l+1} - E_l)) \\
&+ (\text{Days should be in interval B} * (B_{l+1} - E_l)) \\
&+ (\text{Days should be in Interval C} * (C_{l+1} - E_l)) \\
&+ (\text{Days Should be in Interval D} * (D_{l+1} - E_l))
\end{aligned} \tag{22}$$

Next, we will use a continuous estimate of daily milk production to estimate *Forgone Milk Production_{idl}*, and the opportunity cost of less productive days. We will estimate the continuous daily milk production using the Wood function (Wood 1967). The Wood function is an incomplete gamma function commonly used to model daily milk production over the course of an entire lactation. The Wood Function is:

$$Y_d = ad^b e^{-cd} \tag{5}$$

where Y_d is the milk yield (kg/d) and d is the day in the lactation cycle. a , b , and c are parameters that set the intercept, rate of increase to peak milk production, and rate of decrease in production past peak, respectively. We also converted the estimated daily milk yield, Y_d , from kilograms to pounds. Again, because only days in lactation were known from our data, parameters a , b , and c needed to be adapted from previous research. Dematawewa et al. (2007) modeled the Wood function from 4.2 million test day yields from over 427,000 U.S. Holsteins and reported their estimated Wood Function parameters by lactation for day 305. Kopec et al. (2021) showed how to adjust the Wood function for longer lactations. Therefore, we used Dematawewa et al. (2007) estimates for a , b , and c parameters as starting values and then adjusted them to match the average cumulative milk production of BLV negative cows on day 348 in Lactations 1, 2 and 3+. The Wood function parameters and the curves for each lactation are shown in Table 4 and Figure 4 below.

Table 4: Wood function parameters by lactation

Lactation	1	2	3 +
Parameter A	16.05	19	23.05
Parameter B	0.205	0.206	0.209
Parameter C	0.0019	0.0027	0.0036

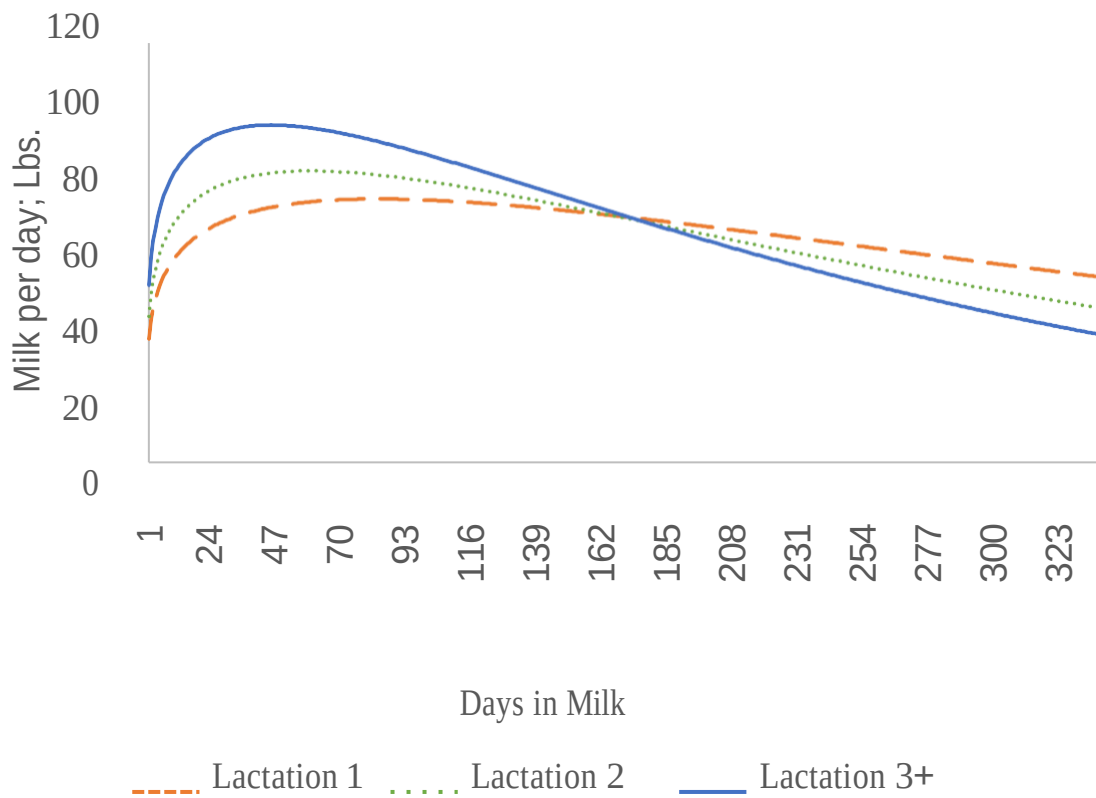


Figure 4: Fitted lactation curves from Wood function

The *Forgone Milk Production*_{idl} will be a function of the same *Difference from Average Calving interval*_{idl}, but now instead of multiplying it by the difference in milk production between the beginning of a new lactation from the end of the previous lactation in the discrete milk production schedule, it will be assigned this difference from the cumulative milk production estimated from the continuous Wood function. Also, cows with a *Difference from Average Calving interval*_{idl} that is negative, meaning they had a

shorter lactation than average, will be assigned a *Forgone Milk Production* that is the difference between the milk produced in the current lactation less the next lactation.

$$Forgone\ Milk\ Production_{idl} \begin{cases} \sum_{d=1}^{D-348} Y_{d1l+1l} - \sum_{D=349}^D Y_{dl} & \text{if } D < 348 \\ 0 & \text{if } D = 348 \\ \sum_D Y_{dl} - \sum_{d=1}^{348-D} Y_{dl+1l} & \text{if } D > 348 \end{cases} \quad (6)$$

Now that the *Forgone Milk Production_{idl}* has been calculated we can now find the *Energy Corrected Forgone Milk Production_{idl}* by inserting the *Forgone Milk Production_{idl}* in the energy correct formula.

$$\begin{aligned} &Energy\ Corrected\ Forgone\ Milk\ Production_{idl} \\ &= (Forgone\ Milk\ Production * .327) + ((Fat \\ &* Forgone\ Milk\ Production) * 12.95) + ((Protein \\ &* Forgone\ Milk\ Production) * 7.65) \end{aligned} \quad (7)$$

Finally, we will calculate the *Opportunity Cost of Fewer Productive Days_{ilt}* by multiplying the *Average Milk Price per Pound*, which varies by farm, f , and Production year, t , by the *Forgone Milk Production_{idl}*. This opportunity cost will be calculated with both milk pounds and the adjusted energy corrected milk as shown in equation (25). The calculation for the *Opportunity Cost of Less Productive Days_{ilt}* is the same for both the discrete and continuous methods, only varying but which *Forgone Milk Production* is used.

$$\begin{aligned} &Opportunity\ Cost\ of\ Fewer\ Productive\ Days_{ilt} \\ &= Average\ Milk\ Price\ per\ Pound_{ft} * Forgone\ Milk\ Production_{idl} \end{aligned} \quad (8)$$

If a cow is culled, they will not have an opportunity cost of less productive days given that they do not have a next lactation.

3.9 Opportunity Cost of Early Cull

Based on our sample, we expect the average cow to be in the milking herd for three lactation cycles. In many instances, however, a cow leaves the herd before their third lactation. A cow could be culled early on in their milking life for many reasons, all based on the discretion of the herd manager. The herd managers participating in our study across the board stated reasons such as poor milk and milk merit production, or mastitis as the top two reasons for culling a cow. A cow that does not reach their third lactation does not produce the total amount milk we would expect them to produce over their lifetime. Given that a cow's milk production generally increases by lactation, having to replace a culled cow that does not reach their third lactation, with a first lactation cow, reduces expected milk production over the timeframe those three lactations would take place in. Bartlett et al. (2013), states that one potential cost of BLV infection is the effect of culling a low milk producing cow before that cow's lifetime milk production is realized. We account for any loss in expected milk production through an *Opportunity Cost of Early Cull* for each cow that leaves the herd in lactation one or lactation two and assign this opportunity cost in the lactation they left the herd.

Table 5: Average total milk pounds per lactations 1-3 for ELISA BLV negative cows on farms A-D

Lactation	Average milk pounds per lactation
<i>1</i>	22,771.91
<i>2</i>	24,343.82
<i>3</i>	25,996.07

Table 5 shows the average milk pounds in the first three lactations for ELISA BLV negative cows in our sample, which increases lactation over lactation. For a given spot in the herd, each farm in our study should be able to capture the total expected milk produced in lactations one through three ($L1+L2+L3$). Using this information, we can create the opportunity cost of early cull that accounts for the difference in the expected milk production from a cow's first three

lactations from what is produced if a cow is culled early and replaced with a different cow (starting back at L1).

We would have expected a cow to milk from lactations one through three (L1, L2, L3). Now consider a cow that is culled in lactation one; that cow will have to be replaced with a different new cow that will be entering their first lactation (milk yield in L1 < milk yield in L2).

Therefore, for any cow culled in the first lactation, the farm will instead yield the milk from two first lactations and one second lactation cow (L1, L1, L2), over the same three year time period. This difference in milk yield, is the expected milk yield less the actual milk yield $[(L1+L2+L3) - (L1+L1+L2) = L3-L1]$, where $(L1+L2+L3)$ is the expected milk yield from a cow, and $(L1+L1+L2)$ is the actual milk yield to the farm when a cow is culled in its first lactation and is then replaced.

This also applies to a cow culled in their second lactation, where the farm will yield the milk from two first lactations and one second lactation (L1, L2, L1). A cow culled in the second lactation will be replaced with a cow entering its first lactation, thus the farm never yields the milk from a third lactation cow in the same time frame. The difference in milk yield for a cow culled in the second lactation can be shown as $[(L1+L2+L3) - (L1+L2+L1) = L3-L1]$, where $(L1+L2+L1)$ are the lactations, the farm is actually yielding milk from when a cow is culled in the second lactation. Consequently, a cow culled in the first or second lactation will yield the same opportunity cost of early cull.

For any cow that is culled in their first or second lactation the farm loses 3,224.16 pounds of milk. We then multiply this loss of milk by the given milk price per pound received by farm f in production year t that cow was culled in to find the opportunity cost of early cull:

$$\text{Opportunity Cost of Early Cull}_{ft} = \text{lost milk pounds} * \text{milk price}_{ft} \quad (9)$$

4. EMPIRICAL MODEL

We use multiple fixed effects regression models to show a more comprehensive picture of the effects of BLV on profit. The data set is an unbalanced panel set by cattle identification number (*CowID*) and calving date of each lactation. While the dataset has both fixed variables that do not vary across groups in the panel, and random variables that do vary across time withingroups of observations, fixed effects models were preferred to a random effects model following the Hausman test ($\chi^2 = 298.49$, $\text{prob} > \chi^2 = 0.000$). Random and fixed effects model estimates in the Hausman test used partial profit calculated with milk pounds and continuous opportunity cost of less productive days as the dependent variable, and ELISA status binary variable (positive or negative) as the key independent variable. Pooled OLS models are another alternative. However, these models require an exogeneity assumption meaning individual time- varying covariates need to be uncorrelated with an error term that is time constant (Wooldridge, 2010). This assumption is relaxed in fixed effects models. Furthermore, if the omitted time- invariant variables do not vary over time, fixed effects models will produce unbiased estimates. One drawback, however, to fixed effects models is that time-invariant variables (like breed) cannot be added to the fixed effects model as covariates.

There are four different partial profit estimates that will be used as the dependent variable; partial profit using continuous opportunity cost of less productive days in equation (26) using both milk pounds (*PP milk pounds cont.*) or energy correct milk pounds (*PP ECM pounds cont.*), and partial profit using the discrete method to calculate equation (26), again using both milk pounds (*PP milk pounds discrete*) or ECM pounds (*PP ECM pounds discrete*). The general form for the regression equation is:

$$\text{Partial Profit}_{it} = \beta_0 + \beta_n X' + e_{it} \quad (10)$$

Here X' is a vector for the time-varying random effects which could include BLV status (ELISA or PVL categories), and other controls. β_n are coefficients to be estimated and e_{it} is the error term. All models were estimated in *STATA15* (StataCorp. 2017. *Stata Statistical Software: Release 15*. College Station, TX: StataCorp LLC.).

BLV status, the key independent variable of interest, is included in the model in two ways – ELISA test only or PVL. *ELISA (V)* is a binary variable assigned to each observation where 0=ELISA BLV negative and 1= ELISA BLV positive. Recall once a cow tests positive or suspect with the ELISA assay, a blood provirus assay follows. *PVLx1000* is given in the data set as a continuous variable from 1 to 3943. However, to more aptly understand the effects of BLV infection the continuous data was transformed into a categorical variable, *PVL (PVL=0,1,2,3,4)*. Categories were assigned based on the quantiles of the pro viral load distribution where 0=ELISA BLV negative (base case); 1= Low, the PVL was at 25% and below of the distribution; 2=Medium-low, the PVL was greater than 25% of the distribution and less than 51% of the distribution; 3= Medium-high, the PVL was greater than 50% of the distribution and less than 76% of the distribution; and 4=High, the PLV was greater than 75% of the distribution.

There are four additional random control variables in each regression model. *Lactation (l)* is a categorical variable representing the lactation number of each cow in the dataset ($l = 1, 2, 3, 4, 5+$). Lactations in the sample ranged from first to tenth, but due to a very small number of observations post the fifth lactation, the lactation variable used in the regression models groups fifth to tenth lactation at 5+. *Month Started Lactating (m)* is a categorical variable for the month of the year (1=January (base) to 12=December) a cow begins their lactation. *Production Year (t)* is another categorical variable controlling for what production year the observation is from (2018-2022). The final random control is a binary variable *Culled*, where 1 is assigned in the year that a cow was culled and 0 otherwise.

Post-estimation tests were run to tease out the effects of *breed* (Holstein or Jersey), a time invariant variable that could not be directly estimated. As previously stated, fixed effects regression controls for all omitted time-invariant variables. However, we were interested in understanding the effects of BLV infection on partial profit within both breed groups. Therefore, to tease out the effects of BLV infection on partial profitability within each breed group, both the Holstein and Jersey breed variables were interacted with either the BLV binary or PVL variables and added to each regression model. Then, the *limcom* post-estimation command in *STATA15* was used to obtain point estimates, standard errors, and p-values for the effects of BLV infection on partial profit within each breed. Note, that the regression models reported in Table 10 and Table 12 do not include these controls for the interaction between BLV or PVL with breed.

Rather, these models were run a second time with these interactions, only to obtain the *lincom* output. The results of each *lincom* test for breed are report in Table 11 and Table 13.

Next, we used the *STATA15* command, *xttest3*, to test for heteroskedasticity. Heteroskedasticity refers to when the variance changes across the population, when conditional on explanatory variables in the model (Wooldridge 2008). In each model we found evidence of heteroskedasticity. However, Wooldridge (2011) explains how the inclusion of clustering standard errors of the cross-section identifier results in standard errors that are completely robust to heteroskedasticity. Thus, we reran each model using the *vce(robust)* command to obtain clustered standard errors around our cross-section identifier (*COWID*). This resulted in lower p-values for each key independent variable, as well as a greater F-statistic for each model. Because of these results, each regression output is reported with robust standard errors.

5. RESULTS

The results section begins with an analysis of descriptive statistics by ELISA BLV group which will show the baseline differences of key variables and partial profits. Descriptive statistics will show that variables such as milk pounds, both opportunity costs, as well as partial profit calculated with milk pounds are all unexpectedly higher, on average, for BLV positive cows.

However, these averages do not utilize the panel structure of the dataset, nor control for time-varying factors. Next, graphs will be presented to further analyze the dynamic trends of BLV, via changes in averages over lactation periods. The figures in this section will show that when reporting means on a lactation basis both average milk production and partial profit are higher for BLV negative cows in most lactations. Next, a section on survival analysis provides context on herd longevity and the importance of if and when a cow tests positive for BLV. The final section reviews regression output results, where we show that there is a reduction in partial profit for ELISA BLV positive cows, on average, when compared to ELISA BLV negative cows. Each portion of the results section builds on the last, providing further context on the relationship between BLV infection and partial profit, especially the importance of controlling for time varying factors such as lactation, production year, and if and when a cow tests positive for BLV.

5.1 Descriptive Statistics

Means, standard deviations, minimums and maximums for each component of partial and other key control variables are reported on a per cow per lactation basis for the whole sample in Table 6 and disaggregated by ELISA negative and ELISA positive observations, along with a one-way ANOVA test are in Table 7. Partial profit means, standard deviations, minimums and maximums and one-way ANOVA tests by BLV status are reported in Table 8. The one-way ANOVA test is a simple technique that allows us to see if averages are significantly different between BLV groups. The F-statistic and the corresponding p-value, along with the chi-squared test for equal variances from the one-way ANOVA tables of all variables is available in appendix C. Recall, there are four different ways we calculate partial profit including using milk pounds or error corrected milk pounds, and continuous or discrete estimates on the opportunity cost of less productive days.

Table 6: Key variable means, standard deviations, and minimums and maximums per lactation (n=6796)

Variable name	Mean (Std. dev)	Minimum	Maximum
<i>MILK POUNDS</i>	24524.15 (9549.13)	55	48671
<i>MILK REVENUE</i>	4811.56 (1943.84)	11.83	12253.93
<i>ECM POUNDS</i>	24555.65 (9460.43)	98.04	48330.45
<i>ECM REVENUE</i>	4842.22 (1982.98)	21.09	12643.23
<i>HEALTHCARE COSTS</i>	19.36 (28.32)	0	251.33
<i>BREEDING COSTS</i>	78.19 (65.98)	0	666.62
<i>DEPRECIATION</i>	153.75 (105.98)	0	436.69
<i>LACTATION CULLED</i>	2.96 (1.43)	1	9
<i>LACTATION LENGTH (DAYS)</i>	397.18 (55.23)	301	819

Table 6 (cont'd)

Variable name	Mean (Std. dev)	Minimum	Maximum
<i>OPPORTUNITY COST OF FEWER PRODUCTIVE DAYS (CONTINUOUS)</i>	55.05 (452.27)	-917.58	4009.55
<i>OPPORTUNITY COST OF FEWER PRODUCTIVE DAYS ³ECM (CONTINUOUS)</i>	54.19 (454.61)	-948.1	5643.63
<i>OPPORTUNITY COST OF FEWER PRODUCTIVE DAYS (DISCRETE)</i>	19.81 (332.67)	-852.79	1997.7
<i>OPPORTUNITY COST OF FEWER PRODUCTIVE DAYS ECM (DISCRETE)</i>	18.87 (329.59)	-881.16	2590.19
<i>OPPORTUNITY COST OF EARLY CULL</i>	643.14 (77.77)	470.38	888.28
<i>OPPORTUNITY COST OF EARLY CULL</i>	173.95 (21.03)	127.22	240.25

³ ECM stands for energy corrected milk as described in equation (5)

Table 7: Key variable means, standard deviations, minimums and maximums, and one-way ANOVA test by ELISA BLV status per lactation(n=6796)

Variable Name	ELISA BLV Negative			ELISA BLV Positive			One-way ANOVA test between negative & positive
	Mean (Std. dev)	Min	Max	Mean (Std. dev)	Min	Max	P-value
<i>Milk Pounds</i>	24255.51 (9517.63)	55	48247	25048.39 (9590.66)	146	48671	0.01
<i>Milk Revenue</i>	4816.13 (1943.48)	11.83	12253.93	4802.65 (1944.93)	36.56	12224.81	0.79
<i>ECM Pounds</i>	24594.18 (9410.58)	98.04	48285.96	24480.40 (9558.61)	199.59	48330.45	0.64
<i>ECM Revenue</i>	4903.72 (1970.17)	21.09	12643.23	4722.13 (2002.72)	49.98	12198.83	<0.01
<i>HealthCare Costs</i>	18.84 (27.91)	0	251.33	20.38 (29.08)	0	235.99	0.03
<i>Breeding Costs</i>	71.068 (62.41)	0	666.62	92.10 (70.39)	0	666.62	<0.01
<i>Depreciation</i>	154.04 (98.9)	0	383.23	153.18 (118.58)	0	436.69	0.73

Table 7 (cont'd)

Variable Name	ELISA BLV Negative			ELISA BLV Positive			One-way ANOVA test between negative & positive
<i>Lactation Length (Days)</i>	398.90 (56.9)	307	819	393.56 (51.38)	301	696	0.76
<i>Opportunity Cost of Fewer Productive Days (Continuous)</i>	71.08 (456.96)	-848.7	4009.55	21.45 (440.58)	-917.58	3843.61	<0.01
<i>Opportunity Cost of Fewer Productive Days ECM (Continuous)</i>	68.15 (4009.54)	-844.13	5643.63	24.91 (449.94)	-948.1	4983.56	0.02
<i>Opportunity Cost of Fewer Productive Days (Discrete)</i>	31.81 (330.52)	-783.66	1915.83	-5.3 (335.89)	-852.79	1997.7	<0.01
<i>Opportunity Cost of Fewer Productive Days ECM (Discrete)</i>	29.2 (327.41)	-778.81	2522.56	-2.79 (333.25)	-881.16	2590.19	0.01
<i>Opportunity Cost of Early Cull</i>	646.07 (74.13)	470.38	888.28	633.84 (87.83)	470.38	888.28	0.02
<i>Opportunity Cost of Early Cull ECM</i>	174.74 (20.05)	127.22	240.25	171.43 (23.76)	127.22	240.25	0.02

The descriptive statistics reported in Table 7 give initial insights into the differences across milk production, longevity, revenue and costs between BLV negative and positive cows. It is important to note however the ANOVA tests (univariate analysis) reported in Table 7 do not control for time varying factors. We will show in later sections how it is critical to control for time-varying factors to understand the effects of BLV infection on longevity and partial profitability. The descriptive statistics allow us to set a baseline in the potential differences in averages per lactation between BLV groups in which we can start to answer our research questions and compared to the findings from previous studies on BLV. To start, the average milk pounds produced is approximately 790 pounds higher for ELISA BLV positive cows when compared to ELISA BLV negative cows, this difference is also statistically significant at the 5% level according to the ANOVA test. This is a surprising result given how many previous studies such as Norby et al. (2016), Nekouei et al. (2016), and Erskine et al. (2012) found an association between BLV herd prevalence and lower milk production. Average milk revenue, however, is lower for ELISA BLV positive cows, but this likely attributed to the fact that more ELISA BLV negative cows' observations are in production years where the average milk price per pound is higher (more negative cows in later production years). Comparing average milk pounds to ECM pounds, we see that ELISA BLV negative cows have higher ECM pounds than their ELISA BLV positive counter parts, showing that BLV could potentially impact milk merit (fat and protein percentages) more so than total milk production, although the difference in average ECM pounds between negative and positive cows is not significant according to the ANOVA test with a P- value of .64.

Moving further down in Table 7 to the cost components of the partial profit equation – healthcare cost, breeding costs, and depreciation – are all higher for ELISA BLV positive cows when compared to ELISA BLV negative cows, but the difference in means is not statistically significant for depreciation. Further, the difference between average healthcare costs for BLV negative and positive cows is quite small.

Moving on to the opportunity costs of less productive days, ELISA BLV positive cows have a lower opportunity cost of fewer productive days for all four alternative calculations (combinations of continuous or discrete, and milk pounds or ECM). This is contrary to our expectation that the opportunity cost of fewer productive days would be higher for ELISA BLV

positive cows. We expected one of the main drivers of this opportunity cost to be the number of breeding attempts a cow has in a lactation but breeding costs (which is a function of breeding attempts) is higher on average for ELISA BLV positive cows. Thus, there may be another driver for herd managers keeping a cow in its current lactation longer than average besides breeding attempts.

The opportunity cost of early cull when using either milk pounds or ECM pounds is higher for BLV negative cows on average. This outcome is again unexpected as we see that BLV negative cows were, on average, culled in their second lactation while BLV positive cows were, on average, culled in their third lactation. This result contradicts with the findings in previous studies such as Bartlett et al. (2013), where they found that BLV positive cows have a higher probability of being culled early in their life than BLV negative cows. However, the disparity in the average lactation culled between BLV positive and negative cows does not however account for when a cow becomes infected with BLV. Thus, further analysis on longevity via when and if a cow becomes infected is warranted. This will be shown later in the longevity analysis section.

Table 8: Partial profit mean, standard deviation, and minimum and maximum by ELISA group and total reported per lactation (n=6,796)

	ELISA BLV Negative			ELISA BLV Positive			Total			ANOVA
Variable Name	<i>Mean & (Std. dev)</i>	<i>Min</i>	<i>Max</i>	<i>Mean & (Std. dev)</i>	<i>Min</i>	<i>Max</i>	<i>Mean & (Std. dev)</i>	<i>Min</i>	<i>Max</i>	<i>P-value</i>
<i>Partial profit (Continuous)</i>	4405.91 (2004.43)	- 1138.94	12049.03	4442.26 (1964.6)	- 1021.83	12147.65	4418.23 (1990.95)	- 1138.94	12147.65	0.48
<i>Partial profit ECM (Continuous)</i>	4591.30 (1974.44)	-551.66	12458.34	4420.20 (1982.92)	-391.43	11830.25	4533.35 (1978.82)	-551.66	12458.34	<0.01
<i>Partial profit (Discrete)</i>	4423.38 (2005.36)	- 1138.94	12049.03	4453.68 (1966.43)	- 1021.83	12147.65	4433.64 (1992.16)	- 1138.94	12147.65	0.55
<i>Partial profit ECM (Discrete)</i>	4609.16 (1974.05)	-551.66	12458.34	4432.01 (1985.22)	-391.43	11830.25	4549.15 (1979.47)	-551.66	12458.34	0.55

Table 8 shows the descriptive statistics for the four ways we calculated partial profit for the whole sample and by BLV status. Most notably, the only means of the partial profit using ECM and the continuous opportunity of less productive days was statistically different between ELISA groups. The partial profits are positive, on average. However, recall that we are estimating partial profit. Therefore, other costs – like fixed costs and other variable costs we assumed were not impacted by BLV – will also be subtracted from the partial profit. Therefore, we cannot say if overall the cows generated an economic profit from our analysis.

While there are important insights to draw from the results in the previous tables, it is important to again note that only looking at averages between ELISA groups, does not show the full extent of how BLV impacts partial profitability. Later we will show the fixed effects models with control variables to account for differences in when and if a cow tested positive for BLV, lactation number, production year, month lactation began, and if a cow was culled in their current lactation or not. We will show that when utilizing the panel structure of our data, controlling for the effects within and between groups along with the previously mentioned time- varying factors, BLV positive cows have an average reduction in partial profitability when compared to BLV negative cows.

5.2 Graphics for Milk Production and Partial Profitability

This next section of graphs shows the average milk production, ECM production, and partial profit using the continuous opportunity cost by lactation, ELISA BLV status, and provirus load groups. Lactations 6 through 10 are grouped together into one cluster due to a lack of observations. Also, PVL is grouped into BLV negative, PVL low, and PVL high, where PVL low is provirus load numbers up to the 50th percentile of distribution of provirus load, PVL high represents observations from the 51st to 100th percentile of the distribution. Later analyses will use more PVL groups.

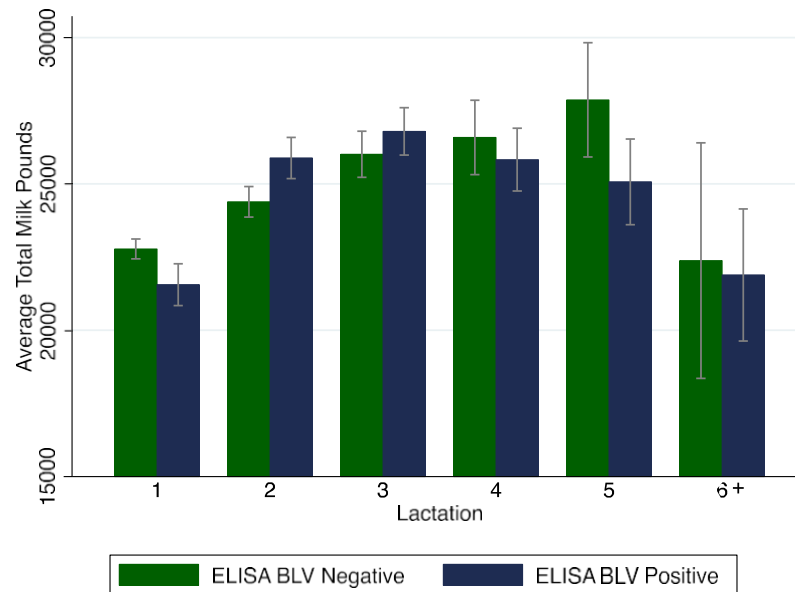


Figure 5: Average milk pounds by lactation and ELISA status

In Figure 5 milk production generally increases lactation over lactation, through lactation four. Notably, there is no clear trend in average milk production between ELISA BLV positive and negative cows. Cows that were ELISA BLV negative produced more milk on average, in lactation one. Next, in lactations two and three ELISA BLV positive cows produce more milk on average, and finally negative cows produce more milk on average in lactations four, five and six plus.

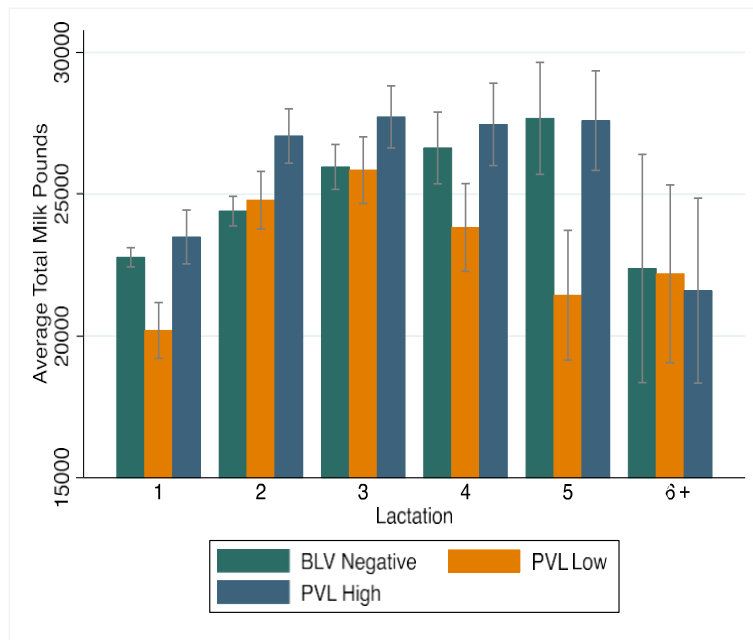


Figure 6: Average milk pounds by lactation and PVL group

Figure 6 shows the average milk production differences by lactation and PVL group. Interestingly, the PVL high group has a higher average milk production than both the PVL low and BLV negative groups; substantially higher than PLV low in all lactation and higher than the BLV negative group through lactation four. It may be difficult however, to draw any conclusions as to why the PVL high group produces higher average levels of milk. Previous studies such as Ohno et al. (2015) found a relationship between high levels of provirus load and lymphocytosis and Watanabe et al. (2019) found a relationship between PVL and severity of clinical mastitis.

Both lymphocytosis and clinical mastitis are known to reduce milk production, which would conflict with the results in Figure 6. However, the clinical effects of BLV may not be impacting infected cattle until later in their life, which could explain why the PVL high group has lower milk production than the BLV negative and the PVL low group in later lactations.

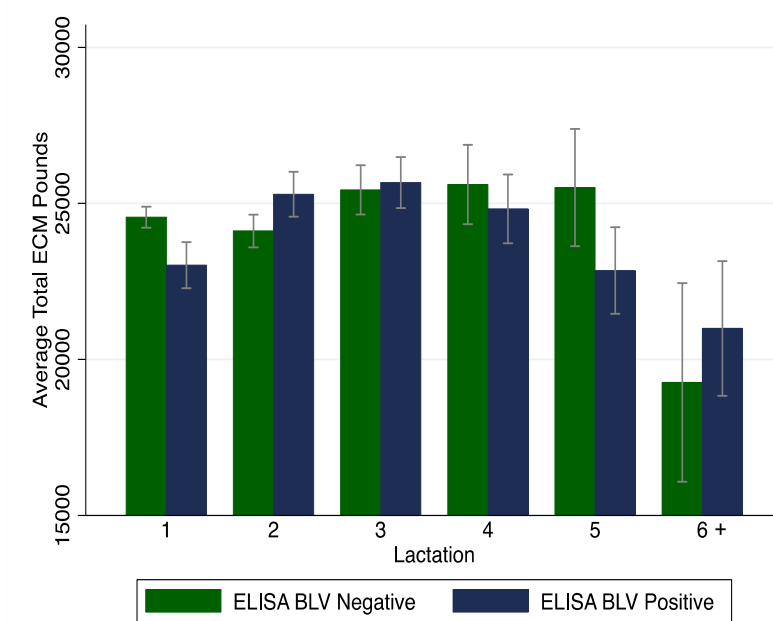


Figure 7: Average ECM pounds by lactation and ELISA status

Figure 7 shows a similar trend to Figure 5, where ELISA BLV negative cows produce more ECM in lactation one, less ECM on average in lactations two and three and then switch back to the higher group in lactations four and five. The most notable difference, however, is that in the six plus lactation group ELISA BLV positive cows produce more ECM on average.

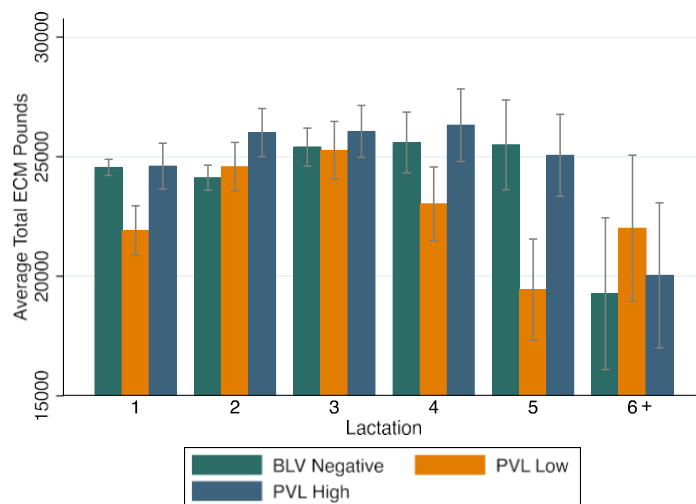


Figure 8: Average ECM pounds by lactation and PVL group

In Figure 8 we see the same general trend in average ECM production by lactation as in Figure 6, where the PVL high group tops the average production in lactation one up to lactation four. One

difference, however, in Figure 8 in lactation group six and up the PVL low group tops both the BLV negative and PVL high groups in average ECM production.

The graphs showing average milk and ECM milk production by lactation and BLV group do not depict a clear story on effect of BLV infection on milk production. However, while these graphs do account difference in the average milk production between lactations, it still does not account for other time varying factors that could be impacting milk production by ELISA BLV groups. Time varying factors such as production year, what month a cow starts lactating, and if a cow was culled in their current lactation could all impact the milk production in any given lactation, and these factors will be accounted for in later regression models.

The next set of figures will show the average partial profit using the continuous opportunity cost of less productive days by, again, energy corrected milk, lactation, ELISA BLV status and PVL group.

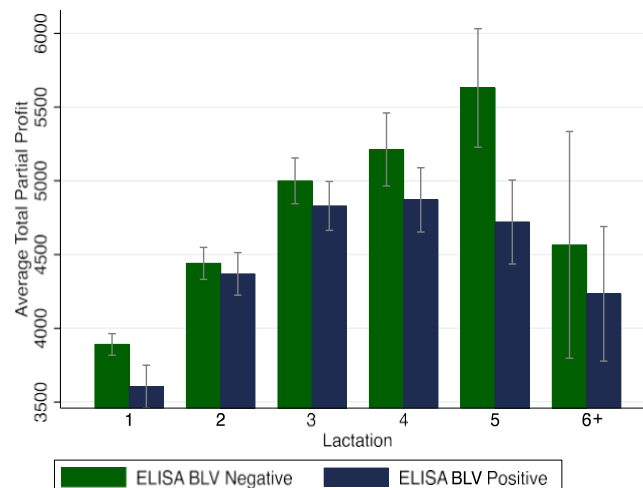


Figure 9: Average partial profit using cont. opp. cost, by lactation and ELISA status

Figure 9 shows that the average partial profit, using the continuous opportunity cost of less productive days, is higher in each lactation for ELISA BLV negative cows, when compared to ELISA BLV positive cows. The disparity in the average profitability increases from lactation two to lactation five, where average partial profit peaks for ELISA BLV negatives cows. When comparing Figure 9 with Figure 5, the average partial profit is consistently greater for the ELISA BLV negative group, whereas in Figure 5 average milk production is greater for the ELISA BLV negative group in only four of the six lactations. This could be evidence that BLV infection has a

greater negative impact on the cost side of the milk production process rather than milk production, via breeding, healthcare, and depreciation expenses.

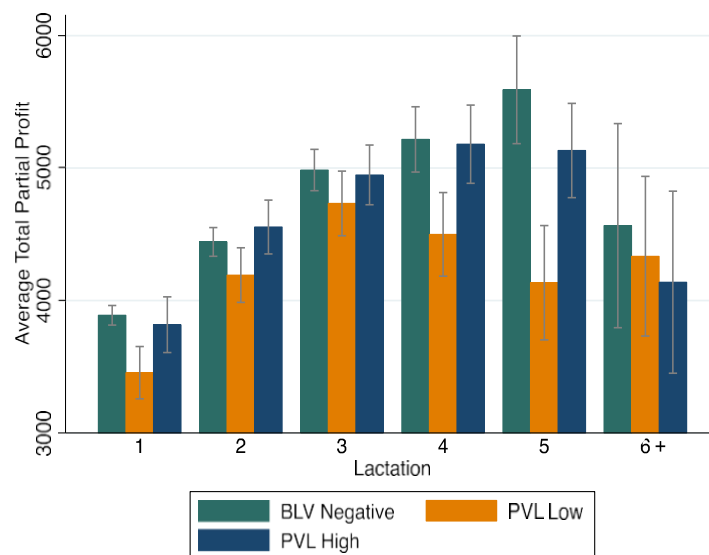


Figure 10: Average partial profit using cont. opp. cost, by lactation and PVL group

In Figure 10 the PVL high group has a greater average partial profitability in each lactation besides lactation six plus, when compared to the PVL low group, this mainly being driven by higher levels of milk production. The BLV negative group in Figure 10 has a higher average partial profit in lactations one, three, four, five, and six plus.

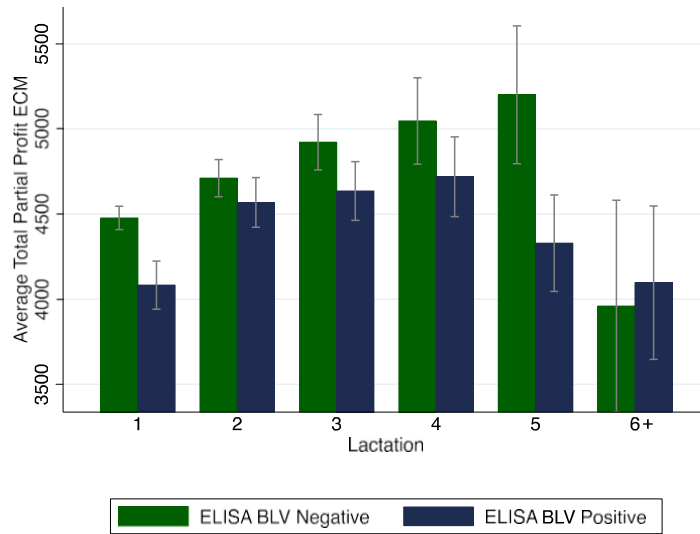


Figure 11: Average partial profit using ECM and cont. opp. cost, by lactation and ELISA status

Figure 11 follows a similar trend in each lactation by ELISA BLV status as in Figure 7, where ELISA BLV negative cows have greater levels of average partial profit in lactations one through five when using ECM and the continuous opportunity cost. A key difference between the two figures, however, is the average partial profit in lactation six plus is higher for ELISA BLV positive group.

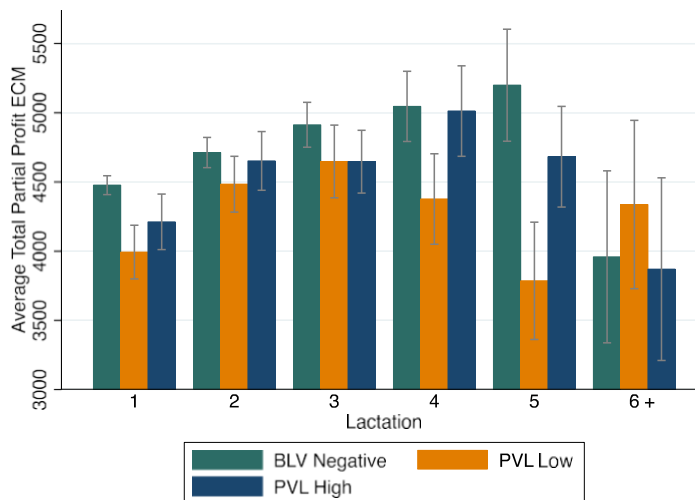


Figure 12: Average partial profit using cont. opp. cost and ECM, by lactation and PVL group

Figure 12 depicts differences in partial profit using ECM and the continuous opportunity cost by PVL group. It follows a similar trend to the average partial profit using milk pounds in Figure 10, where compared to the PVL low group the PVL high group has greater average partial profit in each lactation other than lactation 6 plus. One difference here in Figure 12, however, is that

the BLV negative group has higher levels of average partial profit, when compared to the PVL high group, in every lactation (the PVL high group had higher average total partial profit in lactation two in Figure 10). Also, like the average total ECM production, the PVL low group had the highest average partial profit in lactation six plus.

5.3 Longevity Analysis

The longevity analysis depicts differences in herd longevity in terms of total days in the herd. Partial profitability is, in part, a function of longevity via the opportunity cost of early cull and depreciation costs directly, and indirectly, milk revenue, breeding costs, and healthcare cost change as a cow ages. Understanding the differences in longevity amongst BLV positive and negative cows can provide further clarity to how BLV impacts partial profitability over time. Other studies, such as Bartlett et al. (2013) have done a similar analysis, where they compared survival probabilities within the herd, starting from when cows were tested for BLV, and comparing BLV negative cows to three varying levels of positive cows with different optical density³ values. In this study they found that cows with higher optical density values were more likely to die or be culled when compared to their BLV negative cows herd mates.

For the survival analysis we use Kaplan-Meier survival graphs to compare the survival probability, in days, from the calving date of the lactation a cow first tests positive, to BLV negative cows in that same lactation number. For example, a cow that tests positive for the first time in lactation 2 will be compared to cows that were negative for BLV in lactation 2, even if they contracted the virus in a later lactation. We conducted the analysis for lactations one through four.

The groups used in each survival graph are BLV negative cows, PVL low and PVL high cows. We do not compare cows only within their herd like in Bartlett et al. (2013), rather, we use the entire sample due to large variations in herd size amongst the farms. To our knowledge, this is the first BLV survival analysis to compare BLV positive and negative cows on a first lactation positive basis; other studies will treat a BLV positive cow as positive her whole life, regardless of when she contracted the virus. This method was picked partially based on the nature of the data but proves to be powerful. If we had chosen to follow the longevity of cows from a certain

³ Optical density with regards to ELISA testing refers to virus antibody concertation.

test date, we would lose large portions of data either because a cow in the sample was culled prior to that test date or because a cow entered their first lactation after that test date. However, choosing to compare cows beginning with the first lactation they tested positive to negative cows in that same lactation yielded a unique contribution to BLV survival analysis. As described in the following figures, what lactation a cow first tests positive for BLV is a major determining factor in their probability for survival when compared to BLV negative cows in the same lactation.

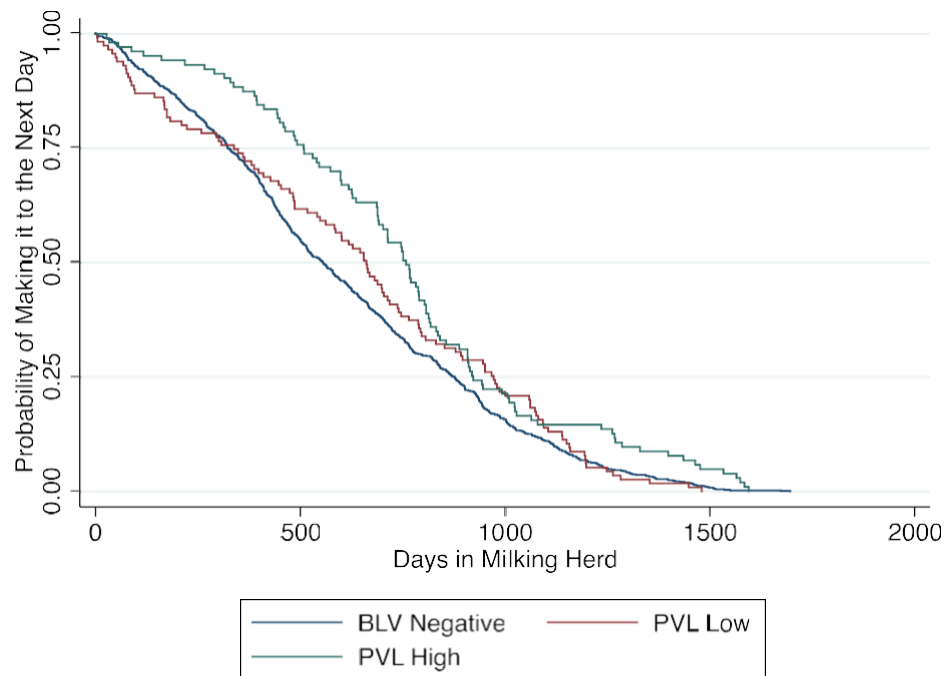


Figure 13: Kaplan-Meier survival graph comparing first lactation positive in first lactation (PVL low & high) to first lactation BLV negative cows

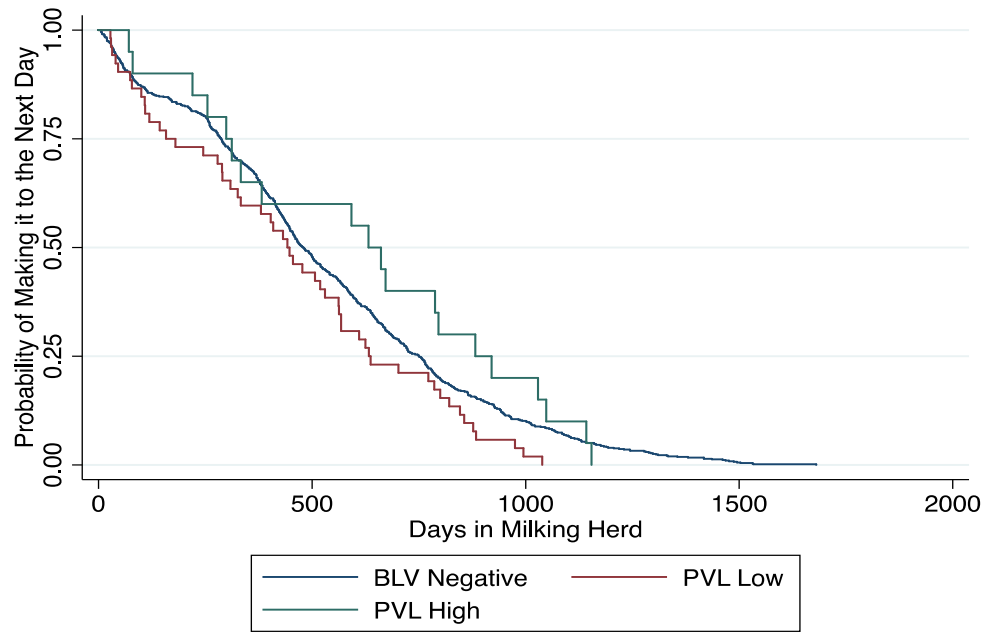


Figure 14: Kaplan-Meier survival graph comparing first lactation positive in second lactation (PVL low & high) to second lactation BLV negative c

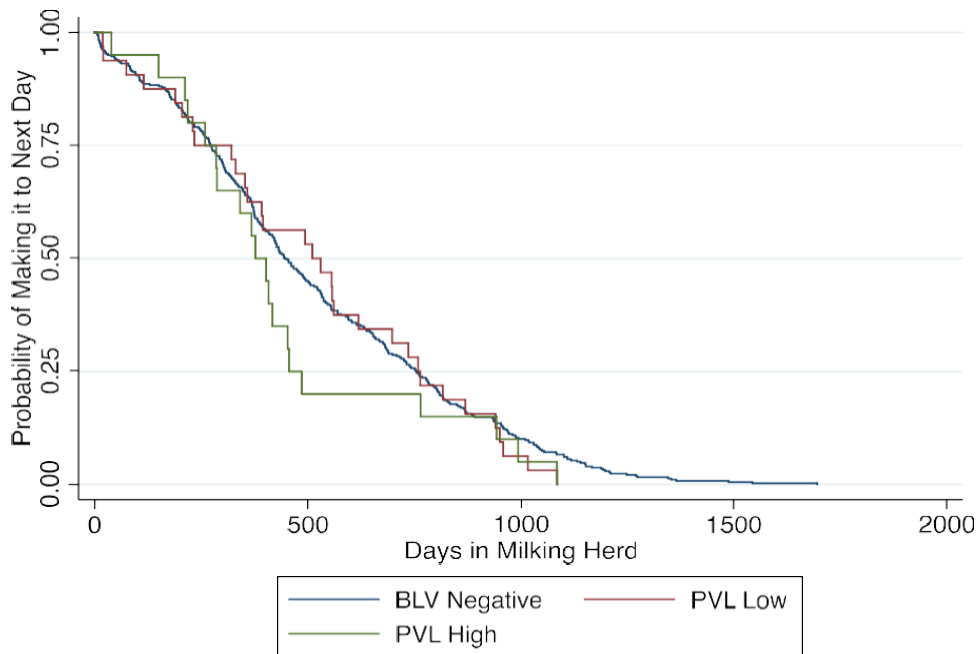


Figure 15: Kaplan-Meier survival graph comparing first lactation positive in third lactation (PVL low & high) to third lactation BLV negative cows

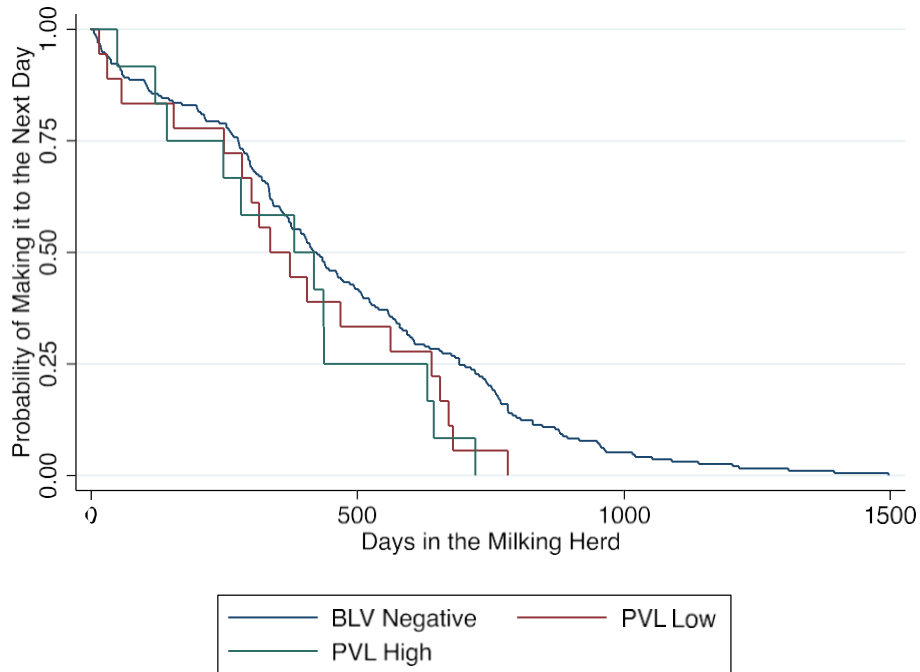


Figure 16: Kaplan-Meier survival graph comparing first lactation positive in fourth lactation (PVL low & high) to fourth lactation BLV negative cows

Kaplan-Meier graphs plot the probability of survival from one time period to the next, over a given time frame. The time frame we are concerned with is the days in the milking herd from the start of a lactation. Therefore, following the plot along the X axis we can see the probability of a cow surviving to the next day from the current day (e.g., the probability of surviving to day 11 if it is day 10). Comparing the shapes of these curves indicates the overall probability of survival from that lactation to the time the last cow was culled. The shape of the BLV negative curves stays rather consistently convex and smooth throughout Figure 13 to Figure 16, whereas the PVL low and high curves start concave in lactation one of Figure 13 and moves to convex starting in lactation three of Figure 16. In Figure 14, comparing first lactation positive cows in the first lactation to BLV negative cows in their first lactation, the BLV negative cows survive the longest number of days, but the probability of surviving to the next day is lower for the majority of days when compared to both groups of positive cows. Further, PVL high cows that first tested positive in their first lactation generally had a lower probability of dying or being culled for most of their lifetime when compared to PVL low cows and BLV negative cows.

Figure 14 show that cows that tested positive for the first time in their second lactation with a low PVL have a lower probability of surviving to the next day than do BLV negative cows in

their second lactation. Conversely, PVL high cows have approximately the same probability of making it to the next day as BLV negative cows until about day 500, but then have a higher probability of surviving until about day 1,200 of the given time frame, where their survival probability drops to zero.

In Figure 15, where we compare first lactation positive in the third lactation cows to BLV negative cows, the PVL high group has the highest probability of leaving the herd (lowest probability of survival) most of the period. Both PVL low and high groups have a shorter overall time in the herd when compared to BLV negative cows.

Finally, in Figure 16 both PVL groups that tested positive for BLV for the first time in their fourth lactation have a higher probability of leaving the herd (lower probability of survival) when compared to BLV negative cows, and both survive for a shorter amount of time.

Comparing all the Kaplan-Meier survival figures, a general trend emerges where cows testing positive for the first time in later lactation periods have a higher probability of leaving the herd when compared to BLV negative cows in the same lactation. Cows that test positive for BLV in their first lactation tend to have better odds of surviving more days when compared to cows that test positive for the first time in later lactations. Even PVL high cows that test positive for the first time in their second lactation, survive fewer days overall when compared to BLV negative cows, even if their probability of survival for one day to the next is higher for most of that time frame. This analysis provides evidence as to why we must interact ELISA status or pro viral load group with lactation in our regression models. The longevity of a cow seems to be determined by not only if a cow tests positive for BLV, but also when they test positive for the virus.

5.4 Regression Results and Discussion

The regression results are shown in four different tables. Within each table, the independent variables will be the same across all models, but the partial profit dependent variable is different. Please refer to Table 9 for a description of each dependent variable. Regression results for four fixed effects models using ELISA status as the key independent variable are found in Table 10. Results of the postestimation for the within breed effects of ELISA status on partial profitability (models 1-4) are in Table 11. The models shown in Table 12 uses the PVL categorical variable as the key independent variables (models 5-8). Finally, results from the breed postestimation with provirus load are in Table 13. Regression tables in the main text

have been condensed to report the most important coefficients; full coefficient output tables are in Appendix D.

Table 9: Partial profit dependent variable descriptions

Model number	Dependent variable	Description
<i>Models 1 & 5</i>	<i>PP milk pounds cont.</i>	Partial profit using milk pounds and continuous opportunity cost of less productive days
<i>Models 2 & 6</i>	<i>PP ECM cont.</i>	Partial profit using ECM and continuous opportunity cost of less productive days
<i>Models 3 & 7</i>	<i>PP milk pounds discrete</i>	Partial profit using milk pounds and discrete opportunity cost of less productive days
<i>Models 4 & 8</i>	<i>PP ECM discrete</i>	Partial profit using ECM and discrete opportunity cost of less productive days

Table 10: Regression output using ELISA test status

VARIABLES	MODEL 1	MODEL 2	MODEL 3	MODEL 4
	<i>PP milk pounds cont.</i>	<i>PP ECM cont.</i>	<i>PP milk pounds discrete</i>	<i>PP ECM discrete</i>
Base: <i>ELISA negative</i>				
<i>ELISA positive</i>	-266.50** (126.82)	-397.91*** (133.03)	-279.7** (127.05)	-413.39*** (133.38)
Base: <i>Not culled in current lactation</i>				
<i>Culled in current lactation</i>	-1,364*** (68.64)	-1227.45*** (68.26)	-1,381*** (68.15)	-1243.37*** (67.75)
<i>Lactation</i>				
<i>Interaction of ELISA Positive and Lactation</i>	Included	Included	Included	Included
<i>Production year</i>	Included	Included	Included	Included
<i>Month started lactating</i>	Included	Included	Included	Included
Constant	3,578*** (149.39)	4,414*** (154.63)	3,708*** (145.90)	4,538.7*** (151.06)
Observations	6,624	6,621	6,624	6,621
Number of COWID's	3,693	3,692	3,693	3,692
R-squared within	0.309	0.324	0.318	0.334
F-Test	59.24	79.85	61.19	83.34

¹ Reported standard errors are robust and clustered around COWID

Table 11: Post-estimation output for interaction between breed and ELISA status

VARIABLES	MODEL 1	MODEL 2	MODEL 3	MODEL 4
	<i>PP milk pounds cont.</i>	<i>PP ECM cont.</i>	<i>PP milk pounds discrete</i>	<i>PP ECM discrete</i>
<i>Holstein interacted with ELISA positive</i>	-222.64* (134.06)	-375.30*** (137.63)	-236.66 (134.41)	- 390.89*** (138.19)
<i>Jersey interacted with ELISA positive</i>	-437.89* (225.83)	-511.10* (280.00)	-446.35** (222.52)	-525.41* (277.17)

¹ Reported standard errors are robust and clustered around COWID

The coefficient estimates in Table 10 can be interpreted as a dollar value change in partial profitability per cow per lactation/production year. Thus, across all four models, a cow that tested positive for BLV had a statistically significantly lower partial profit by at least \$260 per cow when compared to cows that tested BLV negative. Recall in Table 8 the per lactation average partial profit calculated with milk pounds was higher for BLV positive cows. However, in Table 10 BLV positive cows have a significant reduction in partial profit calculated with milk pounds. This emphasizes the importance of conducting a multivariate analysis where we include time varying fixed effects. These regression results do concur with the findings in Kuczewski et al. (2019), where they estimated a \$473 decrease in yearly partial net revenues for BLV positive cows, although they did not account for breed, healthcare, or similar opportunity costs as in our partial profit equation. Ott et al. (2003) found an average reduction of \$59 in the annual value of production for cows that belonged to a herd with any level of BLV infection. However, given that their annual value of production does not account for variable costs, such as breeding and healthcare costs, it is likely an underestimate of the true impact of BLV.

The magnitude and statistical significance of the effect is stronger in models 2 and 4 which use ECM. Thus, this may indicate that BLV infection is impacting the milk components (protein and fat) to a greater extent than it is impacting the milk pounds. To our knowledge, no other economic study on the effects of BLV has estimated the impact of BLV infection on energy corrected milk. Yet, we find that BLV infection is having a greater impact on ECM partial profit when compared to milk pounds. Milk merit, via fat and protein levels, is imperative to a dairy farm's revenue as it effects the price per pound of milk the farm receives. Therefore, the estimates made in models 2 & 4 reflect a more compressive look into the impacts of BLV on partial profitability. Another notable takeaway is that there is a greater reduction in partial profit for ELISA positive cows in models 3 and 4, where partial profit was calculated using the discrete opportunity cost of less productive days.

Additionally, cows, regardless of their BLV status, were less profitable in the lactation they were culled by at least \$1200 compared to cows that were not culled. These results are strongly statistically significant at the 1% level in all four models. Potentially, the large magnitude of the culled coefficients is caused by reduced milk revenue in the lactation a cow was culled in because they may not complete a full lactation's worth of milk production. Also,

recall that if a cow is culled in their first or second lactation, they were assigned an opportunity cost of early cull. This opportunity cost is also contributing to the sizable loss in partial profit in the year that a cow is culled. The magnitude of partial profit loss for the lactations a cow is culled shows how culling a cow earlier than expected has major implications on per cow partial profit and is further evidence of the importance of culling decisions made by herd managers.

Coefficient estimates from the post estimation for the interaction between breed and BLV status are in Table 11 for each of the four regression models shown in Table 10. BLV positive Holstein cows had a partial profit that was at \$220 lower than BLV negative Holstein cows in each of the four models. However, the effect is not statistically significant in the *PP milk pounds discrete* model. Following with the trends in Table 10, partial profits calculated using energy corrected milk resulted in a greater loss in partial profit when compared to partial profit using milk pounds. This same trend is also occurring amongst Jersey cows. However, the estimated reduction in partial profit for BLV positive Jersey cows is greater when compared to BLV positive Holstein cows. For instance, in model 4 where the dependent variable is the *PP ECM pounds discrete*, the reduction in partial profit for ELISA BLV negative Holstein cows is \$391, while the reduction in partial profit for ELISA BLV Jersey cows is \$525. Future economic studies on BLV should build off these results and further investigate if and how economic losses from BLV differ by breed.

Table 12: Regression output using PVL categories

VARIABLES	MODEL 5	MODEL 6	MODEL 7	MODEL 8
	<i>PP milk pounds cont.</i>	<i>PP ECM cont.</i>	<i>PP milk pounds discrete</i>	<i>PP ECM discrete</i>
Base: <i>ELISA negative</i>				
<i>PVL low</i>	-369.90** (168.51)	-467.64*** (180.07)	-366.60** (170.88)	-464.82** (183.07)
<i>PVL medium low</i>	-493.7* (298.99)	-713.04** (300.13)	-547.9* (301.37)	-769.96* (301.73)
<i>PVL medium high</i>	-76.16 (204.16)	-481.23** (214.43)	-105.3 (203.35)	-513.78** (213.81)
<i>PVL high</i>	150.60 (261.43)	65.27 (277.44)	118.80 (256.58)	35.60 (271.48)
Base: <i>Not culled in lactation</i>				
<i>Culled in current lactation</i>	-1,364*** (68.81)	-1,227.81*** (68.40)	-1,381*** (68.36)	-1,243.45*** (67.94)
<i>Lactation</i>	Included	Included	Included	Included
<i>Interaction of ELISA Positive and Lactation</i>	Included	Included	Included	Included
<i>Production year</i>	Included	Included	Included	Included
<i>Month started lactating</i>	Included	Included	Included	Included
Constant	3,555*** (150.88)	4,399.38*** (156.24)	3,685*** (147.50)	4,538.80*** (152.58)
Observations	6,619	6,616	6,619	6,616
Number of COWID's	3,693	3,692	3,693	3,692
R-squared within	0.311	0.327	0.320	0.3373
F-Test	37.89	51.19	39.04	53.33

¹ Reported standard errors are robust and clustered around COW

Table 13: Regression output for interaction between breed & PVL

VARIABLE	MODEL 5	MODEL 6	MODEL 7	MODEL 8
	<i>PP milk pounds cont.</i>	<i>PP ECM cont.</i>	<i>PP milk pounds discrete</i>	<i>PP ECM discrete</i>
<i>Holstein interacted with PVL low</i>	-369.85** (168.38)	-475.52*** (179.13)	-367.47** (170.73)	-473.71*** (182.07)
<i>Holstein interacted with PVL medium low</i>	-494.08 (312.63)	-661.05** (327.58)	-542.49* (313.87)	-711.29** (328.41)
<i>Holstein interacted with PVL medium high</i>	-76.96 (294.16)	-356.85 (370.57)	-92.21 (288.96)	-373.43 (367.73)
<i>Holstein interacted with PVL high</i>	149.38 (414.62)	255.74 (535.10)	138.78 (404.63)	250.53 (528.57)
<i>Jersey interacted with PVL low</i>	-397.76* (208.61)	-428.24* (250.34)	-379.03* (208.92)	-408.59 (251.55)
<i>Jersey interacted with PVL medium low</i>	-516.80 (314.59)	-680.40** (332.85)	-558.19* (315.44)	-723.38** (333.05)
<i>Jersey interacted with PVL medium high</i>	-98.70 (233.79)	-449.38* (258.18)	-115.29 (221.13)	-468.33* (256.07)
<i>Jersey interacted with PVL high</i>	130.21 (273.48)	94.11 (308.54)	109.71 (267.47)	76.75 (302.02)

The key independent variables in models 5 through 8 in Table 12 is a categorical variable for provirus load. Each coefficient estimate of provirus load is compared to ELISA BLV negative cows. Across each model in Table 12 the PVL low group of cows is estimated to have a reduction in partial profit of at least \$360, on average, when compared to ELISA BLV negative cows. This result is significant at the 10% level for models 5 and 7 and at the 5% level for models 6 and 8. The PVL medium low group has an even further reduction in partial profit than the PVL low group, on average, when compared the BLV negative cows. This result is statistically significant at the 10% level. In the PVL medium high a group BLV infection reduced partial profit in all models, but the effect was not statistically significant in Model 5 and 7. The PVL high group has unexpected, but statistically insignificant results where BLV infection increases partial profit.

Given that PVL measures the amount of provirus copies in the blood, we would expect increases in PVL to result in greater magnitudes of partial profit losses per cow. However, based on the coefficient estimates in Table 12 this trend does not fully hold. Results from Table 12 do seem to concur with the trends in partial profitability in Figure 10 where the PVL high group has greater levels of average partial profit across most lactations. However, coefficient estimates in the PVL high group were insignificant across all four models, therefore we cannot say with any confidence that cows in the PVL high group do generate higher partial profit when compared to ELISA BLV negative cows. We explored alternative methods for creating the PVL categorical variable. For instance, we created a PVL category based on PVL low and high groups, having a PVL “null” category for ELISA positive cows that had little to no detected provirus, as well as leaving the PVL variable as continuous. We determined that breaking up the provirus load continuous variable into a categorical variable based on the quantiles of the distribution, and where PVL “null” cows are assigned a value of 1 best fit regression models.

Coefficient estimates for the PVL BLV status impact on Holstein and Jersey cow partial profit are in Table 13. The trend of an inconsistent effect of increasing PVL levels on partial profit when compared to BLV negative cows is similar to coefficients reported in Table 12. Both Holstein and Jersey cows in the PVL low group have a reduction in partial profit when compared to BLV negative cows, with the effect in Model 8 for Jersey cattle being insignificant. Then, once we look at the PVL high groups for both breeds; there is an increase in partial profit, but

these results are not statistically significant. We also see a similar effect across breeds as in Table 11, where BLV infection had a greater negative impact on partial profit for Jersey cows compared to Holsteins.

5.5 Sensitivity Analysis

Portions of the partial profit equation utilized inputs that were based on assumptions or calculated using data from other studies. A sensitivity analysis can determine how robust the BLV profitability impact estimates are to assumptions. The sensitivity analysis will also allow us to determine a range of potential partial profit loss for BLV positive cows, as losses in partial profit can change over time through changes in the milk price or cull values the farm receives, for example. We will conduct a sensitivity analysis on the variables of average milk price per pound, Wood function parameters used to estimate the per cow milk per production per day, and percent change in carcass weight by BLV status used in the depreciation expense.

A one-way sensitivity analysis was conducted to test the change in the coefficients and statistical significance for models 1 through 4, where the key independent variable is the binary variable for ELISA status (the original regression results can be found in Table 10). A one-way sensitivity analysis involves changing the input value of only one variable (here components of partial profit) without changing the value of any other variables. In Table 14, we report three alternative specifications for average milk price per pound, Wood function parameters, and the carcass weight percent change by BLV status and the corresponding ELISA positive partial profit coefficients.

Table 14: Sensitivity of the ELISA positive coefficient estimates

Variable changed	Pounds, Continuous	ECM, Continuous	Pounds, Discrete	ECM, continuous
<i>Original ELISA Positive Coefficients from Models 1-4</i>				
None	-266.50**	-397.91***	-279.7**	-413.39***
<i>Milk price</i>				
\$0.163/lb	-198.34**	-312.17***	-211.53**	-327.64***
\$0.192/lb	-231.15**	-366.66***	-244.33**	-382.13***
\$0.253/lb	-300.16*	-481.28***	-313.34**	-496.76***
<i>Wood function parameters</i>				
Rekik and Ben Gara (2004)	-271.06**	-401.14***	-282.79**	-415.67***
Val-Arreola et al. (2004)	-277.79**	-410.82***	-288.71**	-424.27***
Cole and Null (2009)	-266.93**	-396.61***	-279.56**	-412.83***
<i>Carcass weight change by BLV status</i>				
No change	-234.96*	-366.06***	-248.23**	-381.64***
1238.53lbs	-246.33*	-377.41***	-259.60**	-392.99***
1104.17lbs	-293.67**	-424.70***	-306.94**	-440.27***

In the original models, milk prices received by the farm were used. However, since milk is the main revenue source, milk prices could greatly affect differences in partial profitability. To inform our sensitivity analysis we used the milk price per pound from the USDA National Agriculture Statistic Service (2023) from January 2014 to June 2023, excluding 2020 because of the COVID-19 pandemic. Given that our analysis is on a lactation basis, we created an annual milk price by taking the average of the monthly milk price in that calendar year. The low, average and high milk prices – \$0.163/lb, \$0.192/lb and \$0.253/lb – are used in the

sensitivity analysis. As shown in Table 14, as the milk price per pound increases, so does the reduction in partial profit for ELISA positive cows per lactation. The range of partial profit loss for the milk price sensitivity analysis is \$198.34 to \$496.76. Although this is a large range from changes in milk prices, over \$200 per cow per lactation, a cow infected with BLV still has a statistically and economically significantly lower partial profit than a cow not infected with BLV.

We use three sets of Wood function parameters in the sensitivity analysis from Rekik and Ben Gara (2004), Val-Arreola et al. (2004), and Cole and Null (2009) who estimated their parameters based on historical per cow per day milking records.⁵ The range of estimates for the Wood function parameters resulted in a partial profit loss between \$271.06 to \$496.76 for BLV positive cows, similar to the original coefficients from models 1 to 4.

The lower and upper 95% confidence interval percent changes in carcass weight at culling of -2.5% and -13% for BLV positive cows compared to negative cows were obtained from Nakada et al. (2022). The -2.5% change results in a culling weight for BLV positive cows used in the depreciation schedule of 1238.53lbs, while the -13% change in 1104.17lbs. For comparison the carcass weight used in the depreciation schedule for BLV negative cows is 1270.78lbs. We also use a third scenario where we assume no change in the cull weight by BLV status. Table 14 shows that regardless of the percentage change in carcass weight – even no change in carcass weight – used in the depreciation schedules, ELISA positive cows have a statistically significant reduction in partial profit when compared to ELISA negative cows. As expected, when the percent change in cull weight between BLV groups increases, so does the estimated partial profit loss for BLV positive cows. When there is no percentage change in carcass weight BLV positive cows loses between \$234.96 and \$381.64, while a percent change of -13% results in a partial profit loss ranging from \$293.67 to \$440.27 per cow per lactation.

⁵ Wood function parameters for Rekik and Ben Gara (2004): first lactation- A: 13.89 B: 0.25 C: 0.004 second lactation- A:17.46 B:0.24 C: 0.005 third lactation and greater- A: 19.56 B: 0.23 C: 0.005

Wood function parameters for Val-Arreola et al. (2004): first lactation- A: 12.6 B: 0.17 C: 0.002 second lactation- A: 19.1 B: 0.15 C: 0.004 third lactation and greater- A: 15.1 B: 0.21 C: 0.005

Wood function parameters for Cole and Null (2009): first lactation- A: 13.01 B: 0.27 C: 0.003 second lactation and greater- A: 22.01 B: 0.22 C: 0.004

None of the input values tested in the sensitivity analysis changed the sign of the BLV positive coefficient in any model, also, the BLV positive coefficients remained statistically significant at least at the 10% level. However, the magnitude of the estimated partial profit loss for BLV positive cows vary widely across the sensitivity analysis (\$198.34 to \$496.76 per cow per lactation).

6. IMPLICATIONS AND CONCLUSION

Using fixed effects regression models, which allowed us to control for key time-varying factors, we found that BLV infection negatively impacted dairy cow partial profit. We found that BLV positive cows had a partial profit loss between \$198.34 and \$496.76 per lactation. When accounting for milk merit via energy corrected milk we found that partial profit loss for BLV positive cows was greater when compared to partial profit calculated with milk pounds. Recall, BLV persists in over 94% of dairy operations in North America, with an average herd prevalence of 46% (LaDronka et al. 2006). Thus, our estimated loss in partial profit from BLV could have major implications for most dairy farms in the U.S. Consider, for example, farm A in our study, with a BLV prevalence of 46% in their milking herd, the same as the average herd in North America. Farm A has a herd size of 550 cows, and roughly 253 of those cows are infected with BLV in a given production year. Farm A could be losing between \$198.34 and \$496.76 in partial profit per positive cow, or roughly between \$50,180.02 and \$125,680.28 in any given production year. Farm level profit margins have been shrinking for over 20 years on U.S dairy farms (Salfer 2021), our estimates show that BLV could be a contributing factor to this trend.

Our study did face obstacles in data collection, specifically estimating some costs and revenues on a per cow level, resulting in limitations. For instance, labor costs were only accounted for via veterinarian expenses and estimated on-farm labor cost per healthcare treatment provided to us by the farms. None of the farms in our study allocate labor based on farm activity. Future estimations would benefit from the inclusion of more precise labor costs for milking, healthcare, breeding, and other potential dairy production costs that could be impacted by BLV. Another limitation we faced was not being able to tease out heifer replacement costs or cull values on a per cow basis from the farms' financials. Additionally, cull values could not be attributed on a per cow basis because once a culled cow reached auction or the meat processor, they were assigned a new backtag with a unique identification number that did not match nor was linked to the farms ear tag (identification). Each farm in our study was given the cull sale receipt per cull cow with this new backtag number, making it impossible to track the cull value back to one of the cows culled in the herd. The practice of using backtags is standard in the cattle supply chain and could hurt research efforts such as ours because of the inability to retroactively obtain cull cattle values for a specific animal. It would be advantageous to farmers and researcher if beef

processors and auctions would report back both on farm ear tag numbers and the backtag number when generating cull revenue receipts.

Outside of fluid milk, dairy is an input into many food products, such as cheese, butter, yogurt, and ice cream. Cooperatives, food processors and manufacturers, retailers, and consumers all benefit from dairy products. Thus, we encourage future studies to investigate the potential economic losses from BLV past the farm gate.

One of the motivations for this study was to be able to give farms and other stakeholders a more accurate estimates of the economic impacts of BLV infection in dairy cattle. However, the academic, and extension communities, along with government agencies, need to provide further outreach and materials to farmers on what BLV is and how it could be impacting their cattle herd and bottom line. For instance, government agencies, such as the USDA, have long been an advocate and partner for the U.S dairy industry. In fact, the USDA has had its own dairy division since 1895 (USDA 2023). Moving forward, the USDA should utilize its resources to help educate farmers about the impacts of BLV and mitigate its spread at the farm level given the magnitude of partial profit losses.

While outside of the scope of this study, if a farm does decide to implement BLV mitigation strategies to lessen their herd's BLV prevalence or eradicate it entirely, there will, consequently, be costs associated with doing so. Mitigating BLV, for example, by replacing BLV positive animals has its own set of costs to the farm, including the opportunity cost of replacing a BLV positive animal with a BLV negative one. This is because the farm will have to raise a replacement heifer and lose the current revenue that the milking BLV positive cow is generating for the farm.

Our study most likely underestimates the true economic impact of a BLV positive cow. For example, we do not take into consideration the opportunity cost of a positive cow infecting a negative cow in the herd. Future studies should incorporate this opportunity cost while investigating how BLV spreads through the herd and potential BLV mitigation strategies. Future studies may also make more accurate estimations by collecting data from farms in which the producer does not know the BLV status of the cows in their herd. Even though each of the producers we worked with claimed to not make culling decisions based on BLV status, selection bias could impact analysis because each of our producers had the knowledge of which

cows in their herd were BLV positive.

BIBLIOGRAPHY

- Bartlett, P.C., Norby, B., Byrem, T. M., Parmelee, A., Ledergerber, J. T., & Erskine, R. J. (2013). Bovine leukemia virus and cow longevity in Michigan Dairy Herds. *Journal of Dairy Science*, 96(3), 1591–1597. <https://doi.org/10.3168/jds.2012-5930>
- Bartlett, Paul C., Sordillo, L. M., Byrem, T. M., Norby, B., Grooms, D. L., Swenson, C. L., Zalucha, J., & Erskine, R. J. (2014). Options for the control of bovine leukemia virus in dairy cattle. *Journal of the American Veterinary Medical Association*, 244(8), 914–922. <https://doi.org/10.2460/javma.244.8.914>
- Cole, J.B., et al. “Best Prediction of Yields for Long Lactations.” *Journal of Dairy Science*, vol. 92, no. 4, 2009, pp. 1796–1810, <https://doi.org/10.3168/jds.2007-0976>.
- Dematawewa, C. M. B., Pearson, R. E., & VanRaden, P. M. (2007). Modeling extended lactations of Holsteins. *Journal of Dairy Science*, 90(8), 3924–3936. <https://doi.org/10.3168/jds.2006-790>
- Erskine, R. J., Bartlett, P. C., Byrem, T. M., Render, C. L., Febvay, C., & Houseman, J. T. (2012). Association between bovine leukemia virus, production, and population age in Michigan Dairy Herds. *Journal of Dairy Science*, 95(2), 727–734. <https://doi.org/10.3168/jds.2011-4760>
- Frie, M. C., & Coussens, P. M. (2015). Bovine leukemia virus: A major silent threat to proper immune responses in cattle. *Veterinary Immunology and Immunopathology*, 163(3–4), 103–114. <https://doi.org/10.1016/j.vetimm.2014.11.014>
- Hennessy, D. A., & Feng, H. (2018). *America’s Dairy Industry Facing Difficulties from Long- Running Structural Changes*. Choices Magazine. <https://www.choicesmagazine.org/choices-magazine/theme-articles/americas-dairy-industry-adapting-to-long-running-structural-p pressures/americas-dairy-industry-facing-difficulties-from-long-running-structural-changes>
- Hopkins, S. G., & DiGiacomo, R. F. (1997). Natural transmission of bovine leukemia virus in dairy and beef cattle. *Veterinary Clinics of North America: Food Animal Practice*, 13(1), 107–128. [https://doi.org/10.1016/s0749-0720\(15\)30367-4](https://doi.org/10.1016/s0749-0720(15)30367-4)
- Kettmann, R., Portetelle, D., Mammerickx, M., Cleuter, Y., Dekegel, D., Galoux, M., Ghysdael, J., Burny, A., & Chantrenne, H. (1976). Bovine leukemia virus: An exogenous RNA oncogenic virus? *Modern Trends in Human Leukemia II*, 375–389. https://doi.org/10.1007/978-3-642-87524-3_37
- Kopec, T., Chládek, G., Falta, D., Kučera, J., Večeřa, M., & Hanuš, O. (2021). The effect of extended lactation on parameters of Wood’s model of lactation curve in Dairy Simmental Cows. *Animal Bioscience*, 34(6), 949–956. <https://doi.org/10.5713/ajas.20.0347>

- Kuczewski, A., Hogeveen, H., Orsel, K., Wolf, R., Thompson, J., Spackman, E., & van der Meer, F. (2019). Economic evaluation of 4 bovine leukemia virus control strategies for Alberta Dairy Farms. *Journal of Dairy Science*, 102(3), 2578–2592. <https://doi.org/10.3168/jds.2018-15341>
- LaDronka, R. M., Ainsworth, S., Wilkins, M. J., Norby, B., Byrem, T. M., & Bartlett, P. C. (2018). Prevalence of bovine leukemia virus antibodies in US dairy cattle. *Veterinary Medicine International*, 2018, 1–8. <https://doi.org/10.1155/2018/5831278>
- Livestock Marketing Information Center. (2023, May 26). <https://www.lmic.info/>
- Nakada, S., Fujimoto, Y., Kohara, J., Adachi, Y., & Makita, K. (2022). Estimation of economic loss by carcass weight reduction of Japanese dairy cows due to infection with bovine leukemia virus. *Preventive Veterinary Medicine*, 198, 105528. <https://doi.org/10.1016/j.prevetmed.2021.105528>
- Nekouei, O., VanLeeuwen, J., Stryhn, H., Kelton, D., & Keefe, G. (2016). Lifetime effects of infection with bovine leukemia virus on longevity and milk production of Dairy Cows. *Preventive Veterinary Medicine*, 133, 1–9. <https://doi.org/10.1016/j.prevetmed.2016.09.011>
- Norby, B., Bartlett, P. C., Byrem, T. M., & Erskine, R. J. (2016). Effect of infection with bovine leukemia virus on milk production in Michigan Dairy Cows. *Journal of Dairy Science*, 99(3), 2043–2052. <https://doi.org/10.3168/jds.2015-10089>
- Ohno, A., Takeshima, S., Matsumoto, Y., & Aida, Y. (2015). Risk factors associated with increased bovine leukemia virus proviral load in infected cattle in Japan from 2012 to 2014. *Virus Research*, 210, 283–290. <https://doi.org/10.1016/j.virusres.2015.08.020>
- Olthof, L. (n.d.). *Lactation period example*.
- Ott, S. L., Johnson, R., & Wells, S. J. (2003). Association between bovine-leukosis virus seroprevalence and herd-level productivity on US dairy farms. *Preventive Veterinary Medicine*, 61(4), 249–262. <https://doi.org/10.1016/j.prevetmed.2003.08.003>
- Pelzer, K. D. (1997). Economics of bovine leukemia virus infection. *Veterinary Clinics of North America: Food Animal Practice*, 13(1), 129–141. [https://doi.org/10.1016/s0749-0720\(15\)30368-6](https://doi.org/10.1016/s0749-0720(15)30368-6)
- Rekik, B., and A. Ben Gara. “Factors Affecting the Occurrence of Atypical Lactations for Holstein–Friesian Cows.” *Livestock Production Science*, vol. 87, no. 2–3, 2004, pp. 245–250, <https://doi.org/10.1016/j.livprodsci.2003.09.023>.

- Rhodes, J. K., Pelzer, K. D., & Johnson, Y. J. (2003). Economic implications of bovine leukemia virus infection in mid-Atlantic dairy herds. *Journal of the American Veterinary Medical Association*, 223(3), 346–352.
<https://doi.org/10.2460/javma.2003.223.346>
- Salfer, J. (n.d.). *Margin compression affects dairy producers*. Extension at the University of Minnesota. <https://extension.umn.edu/dairy-milking-cows/margin-compression-affects-dairy-producers>
- StataCorp. 2017. *Stata Statistical Software: Release 15*. College Station, TX: StataCorp LLC
- Val-Arreola, D., et al. “Study of the Lactation Curve in Dairy Cattle on Farms in Central Mexico.” *Journal of Dairy Science*, vol. 87, no. 11, 2004, pp. 3789–3799, [https://doi.org/10.3168/jds.s0022-0302\(04\)73518-3](https://doi.org/10.3168/jds.s0022-0302(04)73518-3).
- Watanabe, A., Murakami, H., Kakinuma, S., Murao, K., Ohmae, K., Isobe, N., Akamatsu, H., Seto, T., Hashimura, S., Konda, K., Shinozuka, Y., & Kawai, K. (2019). Association between bovine leukemia virus pro viral load and severity of clinical mastitis. *Journal of Veterinary Medical Science*, 81(10), 1431–1437. <https://doi.org/10.1292/jvms.19-0285>
- Wood, P. D. (1967). Algebraic model of the lactation curve in cattle. *Nature*, 216(5111), 164–165. <https://doi.org/10.1038/216164a0>
- Wooldridge, Jeffery M. (2011, March 11). *Stata: Data Analysis and Statistical Software*. Stata. <https://www.stata.com/statalist/archive/2011-03/msg00089.html>
- Wooldridge, Jeffrey M. (2010). *Introductory Econometrics: A Modern Approach, 4th Edition*.

**APPENDIX A. LIST OF MEDICINES AND THEIR ASSOCIATED COSTS USED IN HEALTHCARE TREATMENT
CALCULATIONS**

Table A 1: List of medicines, dosages, and total costs per treatment

<i>Medicine List</i>	<i>Amount per container (ml)</i>	<i>Amounts administer (ml)</i>	<i>cost per container</i>	<i>Cost per admin.</i>	<i>Labor charge</i>	<i>Total cost per treatment</i>
<i>Excenel</i>	250	10	\$182.54	\$7.30	\$5.00	\$12.30
<i>Polyflex</i>	25000	2000	\$48.65	\$3.89	\$5.00	\$8.89
<i>Cefenlin</i>	250	10	\$162.32	\$6.49	\$5.00	\$11.49
<i>Excede</i>	250	15	\$567.10	\$34.03	\$5.00	\$39.03
<i>Nuflor</i>	500	30	\$317.99	\$19.08	\$5.00	\$24.08
<i>Inforce 3</i>	100	1	\$76.91	\$0.77	\$5.00	\$5.77
<i>Penicillin</i>	500	15	\$40.99	\$1.23	\$5.00	\$6.23
<i>Lute</i>	100	5	\$59.22	\$2.96	\$5.00	\$7.96
<i>Tet</i>	250	5	\$52.99	\$1.06	\$5.00	\$6.06
<i>Dexasone</i>	100	1	\$9.50	\$0.10	\$5.00	\$5.10
<i>Today</i>	144	1	\$612.4	\$4.25	\$5.00	\$9.25
<i>Calcium</i>	500	250	\$5.43	\$2.72	\$5.00	\$7.72
<i>Bovikalc</i>	48	1	\$354.11	\$7.38	\$5.00	\$12.38

APPENDIX B. DEPRECIATION TABLES

Table B 1: Depreciation schedule; BLV negative, culled in Lactation 1

MODEL INPUTS				
Heifer replacement cost		\$1106/head		
Useful life		3 years		
Lactation culled		1		
Cull value; BLV negative		\$722.77		
Cull value; BLV positive		\$669.51		
Difference in depreciation		\$53.26		
SCHEDULE				
	Value at beginning of year	Depreciation	Value at end of year	BLV status
year 1	1106	383.23	722.77	NEG
Total Depreciation		383.23		

Table B 2: Depreciation schedule; BLV positive, culled in Lactation 1

MODEL INPUTS				
Heifer replacement cost		\$1106/head		
Useful life		3 years		
Lactation culled		1		
Cull value; BLV negative		\$722.77		
Cull value; BLV positive		\$669.51		
Difference in depreciation		\$53.26		
SCHEDULE				
	Value at beginning of year	Depreciation	Value at end of year	BLV status
year 1	1106	436.49	669.51	POS
Total Depreciation		436.49		

Table B 3: Depreciation schedule; BLV negative, culled in Lactation 2

MODEL INPUTS				
	<i>Heifer replacement cost</i>		\$1106/head	
	<i>Useful life</i>		3 years	
	<i>Lactation culled</i>		2	
	<i>Cull value; BLV negative</i>		\$722.77	
	<i>Cull value; BLV positive</i>		\$669.51	
	<i>Difference in deprecation</i>		\$53.26	
SCHEDULE				
	<i>Value at beginning of year</i>	<i>Depreciation</i>	<i>Value at end of year</i>	<i>BLV status</i>
year 1	1106	127.74	978.26	NEG
year 2	978.26	255.49	722.77	NEG
Total Depreciation		383.32		

Table B 4: Depreciation schedule; BLV positive in lactation 2, culled in Lactation 2

MODEL INPUTS				
	<i>Heifer replacement cost</i>		\$1106/head	
	<i>Useful life</i>		3 years	
	<i>Lactation culled</i>		2	
	<i>Cull value; BLV negative</i>		\$722.77	
	<i>Cull value; BLV positive</i>		\$669.51	
	<i>Difference in deprecation</i>		\$53.26	
SCHEDULE				
	<i>Value at beginning of year</i>	<i>Depreciation</i>	<i>Value at end of year</i>	<i>BLV status</i>
year 1	1106	127.74	978.26	NEG
year 2	1031.51	362.00	669.51	POS
Total Depreciation		489.74		

Table B 5: Depreciation schedule; BLV positive in lactation 1, culled in Lactation 2

MODEL INPUTS				
	<i>Heifer replacement cost</i>		\$1106/head	
	<i>Useful life</i>		3 years	
	<i>Lactation culled</i>		2	
	<i>Cull value; BLV negative</i>		\$722.77	
	<i>Cull value; BLV positive</i>		\$669.51	
	<i>Difference in depreciation</i>		\$53.26	
SCHEDULE				
	<i>Value at beginning of year</i>	<i>Depreciation</i>	<i>Value at end of year</i>	<i>BLV status</i>
year 1	1106	145.50	960.50	POS
year 2	960.50	290.99	669.51	POS
Total Depreciation		436.49		

Table B 6: Depreciation schedule; BLV negative, culled in Lactation 3

MODEL INPUTS				
	<i>Heifer replacement cost</i>		\$1106/head	
	<i>Useful life</i>		3 years	
	<i>Lactation culled</i>		3	
	<i>Cull value; BLV negative</i>		\$722.77	
	<i>Cull value; BLV positive</i>		\$669.51	
	<i>Difference in depreciation</i>		\$53.26	
SCHEDULE				
	<i>Value at beginning of year</i>	<i>Depreciation</i>	<i>Value at end of year</i>	<i>BLV status</i>
year 1	1106	127.74	978.26	NEG
year 2	978.26	127.74	850.51	NEG
year 3	850.51	127.74	722.77	NEG
Total Depreciation		383.22		

Table B 7: Depreciation schedule; BLV positive in lactation 3, culled in Lactation 3

MODEL INPUTS				
	<i>Heifer replacement cost</i>		\$1106/head	
	<i>Useful life</i>		3 years	
	<i>Lactation culled</i>		3	
	<i>Cull value; BLV negative</i>		\$722.77	
	<i>Cull value; BLV positive</i>		\$669.51	
	<i>Difference in deprecation</i>		\$53.26	
SCHEDULE				
	<i>Value at beginning of year</i>	<i>Depreciation</i>	<i>Value at end of year</i>	<i>BLV status</i>
year 1	1106	127.74	978.26	NEG
year 2	978.26	127.74	850.51	NEG
year 3	903.77	234.26	669.51	POS
Total Depreciation		489.74		

Table B 8: Depreciation schedule; BLV positive lactation 2, culled in Lactation 3

MODEL INPUTS				
	<i>Heifer replacement cost</i>		\$1106/head	
	<i>Useful life</i>		3 years	
	<i>Lactation culled</i>		3	
	<i>Cull value; BLV negative</i>		\$722.77	
	<i>Cull value; BLV positive</i>		\$669.51	
	<i>Difference in deprecation</i>		\$53.26	
SCHEDULE				
	<i>Value at beginning of year</i>	<i>Depreciation</i>	<i>Value at end of year</i>	<i>BLV status</i>
year 1	1106	127.74	978.26	NEG
year 2	1031.51	181.00	850.51	POS
year 3	850.51	181.00	669.51	POS
Total Depreciation		489.74		

Table B 9: Depreciation schedule; BLV positive lactation 1, culled in Lactation 3

MODEL INPUTS				
	<i>Heifer replacement cost</i>		\$1106/head	
	<i>Useful life</i>		3 years	
	<i>Lactation culled</i>		3	
	<i>Cull value; BLV negative</i>		\$722.77	
	<i>Cull value; BLV positive</i>		\$669.51	
	<i>Difference in depreciation</i>		\$53.26	
SCHEDULE				
	<i>Value at beginning of year</i>	<i>Depreciation</i>	<i>Value at end of year</i>	<i>BLV status</i>
year 1	1106	145.50	960.50	POS
year 2	960.50	145.50	815.01	POS
year 3	815.01	145.50	669.51	POS
Total Depreciation		436.50		

Table B 10: Depreciation schedule; BLV negative, culled in Lactation 4+

MODEL INPUTS				
	<i>Heifer replacement cost</i>		\$1106/head	
	<i>Useful life</i>		3 years	
	<i>Lactation culled</i>		4	
	<i>Cull value; BLV negative</i>		\$722.77	
	<i>Cull value; BLV positive</i>		\$669.51	
	<i>Difference in depreciation</i>		\$53.26	
SCHEDULE				
	<i>Value at beginning of year</i>	<i>Depreciation</i>	<i>Value at end of year</i>	<i>BLV status</i>
year 1	1106	127.74	978.26	NEG
year 2	978.26	127.74	850.51	NEG
year 3	850.51	127.74	722.77	NEG
year 4	722.77	0	722.77	NEG
Total Depreciation		383.22		

Table B 11: Depreciation schedule; BLV positive lactation 3, culled in Lactation 4+

MODEL INPUTS				
<i>Heifer replacement cost</i>			\$1106/head	
<i>Useful life</i>			3 years	
<i>Lactation culled</i>			4	
<i>Cull value; BLV negative</i>			\$722.77	
<i>Cull value; BLV positive</i>			\$669.51	
<i>Difference in deprecation</i>			\$53.26	
SCHEDULE				
	<i>Value at beginning of year</i>	<i>Depreciation</i>	<i>Value at end of year</i>	<i>BLV status</i>
year 1	1106	127.74	978.26	NEG
year 2	978.26	127.74	850.51	NEG
year 3	903.77	234.26	669.51	POS
year 4	669.51	0	669.51	POS
Total Depreciation		489.74		

Table B 12: Depreciation schedule; BLV positive lactation 2, culled in Lactation 4+

MODEL INPUTS				
<i>Heifer replacement cost</i>			\$1106/head	
<i>Useful life</i>			3 years	
<i>Lactation culled</i>			4	
<i>Cull value; BLV negative</i>			\$722.77	
<i>Cull value; BLV positive</i>			\$669.51	
<i>Difference in deprecation</i>			\$53.26	
SCHEDULE				
	<i>Value at beginning of year</i>	<i>Depreciation</i>	<i>Value at end of year</i>	<i>BLV status</i>
year 1	1106	127.74	978.26	NEG
year 2	1031.51	181.00	850.51	POS
year 3	850.51	181.00	669.51	POS
year 4	669.51	0	669.51	POS
Total Depreciation		489.74		

Table B 13: Depreciation schedule; BLV positive lactation 1, culled in Lactation 4+

MODEL INPUTS				
<i>Heifer replacement cost</i>			\$1106/head	
<i>Useful life</i>			3 years	
<i>Lactation culled</i>			4	
<i>Cull value; BLV negative</i>			\$722.77	
<i>Cull value; BLV positive</i>			\$669.51	
<i>Difference in depreciation</i>			\$53.26	
SCHEDULE				
	<i>Value at beginning of year</i>	<i>Depreciation</i>	<i>Value at end of year</i>	<i>BLV status</i>
year 1	1106.00	145.50	960.50	POS
year 2	960.50	145.50	815.01	POS
year 3	815.01	145.50	669.51	POS
year 4	669.514	0	669.51	POS
Total Depreciation		436.50		

APPENDIX C. ONE-WAY ANOVA TESTS

Table C 1: One-way ANOVA test for all model input variables and partial profits

<i>Variable Names</i>	<i>F-statistic</i>	<i>P-value</i>	<i>χ^2 test for equal variable</i>	<i>P-value</i>
<i>Milk Pounds</i>	10.3	0.0013	0.1736	0.677
<i>Milk Revenue</i>	0.07	0.7914	0.0016	0.968
<i>ECM Pounds</i>	0.22	0.6357	0.7246	0.395
<i>ECM Revenue</i>	12.55	0.0004	0.7989	0.371
<i>HealthCare Costs</i>	4.48	0.0344	5.1414	0.023
<i>Breeding Costs</i>	158.06	0.0000	45.1409	0.000
<i>Depreciation</i>	0.12	0.7331	103.8301	0.000
<i>Lactation Culled</i>	296.63	0.0000	18.2411	0.000
<i>Lactation Length (Days)</i>	6.34	0.0119	13.3963	0.000
<i>Opportunity Cost of Less Productive Days (Continuous)</i>	8.17	0.0043	1.7334	0.188
<i>Opportunity Cost of Less Productive Days ECM (Continuous)</i>	5.85	0.0157	0.2505	0.617
<i>Opportunity Cost of Less Productive Days (Discrete)</i>	8.38	0.0038	0.3411	0.559
<i>Opportunity Cost of Less Productive Days ECM (Discrete)</i>	6.06	0.0139	0.4014	0.526
<i>Opportunity Cost of Early Cull</i>	5.57	0.0184	13.5917	0.000

Table C 1 (cont'd)

Variable Names	F-statistic	P-value	χ^2 test for equal variable	P-value
<i>Opportunity Cost of Early Cull ECM</i>	5.57	0.0184	13.5917	0.000
<i>Partial profit (continuous)</i>	0.50	0.4789	1.1902	0.275
<i>Partial profit ECM (continuous)</i>	11.10	0.0009	0.0546	0.815
<i>Partial profit (discrete)</i>	0.35	0.5548	1.1354	0.287
<i>Partial profit ECM (discrete)</i>	11.90	0.0006	0.0946	0.758

APPENDIX D. REGRESSION OUTPUT TABLES

Table D 1: Full regression output for models 1-4, using ELISA status & robust standard errors

VARIABLES	MODEL 1	Model 2	Model 3	Model 4
	<i>PP milk pounds</i>	<i>PP ECM</i>	<i>PP milk pounds</i>	<i>PP milk pounds</i>
Base: <i>ELISA negative</i>	<i>cont.</i>	<i>cont.</i>	<i>discrete</i>	<i>discrete</i>
<i>ELISA positive</i>	-266.5** (126.8)	-397.9*** (133)	-279.7** (127)	-413.4*** (133.4)
Base: <i>Lactation1</i>				
<i>Lactation 2</i>	127.1 (150.4)	-329.2** (152.5)	209.7 (146.1)	-245.8* (147.6)
<i>Lactation 3</i>	-134.2 (289.70)	-521.6* (293.20)	38.81 (282.10)	-337.9 (284.80)
<i>Lactation 4</i>	-825.7* (427.10)	-1,189*** (428.00)	-566.7 (416.30)	-911.2** (415.70)
<i>Lactation 5 +</i>	-1,662*** (585.20)	-2,229*** (596.30)	-1,298** (570.10)	-1,841*** (578.70)
Base: <i>Interaction of ELISA positive & Lactation 1</i>				
<i>Elisa positive & Lactation 2</i>	35.26 (97.48)	258.9** (105.80)	48.61 (97.74)	278.0*** (106.10)

Table D 1 (cont'd)

<i>Elisa positive & Lactation 3</i>	235.1*	358.3**	250.4*	377.3**
	(132.00)	(147.30)	(131.70)	(147.00)
<i>Elisa positive & Lactation 4</i>	334.1*	451.8**	355.6**	476.0**
	(177.20)	(185.10)	(177.00)	(184.90)
<i>Elisa positive & Lactation 5+</i>	394.8	676.3**	416.6	698.7***
	(265.50)	(272.10)	(263.00)	(269.30)
 Base: Production year 2018				
<i>Production year 2019</i>	1,124***	1,336***	1,045***	1,251***
	(143.40)	(149.90)	(139.00)	(144.90)
<i>Production year 2020</i>	2,038***	2,135***	1,849***	1,930***
	(267.60)	(276.50)	(258.70)	(266.40)
<i>Production year 2021</i>	2,761***	990.5**	2,492***	691.4*
	(396.30)	(410.20)	(382.90)	(395.30)
<i>Production year 2022</i>	1,978***	1,567***	1,600***	1,159**
	(538.30)	(549.40)	(520.10)	(528.80)

Table D 1 (cont'd)

Base: Month started lactating; January

<i>February</i>	223.4*	219.6	233.0*	230.5*
	(119.70)	(135.00)	(119.30)	(134.90)
<i>March</i>	281.2**	237.3*	275.3**	231.7*
	(116.80)	(126.40)	(116.60)	(125.90)
<i>April</i>	416.4***	430.1***	403.2***	420.0***
	(125.10)	(139.20)	(125.20)	(139.50)
<i>May</i>	458.0***	344.6**	417.6***	304.4**
	(123.90)	(133.70)	(122.60)	(132.10)
<i>June</i>	263.9**	286.5**	208.7	239.7*
	(131.50)	(144.50)	(131.30)	(144.10)
<i>July</i>	-144.5	-131.3	-203	-185.5
	(145.90)	(153.80)	(145.10)	(153.30)
<i>August</i>	-878.9***	-976.9***	-964.8***	-1,066***
	(169.20)	(175.00)	(167.60)	(173.50)
<i>September</i>	-1,529***	-1,608***	-1,544***	-1,618***

Table D 1 (cont'd)

	(157.20)	(170.20)	(156.60)	(169.50)
<i>October</i>	-1,516***	-1,534***	-1,485***	-1,510***
	(179.70)	(197.10)	(179.00)	(196.90)
<i>November</i>	-751.2***	-750.6***	-783.2***	-784.9***
	(203.40)	(222.00)	(202.50)	(220.20)
<i>December</i>	-807.6***	-891.3***	-812.9***	-894.8***
	(135.60)	(153.60)	(135.30)	(153.20)
Base: <i>Not culled in current lactation</i>				
<i>Culled in current lactation</i>	-1,364***	-1,227***	-1,381***	-1,243***
	(68.64)	(68.26)	(68.15)	(67.74)
Constant	3,578***	4,399***	3,708***	4,539***
	(149.40)	(154.80)	(145.90)	(151.10)

Table D 1 (cont'd)

Observations	6,624	6,621	6,624	6,621
R-squared	0.309	0.324	0.318	0.334
Number of COWID's	3,693	3,692	3,693	3,692
R-squared overall	0.0422	0.0422	0.0422	0.0422
R-squared between	0.00705	0.00705	0.00705	0.00705
F-Test	59.24	79.85	61.19	83.34

Table D 2: Regression output table for models 5-8, using PVL categories & Robust standard errors

VARIABLES	MODEL 5	MODEL 6	MODEL 7	MODEL 8
	<i>PP milk pounds cont.</i>	<i>PP ECM cont.</i>	<i>PP milk pounds discrete</i>	<i>PP ECM discrete</i>
Base: BLV negative				
PVL low	-369.9** (168.50)	-467.6*** (180.10)	-366.6** (170.90)	-464.8** (183.10)
PVL medium low	-493.7* (299.00)	-713.0** (300.10)	-547.9* (301.40)	-770.0** (301.70)
PVL medium high	(76.16) (204.20)	-481.2** (214.50)	(105.30) (203.30)	-513.8** (213.80)
PVL high	150.6 (261.40)	65.27 (277.40)	118.8 (256.60)	35.6 (271.50)
Base: Lactation 1				
Lactation 2	121.8 (151.50)	-332.8** (153.60)	204.2 (147.20)	-249.7* (148.70)
Lactation 3	-148.8 (291.80)	-532.9* (295.50)	24.9 (284.00)	-348.8 (286.70)
Lactation 4	-840.3* (430.10)	-1,194*** (431.40)	-581.9 (419.30)	-917.5** (418.80)
Lactation 5+	-1,679*** (589.30)	-2,235*** (600.70)	-1,317** (574.10)	-1,849*** (582.80)
Base: Interaction PVL low & lactation 1				
PVL low & lactation 2	109.6 (144.30)	394.3** (160.40)	106.6 (147.40)	393.5** (163.60)

Table D 2 (cont'd)

<i>PVL low & lactation 3</i>	309.7 (192.40)	494.2** (216.70)	305.2 (193.50)	491.2** (218.10)
<i>PVL low & lactation 4</i>	388.3 (247.70)	490.0* (256.70)	402.2 (248.50)	505.9* (258.20)
<i>PVL low & lactation 5+</i>	546.7* (317.00)	874.1*** (335.20)	545.4* (315.10)	868.5*** (333.50)
Base: Interaction PVL medium low & lactation 1				
<i>PVL medium low & lactation 2</i>	-81.32 (264.40)	170.9 (280.70)	-72.2 (264.70)	186.1 (280.40)
<i>PVL medium low & lactation 3</i>	567.2 (365.20)	852.5** (398.70)	577 (365.30)	866.2** (397.70)
<i>PVL medium low & lactation 4</i>	638.5* (343.70)	800.2** (366.10)	654.1* (347.10)	815.3** (367.20)
<i>PVL medium low & lactation 5+</i>	868.6 (665.90)	1,336** (671.40)	885 (664.90)	1,346** (667.00)
Base: Interaction PVL medium high & lactation 1				
<i>PVL medium high & lactation 2</i>	-95.61 (175.60)	171.9 (187.50)	-56.6 (174.10)	220.1 (185.90)
<i>PVL medium high & lactation 3</i>	154.4 (205.30)	376.4* (224.80)	185.1 (205.40)	414.0* (225.00)
<i>PVL medium high & lactation 4</i>	148.9 (301.70)	335.1 (314.50)	187.6 (302.50)	378.4 (314.30)

Table D 2 (cont'd)

<i>PVL medium high & lactation 5+</i>	128.4 (393.70)	530 (407.10)	157.9 (391.70)	564 (404.60)
<i>PVL high & lactation 2</i>	65.43 (196.40)	88.37 (211.60)	88.87 (192.40)	118.2 (205.60)
<i>PVL high & lactation 3</i>	-16.78 (248.10)	-176.2 (262.80)	17.26 (244.20)	-141.4 (256.80)
<i>PVL high & lactation 4</i>	130.6 (306.00)	130.6 (330.70)	166.6 (302.70)	167.9 (326.20)
<i>PVL high & lactation 5+</i>	70.95 (421.00)	45.71 (412.70)	129.9 (413.90)	108.8 (405.50)
Base: Production year 2018				
<i>Production year 2019</i>	1,132*** (143.90)	1,345*** (150.40)	1,054*** (139.50)	1,262*** (145.50)
<i>Production year 2020</i>	2,050*** (268.70)	2,150*** (277.60)	1,862*** (259.80)	1,946*** (267.40)
<i>Production year 2021</i>	2,773*** (398.10)	1,001** (412.00)	2,505*** (384.70)	703.3* (397.00)
<i>Production year 2022</i>	1,997*** (541.60)	1,575*** (552.90)	1,621*** (523.40)	1,171** (532.10)
Base: Month started lactating; January				
<i>February</i>	216.7* (119.70)	214.1 (135.00)	226.8* (119.20)	225.4* (134.90)

Table D 2 (cont'd)

<i>March</i>	285.4** (116.00)	240.7* (126.00)	279.7** (115.80)	235.4* (125.50)
<i>April</i>	424.9*** (125.00)	428.8*** (138.90)	411.9*** (125.10)	419.1*** (139.10)
<i>May</i>	458.2*** (124.30)	347.0*** (134.20)	418.3*** (122.90)	307.2** (132.50)
<i>June</i>	263.7** (132.30)	282.9* (145.50)	208.5 (132.00)	236 (145.00)
<i>July</i>	-139.8 (146.30)	-131.2 (154.10)	-198.9 (145.40)	-186.1 (153.60)
<i>August</i>	-881.4*** (169.60)	-982.9*** (175.90)	-967.9*** (167.90)	-1,073*** (174.30)
<i>September</i>	-1,536*** (158.80)	-1,624*** (171.50)	-1,551*** (158.10)	-1,635*** (170.70)
<i>October</i>	-1,527*** (180.50)	-1,555*** (198.20)	-1,497*** (179.60)	-1,532*** (197.80)
<i>November</i>	-757.0*** (203.80)	-752.2*** (221.60)	-788.7*** (202.80)	-786.2*** (219.90)
<i>December</i>	-807.3*** (137.20)	-902.1*** (154.30)	-812.7*** (136.80)	-905.7*** (153.80)
Base: Not culled in current lactation				
<i>Culled in current lactation</i>	-1,364*** (68.81)	-1,228*** (68.40)	-1,381*** (68.36)	-1,243*** (67.94)

Table D 2 (cont'd)

Constant	3,555*** (150.90)	4,399*** (156.20)	3,685*** (147.50)	4,539*** (152.60)
Observations	6,619	6,616	6,619	6,616
R-squared	0.311	0.327	0.32	0.337
Number of COWID's	3,693	3,692	3,693	3,692
R-squared overall	0.0236	0.0216	0.0408	0.0419
R-squared between	0.0055	0.0002	0.0170	0.0070
F-Test	37.89	51.19	39.04	53.33