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The Economic Impact of Infectious Bronchitis on the Canadian Poultry Industry

by

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Abstract

Infectious bronchitis is a common, highly contagious, acute, and economically important viral disease of chickens caused by infectious bronchitis virus (IBV), a gammacoronavirus. It affects the respiratory system, reproductive organs, and kidneys. Morbidity is 100%, and mortality can go well up to 30%, while egg production drops by up to 50% or more depending upon secondary infection by bacterial pathogens. Emerging IBV variants have led to outbreaks in vaccinated flocks due to a lack of cross-protective immunity, which represents a concern for producers. It is imperative that we assess the economic impact of IBV on the Canadian poultry industry to make important decisions on control and mitigation.

I hypothesized that vaccination to prevent infectious bronchitis (IB) in poultry layers would have net positive economic benefits for Canadian poultry producers. A multiple scenario framework with Monte Carlo simulation and benefit-cost analysis was applied. The economic impact of IB on layer farms in Canada was examined by setting up models of Canadian layer poultry farms using data from Agriculture and Agri-Food Canada, scientific papers, the internet, and industry sources to perform simulations for various revenue classes across a range of IBV infection scenarios while considering possible control and prevention options.

The results show that the impact of IB outbreaks on Canadian poultry industry is estimated to be around 207 billion CAD annually. The high benefit-cost ratios (5-9) from adopting IB vaccines suggest that vaccination as a preventive strategy would be highly cost effective. The study demonstrated the value of vaccination as a preventive or mitigation strategy against potential losses due to IBV. Understanding the extent of economic losses IB outbreaks cause to layer producers would inform the development of timely and cost-effective disease control and preventive measures in order to minimize the impact of IB on egg and chicken production.

Keywords: infectious bronchitis virus, economic impact, benefit-cost analysis, and Monte Carlo simulation.

Table of Contents

List of tables

List of figures and illustrations

List of symbols, abbreviations, and nomenclature

Symbol	**Definition**
AAFC	Agriculture and Agri-Food Canada
AB	Alberta
ACM	Alternative control measures
AD	Anderson-Darling
AE	Avian encephalomyelitis
AIC	Akaike information criteria
All rev cat	All revenue categories
AvLogL	Average Log-Likelihood
BC	British Columbia
BCA	Benefit-cost analysis
BCR	Benefit-cost ratio
BIC	Bayesian Information Criteria
CAD	Canadian dollar
CAN	Canada
CAV	Chicken anemia virus
CCP	Current control program
CEMA	Canadian Egg Marketing Agency
CFC	Chicken Farmers of Canada
ChiSq	Chi-squared Statistic
Conn	Connecticut strain
COVID-19	Coronavirus disease 2019
DMV	Delmarva strain
DNA	Deoxyribonucleic acid
DR	Discount rate
E	Envelope
ExtValue	External value
ExtValueMin	External value minimum
FP	Fowl pox
GDP	Gross domestic product
HPAI	Highly pathogenic avian influenza
IB	Infectious bronchitis
IBDV	Infectious bursal disease virus
IBV	Infectious bronchitis virus
ILT	Infectious laryngotracheitis
Inci	Incidence

IRR	Internal rate of return
KS	Kolmogorov-Smirnov
M	Matrix
Mass	Massachusetts strains
MC	Monte Carlo
Mort	Mortality
N	Nucleocapsid
ND	Newcastle disease
NDV	Newcastle disease virus
NFACC	National Farm Animal Care Council
NPV	Net present value
OAHN	Ontario Animal Health Network
ON	Ontario
PHMCP	Poultry Health Management for Commercial Poultry
poly(A)	poly (adenine nucleotides)
Prodn	Production
PV	Present value
QC	Quebec
RNA	Ribonucleic acid
S	Spike
SM	Supply management
SPF	Specific pathogen free
StatCan	Statistics Canada
TAFS Forum	Transmissible animal disease and food safety forum
Unvax	Unvaccinated
USD	US dollar
UTR	Untranslated region
Vax	Vaccinated
Vax eff	Vaccine efficacy

Chapter 1

Literature review of infectious bronchitis virus and its economic impact

1.1 Introduction

Infectious bronchitis (IB) is a common, highly contagious, acute, and economically important viral disease of chickens caused by infectious bronchitis virus (IBV), a gamma-coronavirus (David Cavanagh & Gelb, 2008; Jones, 2010; AWAD *et al.*, 2014; Bande *et al.*, 2016). The virus is acquired following inhalation or direct contact with contaminated poultry, litter, equipment, or other fomites. It is highly infectious and affects the upper respiratory tract and the reproductive tracts, and some strains cause nephritis (Dave Cavanagh, 2007; David Cavanagh & Gelb, 2008; Winter *et al.*, 2006; Shahwan *et al.*, 2013). Overall, the mortality rate reaches 30% while the drop in egg production can go up to 50%. Besides damaging the ovaries and fallopian tubes of infected chicken, it affects the internal (watery albumin) and external quality (such as thin shell, rough shell, discolored shell, or no eggshell) of eggs (Dave Cavanagh, 2007; Jones, 2010).

IB is an OIE-listed poultry disease recognized worldwide due to its economic impact on poultry production and global trade due to the risk of the virus spreading among multiple countries (Bagust, 2013; Ike et al., 2021). Factors such as virus strains, environment, and host influence the occurrence of outbreaks and severity of the disease. Despite the concerted efforts to control the disease using vaccines, this virus still causes huge production losses and poor health raising issues of welfare and concern. All types of chickens are vaccinated in most countries, with live and inactivated IBV vaccines (Bande *et al.*, 2015a). In the literature review, etiology, host range and susceptibility, viral genotype diversity, pathogenesis, and poultry health economics and choice analysis are discussed.

1.2 Etiology

IBV is a gamma-coronavirus of the order *Nidovirales*, family *Coronaviridae*, with over seventy-two known genotypes worldwide (Jackwood, 2012a; Snyder *et al.*, 1983; Bande *et al.,* 2016). The coronavirus genome is made up of a single-stranded enveloped RNA that measures from 27 to 32 kb, making them the largest of the RNA viruses with a diameter ranging from 80 to 120 nm (Lai & Cavanagh, 1997; Cavanagh, 2005). Four different genes in the IBV genome encode for the structural proteins designated as spike (S), envelope (E), matrix (M), and nucleocapsid (N). The interspaces between these four structural proteins contain the genes that code for accessory proteins, arranged in the order of 5' to 3’ direction as UTR-1a/1ab-S3a-3b-E-M5a- 5b-N-3-UTR-poly(A). Among the structural protein genes, the S1 and N proteins have epitopes that are associated with the immune response of the host (Jackwood, 2012b; Bande *et al.,* 2016; Bande *et al.,* 2015a; Haan *et al.,* 2000). Antibodies directed toward some of the S1 subunit epitopes can be neutralizing *in vitro* and can be used for serotyping; this protein is involved in cell attachment and is thought to be the determinant of the diversity of the virus and immunity (Ignjatović & Sapats, 2000a; Jackwood *et al.,* 2012; Bande *et al.,* 2015a).

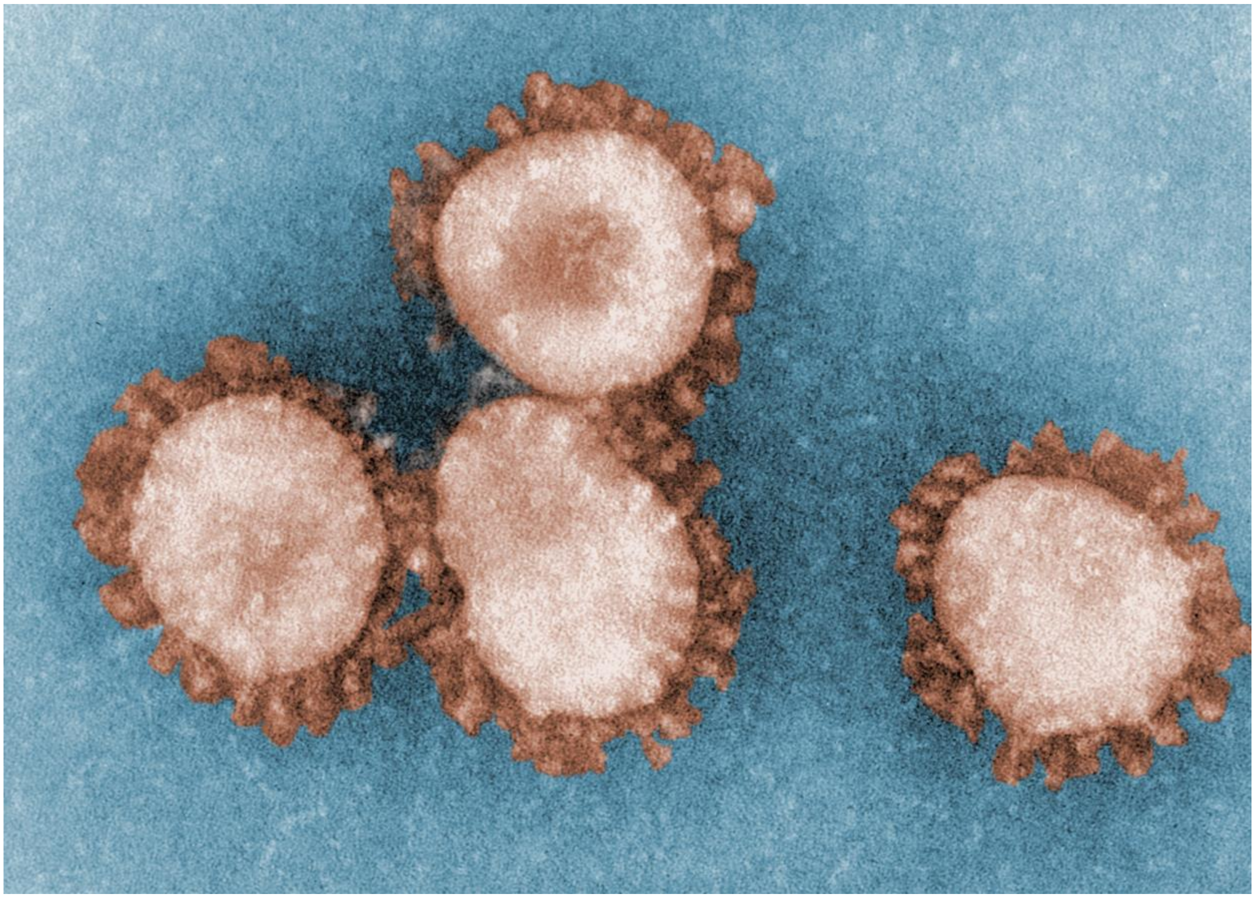

Figure 1. 1 Transmission electron micrograph of IBV particles. The surface of each particle is covered in club-shaped spikes (CDC, 1975).

1.3 Host range and susceptibility

Although it is agreed that the chickens are the most significant natural hosts, it has been found that farmed pheasants are also natural hosts of IBV (D. Cavanagh *et al.,* 2002; Ignjatović & Sapats, 2000b). Going by the history of reports of a drop in egg production and clinical respiratory disease, pheasants are thought to be the secondary natural hosts for IBV. Not all the species of pheasants are susceptible to the virus and perhaps only certain strains of IBV may infect pheasants (Ignjatović & Sapats, 2000a). To date, the virus tends to cause clinical disease only in chickens, even though IBV-like coronaviruses have been isolated from some migratory birds (Dave Cavanagh, 2007; J. J. de Wit & Cook, 2019; Jonassen *et al.,* 2005; Circella *et al.,* 2007). Of late, there has been more evidence suggesting a wider host range of IBV than was previously thought and it is not only limited to galliforms (chicken-like birds) (Cavanagh, 2007). The spread of IBV strains over the world might be attributed to other species of birds such as pigeons, ducks, and geese, and possible introduction from wild birds to domestic birds. Unfortunately, it is not known how wild birds are involved in the spread of IBV (de Wit & Cook, 2019).

1.4 Viral evolution and genotype diversity

New variants of IBV continue to arise which makes it extremely difficult to control and poses challenges to poultry industries and vaccine developers worldwide (Jackwood, 2012b; Awad *et al.,* 2014). It changes by both spontaneous mutation and by genetic recombination because it is a single-stranded RNA virus (Cavanagh, 2007; Wood *et al.,* 2009). If any of these two events occurs in the hypervariable regions of the S gene in IBV, it will most likely result in the emergence of new variants (Wit *et al.,* 2017; Jones, 2010). Many countries have their variants of indigenous IBV which are characterized and very often named after a laboratory, or a researcher associated with its first isolation. For example, QX, Arkansas, D274, Massachusetts, and Connecticut are the IB serotypes first identified in these locations of the world. Only in very few geographic locations do some of these variants manage to become of either clinical or economic significance, while many of these new variants are not capable of replicating and surviving for long (de Wit *et al.,* 2011). There are several emerging IBV variants (different serotypes and genetic types of the virus identified worldwide that may include antigens that are not recognized by vaccine induced antibodies) that have led to IB outbreaks in vaccinated flocks due to a lack of cross-protective immunity, resulting in significant production losses. Therefore, these outbreaks are due to infections with strains that are serotypically different from the ones used in vaccines

(Ignjatović & Sapats, 2000a; Awad *et al.*, 2014).

Canadian IBVs are divided into nine genotypes belonging to four groups based on similarities in their S gene sequences: Canadian variant virus, strain Qu_mv; US variant-like virus strains, California 1734/04, California 99, CU_82792, Pennsylvania 1220/98, and Pennsylvania Wolg/98; the classic, vaccine-like viruses, Connecticut and Massachusetts; and non-Canadian, non-US virus, strain 4/91, (Martin *et al.*, 2014).

A recent study that carried out a complete genomic sequence analysis revealed evidence of recombination for at least three different IBV strains, namely a Conn vaccine-like strain, a 4/91 vaccine-like strain, and one strain that is yet-unidentified, and suggested the possible contribution of the genomic regions of S, 3, and membrane (M) genes of the five Canadian IBV/Delmarva(DMV) isolates by the unidentified strain (Hassan *et al.*, 2019). The usage of live attenuated vaccines also appears to impact the genetic profile of similar IBV variants in the field (Jackwood & Lee, 2017).

1.5 Transmission, pathogenesis, and clinical manifestation

The incubation period of IBV is 24 to 48 hours and aerosol and mechanical transmission spread the virus to the rest of the chickens in a flock. It replicates in the upper respiratory tract initially where the ciliated epithelium of the trachea sloughs off. The emergence of QX strain has reinforced the virulence of some IBV strains in damaging reproductive tracts of breeder and layer birds, causing a delay in the onset of production, poor peak in egg production, a high proportion of false-layers, and deteriorated quality of eggs (Ganapathy, 2009; Jones, 2010; David Cavanagh & Gelb, 2008). Sometimes, it can be associated with male infertility and enteritis (Villarreal *et al.,* 2007) and there can be a potential vertical transmission of IBV (Pereira *et al.,* 2016).

Typical signs of IBV in chickens of less than six weeks of age are depression, huddling under a heat source, difficulty breathing (often more noticed at night when the birds are resting), gasping, coughing, tracheal rales, nasal discharge, lethargy, watery eyes, and mildly swollen sinuses in severe conditions (Ganapathy, 2009). A study on Ontario farms with a history of IB outbreaks suggests that birds could carry the virus without exhibiting clinical signs (Stachowiak *et al.*, 2005).

The disease is not serious in chicks five weeks or older in uncomplicated cases, but baby chicks may die of it. In any age group, if an outbreak of IB occurs along with other pathogens, more severe pathology and mortality will be observed (Cavanagh, 2007) and affected layer flocks are unlikely to return to the normal level of production (Benyeda *et al*., 2009; Ganapathy, 2009). While the morbidity rate can reach 100% in affected flocks, the mortality rate depends on the presence of secondary bacteria, other infections, age, immunity, management, and environmental factors. The mortality rate for young chickens is between 25-30% but it can reach 80% depending on the virulence of the strains (David Cavanagh & Gelb, 2008; Ariaans *et al.*, 2008; Gallardo *et al.*, 2012). Although all the age groups of chicks are susceptible, baby chicks are more susceptible than older chicks (David Cavanagh & Gelb, 2008; Smith *et al*., 2015; Crinion, 1972). Mortality due to IBV infection alone is usually very low but can be significant following secondary infections with bacteria such as *Escherichia coli* (de Wit & Cook, 2019; David Cavanagh & Gelb, 2008).

1.6 IB vaccines

A single vaccine application should target to induce the desired cross-protection within a week after the application, preferably by a less-invasive mass method of application, and one that can be used at any stage of growth. Maternal antibodies of immunity of the host should not interfere with the development of protective immunity and it would be highly desirable to have a vaccine against this virus combined with other vaccines. It is apparent from such demands why the new vaccines against IB are challenging to produce, in comparison with the vaccines for various other infectious poultry diseases (Jackwood & de Wit, 2017). The very first and important step to having a successful vaccination program is to have a knowledge of strains present in the region. Usually, when there are new IB strains and if there is no commercial vaccine currently, it is quintessential to assess if some sort of cross-protection is provided by available vaccines against it (Torres, 2021).

A typical Canadian poultry vaccination program includes various strains of Newcastle disease virus (NDV) and infectious bronchitis virus (IBV) that are often given together; infectious bursal disease (IBD); avian encephalomyelitis (AE); reovirus; chicken anemia virus (CAV) (broiler and layer breeders); fowl pox (FP); and infectious laryngotracheitis (ILT) (Inglis, 2018). All the poultry industry sectors most commonly use live attenuated IBV vaccines and pathogenic field isolates are used to manufacture these vaccines where serial passaging is done in embryonated specific-pathogen-free (SPF) eggs (Bijlenga *et al.,* 2004). The attenuation of a field virus takes up to one year while rapid attenuation can sometimes be accomplished by combining limited egg passage and heat treatment (Jackwood *et al.,* 2010).

In layers and layer breeders, killed or inactivated IB vaccines are used routinely. While the emergence of novel serotypes and variants has led to the production of regionally important serotypes, Massachusetts (Mass) serotype has been the only IBV vaccine used throughout the world for many years as it was the first vaccine type produced and available (Jackwood *et al.,* 2012). Some recombinant IBV vaccines express IBV antigens alone ((Johnson *et al.,* 2003) and others express in combination with antigens from other viruses/pathogens (Yin *et al.,* 2016), but they have yet to evince either similar immune-protective level as live-attenuated vaccines or the convenience of administration for mass application in hatcheries. Recombinant DNA technology in recent times has shown evidence of the efficacy of antibody and T-cell responses, at par with live attenuated vaccines, and targets multiple serotypes with improved efficacy that applies nano-adjuvants, delivery vectors, and *in ovo* vaccination techniques. So far, there is no recombinant IB vaccine that is licensed for use in the commercial poultry industry (Bande *et al.,* 2015a; Jordan, 2017).

As far as methods of application are concerned, IBV being an encapsulated virus and thus not environment-resistant, an important consideration to make is that the infection starts in the upper respiratory tract generally. Therefore, ideally, the route of vaccine administration for live IB vaccines is eyes (as eye drops), or inhalation, and sometimes, in drinking water, abiding by all the vaccination procedures such as the temperature of drinking water and intake time (Torres, 2021). Also, an automated system of spray vaccination for IB in a house significantly improves seroconversion and geometric mean titer, compared to using an archetypal backpack blower-based sprayer (Purswell *et al.,* 2019).

1.7 Impact of vaccines

At an individual bird level, vaccines reduce the severity of the disease and transmission to other birds (Fadly *et al.,* 2009). This gives protection to the entire poultry population due to flock immunity that becomes effective in vaccinated birds at two important levels, namely flock level and country/region level (Marangon & Busani, n.d. ; de Wit *et al.,* 1998). Producers can reduce antimicrobial use on their farms by vaccinating their birds to control diseases. Pathological damage caused by IBV to the upper respiratory tracts, especially the trachea, predisposes birds to subsequent bacterial infections such as colibacillosis which can result in higher condemnations.

Proper vaccination against IB, along with other mitigating strategies, has been observed to lessen the negative impact and losses caused by a secondary bacterial infection (Sanei, 2018).

Tomo *et al*., (2012) assessed the impact of vaccinating village chickens against Newcastle disease (ND) and whether it raised the income of farmers in rural Mozambique using a dynamic simulation model combined with benefit-cost techniques. Results of the study revealed that control of ND led to a significant increase in farmers' income. Low rates of vaccination of chickens were due not to economic reasons but lack of efforts regarding strategies of extension and distribution of the vaccine.

1.8 Poultry production (Canada)

1.8.1 Production system

The production and marketing of eggs, egg products, and chicken in Canada are controlled by a system of supply management (SM), wherein production quotas regulate output, and a system called tariff-rate quotas restrict imports (Cardwell *et al.*, 2015; Mbaga, 1994).

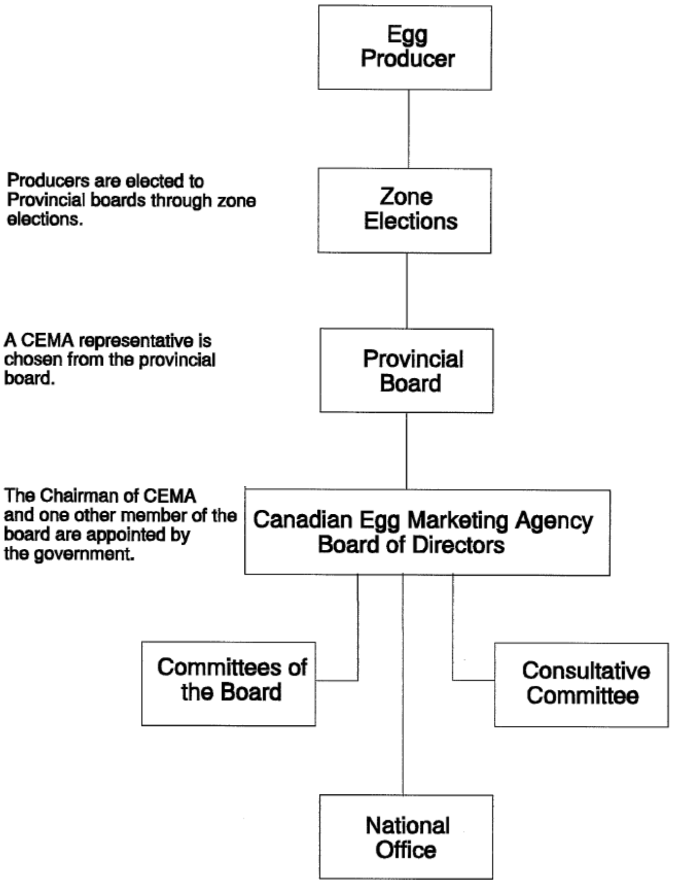

Figure 1. 2 Structural summary of supply management (Mbaga, 1994).

Figure 1.2 depicts the structure of marketing boards for eggs and egg products. Egg producers in all the provinces are regulated and organized under the provincial marketing boards. All these provincial marketing boards and the Canadian Egg Marketing Agency (CEMA) have joint jurisdiction through a federal-provincial agreement. Provincial legislation grants regulatory powers to these marketing boards (Mbaga, 1994).

Chicken Farmers of Canada (2013) explains that the SM is an approach unique to the Canadian agricultural production system that benefits producers, processors, and consumers of Canada. This makes it possible for “farmers to get a fair return for their products, processors get a reliable supply of raw ingredients, and Canadians get a consistent choice of excellent and high-quality chicken at reasonable prices” with the government not needing to subsidize prices. The three important pillars of the supply management are: 1) Production planning pillar - producers must plan their production in order to maintain a constant supply of quality poultry products that take into account seasonal and other changes in demand, where the quota system comes into the picture to ensure there is neither surplus nor shortage. Those who are already in the business are given a quota, but new producers must buy them through respective provincial marketing boards. To determine how much to produce for a steady supply of products, Chicken Farmers of Canada Directors meet once in eight weeks. This production target is determined based on provincial requests, indications from stakeholders, market forces, and Canadian consumers' demand for chicken and egg products. 2) Import controls pillar – to match supply with demand for products, predicting the amount to be imported into the country is key. This goes into calculating how much needs to be produced domestically to satisfy the country's needs. Therefore, there are "tariff-rate quotas with effective over-quota tariffs" to regulate imports of various forms of chicken and egg products. 3) Producer pricing pillar – ensures that supply-managed producers get a steady income for their hard toil in a sustainable and subsidy-free farming system. Therefore, Canadian chicken farmers negotiate a minimum farm gate price, one that is arrived at based on the production costs.

Agriculture and Agri-Food Canada (2020) published that in 2019, Canada had "2,821 regulated chicken producers and 523 registered turkey producers, 240 broiler hatching egg producers, and 1,172 egg producers". Additionally, there were 4,756 commercial poultry and egg producers in Canada and a large number of businesses associated with these production activities. All in all, in 2019, Canada produced $4.9 (CAD) billion worth of poultry and egg products that contributed 7.4% of cash receipts to the producers. Moreover, chicken is the most consumed source of animal protein for Canadians. In 2019, 35.1 kg of chicken was available for every person in

Canada, as well as 3.9 kg of turkey. Similarly, per capita availability of eggs reached 21.1 dozen in 2019. There were 59 hatcheries that supplied chicks to egg and poultry meat producers. Furthermore, a lot of processors (primary and secondary), and egg-grading and egg-processing industries in Canada rely, in part or fully, on the poultry industries for business.

1.8.2 Poultry policies/IB policies

The most efficacious and economic of all the approaches to controlling IB is vaccination (Meeusen *et al.*, 2007). Although there is some cross-protection among multiple serotypes, new serotypes appear regularly that can evade the immunity and protection given by some vaccines, requiring commercial layers and broilers to be vaccinated as recommended locally. Live vaccines given in water or by spray are best in growing birds, while killed vaccines in oil may be used for adults (Poultry Health Management for Commercial Poultry, 2020).

National Farm Animal Care Council (2021) recommends that for optimum health and welfare of poultry, a good flock management plan of a farm must incorporate the three key pillars of “monitoring, recording, and managing flock health" that helps producers to assess the best practices on a farm for improved outcomes, and for a flock health plan to be effective, it must contribute to the wellbeing of birds by ensuring best strategies for “disease prevention, rapid diagnosis, and effective treatment”. *Inter alia*, a flock plan may include vaccination protocols; protocols for management of internal and external parasites; examining all birds for signs of disease; complete, accurate, and reliable record-keeping; and protocols for the prevention, diagnosis, and treatment of a disease, including setting targets for measuring incidences of disease and injuries (National Farm Animal Care Council, 2021).

Regarding self-quarantine protocol, (Government of Canada, 2014) stipulated that upon the suspicion of the outbreak of infectious poultry disease in a farm, a set of protocols and guidelines should be followed by the producer in order to limit the spread of the disease between barns and, most important of all, the spread of the disease beyond the farm.

Poultry Health Management for Commercial Poultry (n.d.) specifies that the prevention of a disease in a poultry farm can be achieved primarily by three methods: 1) prevention by sanitation; 2) prevention by isolation; 3) prevention by vaccination.

In light of the increasing number of IB cases in December 2016 in Ontario, OAHN issued directives on how to protect flocks from IB. The key strategies were, *inter alia*, maintaining and reviewing biosecurity plans in the barns with a veterinarian and ensuring better communication among suppliers and visitors regarding each farm's plans (OAHN Special IB Report, 2016).

1.9 Economic impact analysis

There is remarkably limited literature on the economic impact analysis of IBV. Here, I summarize what literature I could find for the economic impact of IBV on Canadian poultry industry and more generally on other poultry diseases. The economic impact of IBV infections globally was labelled as a very damaging poultry disease (World Bank, 2011). The severity of clinical signs and impact of the disease may be influenced by the IBV strain(s) involved, environmental conditions (such as climate and weather), circumstances (such as dust, ammonia, density, and cold stress), age, and type of bird, immune status (vaccination, immune suppression, and maternally derived antibodies), and presence of secondary or co-infections (Jackwood & de Wit, 2013). Cook *et al.*, (2001) refer to IB as possibly the most economically important viral respiratory disease of the chickens. Amarasinghe *et al.*, (2018) estimated the economic impact of IB to be CAD $6823 with a 47.6% drop in egg production for 10 days for a single layer flock in Western Canada due to IBV infection (by a Mass strain) of 27-week-old layers at the peak of production. Some work has been done on the impact of various poultry diseases or interventions in poultry, some important findings of which I provide in the following paragraphs, but there is generally a large gap in the literature as far as the economic impact of IB is concerned, be it in Canada or elsewhere in the world.

Colvero *et al.,* (2015) estimated that losses due to IB in Brazil per 1,000 birds (during the study period 2012-2014) were US$3,567.40 and US$4,210.80 at 25–26 and 42 weeks old, respectively, whereas in broilers (48 days old), the estimated loss was US$266.30 per 1,000 birds.

Landman and van Eck (2015) conducted a study on the incidence and economic impact of *Escherichia coli* peritonitis syndrome (EPS) on layer poultry and broiler breeder farmers in the Netherlands. They estimated losses of 10 and 11 mean numbers of eggs per hen housed (phh), and mean slaughter weight losses of 0.2 and 0.5 kg phh in the layer and broiler breeder flocks, respectively. Total loss, accounting for costs of destroying dead hens, compensating for reduced feed intake due to a smaller size of the flock, and cost of using antibiotics against EPS (medicines were given repeatedly, especially in the meat sector) was estimated to be €3.7 million for poultry farming as a whole in the Netherlands.

Rashid *et al.,* (2019) studied the economic impact of the age-wise and seasonal prevalence of coccidiosis in commercial poultry farms in Multan province in Pakistan. The estimate of total economic losses (depending on market conditions of the time) from treatment, prophylaxis, and supportive therapy for coccidiosis was US$45,405.00, while production loss for broiler was (US$2,750,779.00), for layer young and adult (US$13,974.98 and US$104.74, respectively), and golden buff young and adult (US$50,228.76 and US$203.77 respectively). Therefore, the unit loss of coccidiosis alone and coccidiosis with parasites and concurrent infections were estimated at US$0.005 and 0.01, respectively.

Roskam *et al.,* (2019) researched the technical and economic impact of tailor-made interventions by veterinary sectors attempting to reduce antimicrobial use on broiler farms in nine countries in Europe (the names of the countries were anonymized). Antimicrobial resistance is a threat to both human and animal health globally and one of the major causes of antimicrobial resistance is the inappropriate use of antimicrobials in animal production. Results indicated that the average daily gain and mortality rates increased after the intervention while there was a decrease in feed conversion and antimicrobial use. After the interventions, the economic performance also increased.

Zachar *et al.,* (2016) did a study on the incidence and economic impact of variant infectious bursal disease viruses (IBDV) on broiler production in Saskatchewan, Canada to identify the circulating variant strains in Saskatchewan and evaluate their economic impact. They concluded that unique variant IBDV strains were prevalent on Saskatchewan farms and that IBV-infected flocks had higher mortality, poorer feed conversion ratio, and decreased meat production. The study suggested that the variant IBDV strains were attributable to a yearly loss of 3.9 million kilograms of chicken for the broiler industry in Saskatchewan (Zachar *et al.,* 2016).

Thompson & Seitzinger (2019) did the economic evaluation of low pathogenic avian influenza in northeastern US live bird markets using cost estimates from the 2016 outbreak. The total government response was estimated to be US$804 (US$1.24 on a per-bird basis). The market impacts in terms of disruptions affecting business due to cleaning and disinfecting protocols that forced the closure of markets were estimated to be US$419,781 for all markets or US$3,998 per market.

Maples *et al.,* (2021) estimated the impacts of COVID-19 on the US broiler industry. The COVID-19 pandemic affected meat supply chains and the poultry industry creating major disruptions. Chicken demand plummeted due to restaurant closures which in turn led to supply adjustments that affected broiler producers. The results showed that, for the normal scenario with an average of 5.3 flocks per year, the net median cash flow was US$43,503 per year, but if a producer's number of flocks fell to 4.3 on average due to disruptions, the median yearly cash flow fell to just US$18,272. Also, the probability of poultry producers running into a loss (negative cash flow) rose substantially to around 95%.

1.10 Simulation and benefit-cost analysis

Benefit-cost analysis (BCA) is a process used to appraise investment in projects and policies that have measurable outcomes over time. BCA is a branch of welfare economics that assigns monetary values to project inputs, outputs, and external impacts and determines the relative value of each using collectively three fundamental calculations: the benefit-cost ratio (BCR); net present value (NPV); and the internal rate of return (IRR) (Campbell & Brown, 2015). Benefit-cost analysis is a robust economic tool that allows for use under limited data and is easily understood by stakeholders. A classic BCA approach (Campbell & Brown, 2015) will be applied. The first step of the BCA approach is to determine the net present value (NPV) of accrued benefits (*e.g.,* increase in production measured by market output, costs averted measured by losses, and feed costs prevented) divided by the net present value of accrued costs (*e.g.,* additional costs from vaccination and surveillance) to estimate a benefit-cost ratio (BCR). I will also incorporate sensitivity analysis of discount rates, both market and social price-based, and the internal rate of return.

If the value of benefits is more than the value of costs, indicating that a benefit-cost ratio exceeds unity (*i.e.*, BCR is greater than one), it would give the presumption that the project is favourable but there are many factors to consider, including whom this benefit would go to and who would be bearing the costs (Campbell & Brown, 2003).

There is no work on the BCA of IB per se, but some work has been done on benefit-cost analyses of various poultry diseases, which are provided in the following paragraphs.

A benefit-cost analysis of costs of outbreak and surveillance for poultry HPAI H5N1 was done in Nigeria (Fasanmi *et al*., 2018). (Dijkhuizen, (1995) applied systems simulation and benefit-cost analysis in decision making in the veterinary field concerning foot and mouth disease outbreaks in the Netherlands.

Tran *et al.,* (2016) did a geospatial cost-effectiveness analysis to study the trade-off between Vietnam’s poultry vaccination program that implemented bi-annual HPAI H5N1 vaccination for the entire area of Red River Delta and an alternative program that vaccinated birds for every cycle of production at recommended ages in high-risk areas in this Delta. The results suggested that the alternative program would have had more impact in minimizing the rate of disease occurrence and the total vaccination cost, compared with the national program.

Karki *et al.,* (2015) used benefit-cost analysis to study and compare the current control program (CCP) of avian influenza with the two alternatives of *the* absence of control measures (ACM) and vaccinating 60% of all the poultry population twice a year. There was a return of US$1.94 for a dollar spent in CCP compared with ACM indicating a benefit-cost ratio of greater than 1 and the net present value of the current program was US$861,507, that is, the monetized benefits of implementing CCP in contrast to ACM. Whereas the vaccination strategy yielded a return of US$2.32 for each dollar spent compared with CCP and the net present value of vaccination against CCP was around US$12 million indicating that although CCP was better than ACM, vaccinating 60% of the national flock could have been economically more beneficial.

Lapar *et al*., (2011) studied the cost-effectiveness analysis of mass vaccination activities to identify more effective control strategies against HPAI in poultry in Indonesia. The results suggested that the cost associated with mass vaccination was higher than the price the target beneficiaries were willing to pay. The belief of risk and uncertainty surrounding outbreaks of HPAI in their farms greatly influenced their decision about whether or not to adopt.

Such beliefs, preferences, and choices influence the decisions that poultry producers make in terms of either adopting new biotechnological approaches to controlling and mitigating diseases on their farms, or when choosing from among a host of different production systems.

1.11 Theories and models

Therefore, a study to estimate the economic impact of IB is warranted due to the severity of clinical cases in birds and the extent of damage it causes to poultry industries globally. One big stumbling block to such studies and knowledge pool is the complexity of the production networks of poultry, coupled with very limited access to trade and production data. This study will clarify the value of vaccinating as a preventive and/or response strategy as well as avert the longer-term damage from IBV due to its crippling effect on reproductive tracts of breeders and layers at an individual bird level. Findings can be the premise for broader policy changes regarding control and mitigation strategies for associations and governments at the provincial and federal levels, much less fill the big gap in the literature. Therefore, I will outline this problem and the solutions with the Conceptual, Theoretical, and Statistical Models in the following paragraphs.

1.11.1 Conceptual model

The benefits of vaccination to prevent IB in layer poultry birds in Canada by layer producers can be assessed.

1.12 Research questions

Can I develop a model that estimates the impact of vaccination of layers by Canadian poultry producers including the threat of new strains?

1.13 Hypotheses/objectives

Vaccination to prevent IB in poultry layers in Canada has net positive economic benefits for Canadian poultry producers.

1.14 Theoretical model

1.14.1 Benefit-cost analysis

BCA is a branch of welfare economics that assigns monetary values to project inputs, outputs, and external impacts and determines the relative value of each using collectively three fundamental calculations: the benefit-cost ratio (BCR); net present value (NPV); and the internal rate of return (IRR) (Campbell & Brown, 2015). A BCR is calculated by determining the net present value of accrued benefits (*e.g.*, increase in production measured by market output, costs averted measured by losses, and feed costs prevented) divided by the net present value of accrued costs (*e.g.*, additional costs from vaccination and surveillance) to estimate a benefit-cost ratio (BCR). BCR calculation is a robust economic tool that allows for use under limited data and is easily understood by stakeholders (Campbell & Brown, 2015).

A benefit-cost ratio is calculated as:

$\text{The ratio of benefits to costs (benefit} - \text{cost ratio)} = \frac{PV(benefits)}{PV(costs)}$,

$PV(benefits) -$ Present value of benefits, and

$PV(costs) -$ Present value of costs (Campbell & Brown, 2015).

1.15 Statistical model – Monte Carlo simulation

The Monte Carlo simulation helps to build models of possible results by substituting a set of values according to a probability distribution for any variable with uncertainty and it calculates these values over and over, every time using random values from the probability functions. Many advanced statistical tools exist to create Monte Carlo simulation, but it is much easier to simulate using Microsoft Excel and bypass the mathematical underpinnings. Monte Carlo simulation chooses a range of random possible outcomes each time just like rolling dice in a casino. Monte Carlo simulation could involve tens of thousands of recalculations before it is complete depending on uncertainties and the distribution ranges specified for them. Monte Carlo simulation produces distributions of possible outcome values. By using probability distributions, variables can have different probabilities of different outcomes occurring, which explains why using probability distributions is a much more realistic way of describing uncertainty in variables of a risk analysis (Harrison, 2010; Frey & Pfeifer, 2013; Korn *et al.*, 2010).

I assume that the input variables for this study take a normal distribution and for each of them, statistical distribution functions will be assigned depending on assumptions made under available data in the literature and other sources. The means and standard deviations of the input variables will be specified for each scenario to define the probability density distribution for an input variable on @Risk, depending on the setup of scenarios and expected population parameters of the input variables.

Chapter 2

Methodology

2.1 Research gaps

Although infectious bronchitis virus (IBV) has been extensively studied in order to understand virology, epidemiology, genotype diversity, vaccines, and new variants, there is very little work done to estimate the economic impact of IB on the poultry industry thus far while Cook *et al.,* (2012) refer to infectious bronchitis (IB) as possibly the most economically important viral respiratory disease of the chickens. Hassan *et al.,* (2021) noted that the incidence of false layer syndrome in layers in Eastern Canada involved Canadian (DMV)/1839 and their experiments confirmed that the strain damaged female reproductive tract due to cystic oviduct lesions, among others.

IB is such a significant disease in poultry that it could potentially disrupt the whole supply value chain of eggs and poultry products, mainly due to new emerging variants that pose a big challenge to vaccine development (Jackwood & de Wit, 2013; World Bank, 2011) due to the lack of cross-protective immunity (Jordan, 2017). The economic aspect of IB, therefore, remains poorly understood. In hindsight, some work has been done on the impact assessment of various poultry diseases and interventions that were discussed in the previous chapter which either followed similar methods as this study either in using BCA models or simulations models such as Monte Carlo or Markov's models, but there is a large gap in the literature as far as the economic impact of IB and the benefits of the IB vaccine uptake are concerned, either in Canada or elsewhere in the world.

Therefore, a study to estimate the economic impact of IB was warranted due to the severity of clinical cases in birds and the extent of damage it causes to poultry industries globally. One huge stumbling block to such studies and knowledge pool is the complexity of the production networks of poultry, coupled with limited access to trade and production data. This study would clarify the value of vaccination as a preventive or response strategy in general and to avert the longer-term damage from IBV due to its crippling effect on reproductive tracts of breeders and layers at an individual bird level (Amarasinghe *et al.,* 2018). The findings of this research could form the premise for broader policy changes regarding control and mitigation strategies for associations and governments at the provincial and federal levels. As well, it will fill a large gap in the literature. To outline this problem and approach toward solutions, the Conceptual, Theoretical, and Statistical Models that form the basis for this thesis are presented in the following paragraphs.

2.2 Conceptual model

Agricultural producers want to optimize income by reducing production costs, including costs caused by disease, which results in increased income. Vaccination of animals to prevent disease, including vaccination of egg layer birds by Canadian poultry producers, is a well-established method that can complement a biosecurity strategy that can contribute toward lowering production costs. The presumption is that the vaccination of egg-laying birds against IB has net positive economic benefits.

2.3 Theoretical model

There is a wide and long-standing, theoretical agricultural economics literature supporting the concept that actively reducing costs through mitigation strategies increases profit, assuming same level of production is maintained. Several key theoretical models that support the Conceptual

Model are worthy of mention in this section, covering welfare, production, and resource economics. Producers are interested in optimizing their welfare, consistent with the theoretical concepts of the Engel curve[1] (Allen & Bowley, 1935; Johansson, 1991), Gini coefficient[2] (Dorfman, 1979; Ceriani & Verme, 2012; Gini, 1912), Pareto optimality[3] (Pareto 1896), and Kaldor-Hicks (KH) Criterion[4] (Kaldor, 1939; Hicks, 1939; (Anonymous, BCA History, n.d.) Persky, 2001; Evans report, 2009; Persky, 1992).

Furthermore, production models are typically driven by welfare optimization (Johansson, 1991; Varian, 2014; Mas-Colell *et al.*, 1995). Theoretical development of both welfare and production economics has been driven by application in natural resource economics (Carlsson *et al.*, 2001; Brewer, 2010) particularly optimization of stakeholder welfare, utility, and total productivity (O'Sullivan *et al.*, 2003; Davis, 2016; Pindyck & Rubinfeld, 2013). Benefit-cost analysis (BCA – analysis of the ratio of benefits and costs of options with knowledge of private and social values) in particular relies on those foundational economic theories (Campbell & Brown, 2015; Boardman, 2014; Zerbe & Bellas, 2006) and is discussed in the next section (Statistical model).

Therefore, the benefits can be estimated and the recent literature suggests that these benefits can

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[1] The Engel curve measures deviations in family expenditure from the average, using preference curves premised upon curves of indifference, which provides a means by which a new theory can be developed, or an existing theory can be assessed.

[2] The Gini coefficient is an established system of conventional measures to determine income inequality.

[3] Pareto optimality exists when a change is made such that at least some members are better off, and no one is made worse off.

[4] The KH Criterion acknowledges that the comparison of individual satisfaction cannot be established scientifically and that a venture is desirable if the monetary value measure of profits exceeds the monetary measure of losses.

be assessed through simulation (Frey & Pfeifer, 2013; Clemen, 2014; Korn *et al.*, 2010; Palisade, 2018; Mooney, 1997). The theoretical model of this study was that simulations with BCA could be used to estimate the welfare and improvement of layer poultry birds in Canada through vaccination deriving from the host of welfare optimization theories. For instance, the first use of BCA was formalized with some guiding protocols by the US Corps of Engineers (Federal Navigation Act of 1936 and Flood Control Act, 1936 stipulate mandatory CBA) for federal waterway infrastructure analysis (Evans report, 2009).

2.4 Statistical model – Monte Carlo simulation with benefit-cost analyses

Benefits and costs can be assessed through benefit-cost analysis, and where data are scarce, in a Monte Carlo simulation framework. BCA is a branch of welfare economics that assigns monetary values to project inputs, outputs, and external impacts and determines the relative value of each, calculated by determining the net present value of accrued benefits divided by the net present value of accrued costs to estimate a benefit-cost ratio (BCR) (Campbell & Brown, 2003).

The Monte Carlo simulation helps build models of possible results by substituting values according to a probability distribution for any variable with uncertainty. It calculates these values repeatedly, using random values from the probability functions. These simulations produce distributions of possible outcome values. With the use of probability distributions, variables can have different probabilities of different outcomes occurring, which explains why using probability distributions is a much more realistic way of describing uncertainty in variables of a risk analysis (Harrison, 2010; Frey & Pfeifer, 2013; Korn *et al.*, 2010; Winston, 1999; Law *et al.*, 2000; Clemen, 2014).

2.5 Method - Multiple scenario framework and benefit-cost analyses

A model Canadian layer farm would be set up from the available data, and multiple scenarios would be created for simulations of the impact of IB by assuming changes in various input variables such as the epidemiolocal parameters of IB and assumed parameters of new strains of IBV, along with changes to costs of production and vaccine costs. For simulations, several scenarios across different revenue classes of Canada overall and provincial layer farms would be considered. Benefit-cost analysis (BCA) is a process used to appraise investment in projects and policies that have measurable outcomes over time. A benefit-cost ratio (BCR) calculation will be vital in assessing if the scenarios favour vaccination and if there are benefits to adopting IB vaccines in the simulated scenarios compared to scenarios that do not adopt IB vaccines.

2.5.1 Benefit-cost analysis

BCA determines the three fundamental calculations, namely benefit-cost ratio, net present value (NPV), and internal rate of return (IRR) (Campbell & Brown, 2015). A benefit-cost ratio (BCR) is calculated as the net present value of accrued benefits (*e.g.*, increase in production measured by market output, costs averted measured by losses, and feed costs prevented) divided by the net present value of accrued costs (*e.g.,* additional costs from vaccination and surveillance). BCR calculation is a robust economic tool that allows use under limited data and is easily understood by stakeholders (Campbell & Brown, 2015). If the value of benefits is more than the value of costs, indicating that a benefit-cost ratio exceeds unity (*i.e.*, a BCR is greater than one), *ceteris paribus*, it could be presumed that the project is favourable (Campbell & Brown, 2003).

A BCR is calculated as follows:

$$\text{The ratio of benefits to costs (benefit} - \text{cost ratio)} = \frac{PV(benefits)}{PV(costs)} \qquad (1)$$

$PV(benefits) -$ present value of benefits, and

$PV(costs) -$ present value of costs (Campbell & Brown, 2015).

Therefore, the benefit-cost ratios were computed across thousands of iterations of simulations, making a correct assumption regarding the probability density distributions of the input variables of paramount importance. The assumptions for the input variables for this study were that they were normally distributed, and for each of them, statistical distribution functions could be assigned depending on the assumptions made under available data in the literature and other sources. The means and standard deviations would be specified for each scenario to define the probability density distribution for each input variable on @RISK depending on the setup of scenarios and expected values of population parameters of these variables.

2.6 Correlation assessment for simulated input variables

It was likely that the input variables chosen are correlated. A correlation measures the dependency of a random variable on another. These two random variables can either be positively correlated when they tend to move in the same direction or negatively correlated, when they move in opposite directions (Frey & Pfeifer, 2013; Clemen, 2014). For example, the incidence rate may be positively correlated with abnormal mortality rate.

The rank-order correlation coefficient developed by C. Spearman (1900’s) is used by @RISK to compute the rank-order correlation analysis, not Pearson linear correlations. The Pearson correlations assume linear distribution, but most of the distributions in nature are non-linear, and hence Spearman correlations are more suitable for distributions that are non-linear. @RISK takes samples for correlated variables before simulating the first iteration, while for non-correlated variables, samples are drawn within each iteration. It adjusts the ranking of samples with the number of iterations to be performed within each iteration to provide the defined correlation values, and this correlation is computed using the rankings values, not actual values. The "ranks" of these values are governed by their positions within the range of possible values for a variable, generating paired random numbers for correlated distributions during an iteration. It is called a "distribution-free” approach because any distribution may be correlated. Even if there is a correlation among samples drawn for the two distributions, the original distribution maintains its integrity (Palisade, 2021).

For this study, a correlation assessment was performed using @RISK for the input variables such as incidence, vaccine adoption, abnormal mortality, abnormal production, efficacy, and feed cost.

2.7 Stakeholders

The three main categories of stakeholders are producers (*e.g.*, layer producers, hatcheries, and vaccine producers); consumers (*e.g.*, people who eat eggs and egg products); and government/governance (*e.g.*, provincial poultry associations, Agriculture and Agri-food Canada, and the federal government). For a complete list of stakeholders, refer to Appendix 2.

2.8 Demographics

I used data for farm revenue and expenses per farm reporting from Statistics Canada for the year 2019 for different revenue classes and geographical regions (Canada, provinces, and territories). The data for the number of poultry farms in Canada and provinces were that of the year 2016 since Statistics Canada releases these data only once in five years (S. C. Government of Canada, 2018b), and the latest data on the website when accessed were of 2016 (pending release of data for 2021). I chose to perform simulations for Canada (to get an overall picture of the country), Alberta (AB) (because this study is conducted in an Albertan university), British Columbia (BC), Ontario (ON), and Quebec (QC) (because these are the provinces that produce the largest amount of chicken, eggs, and egg products).

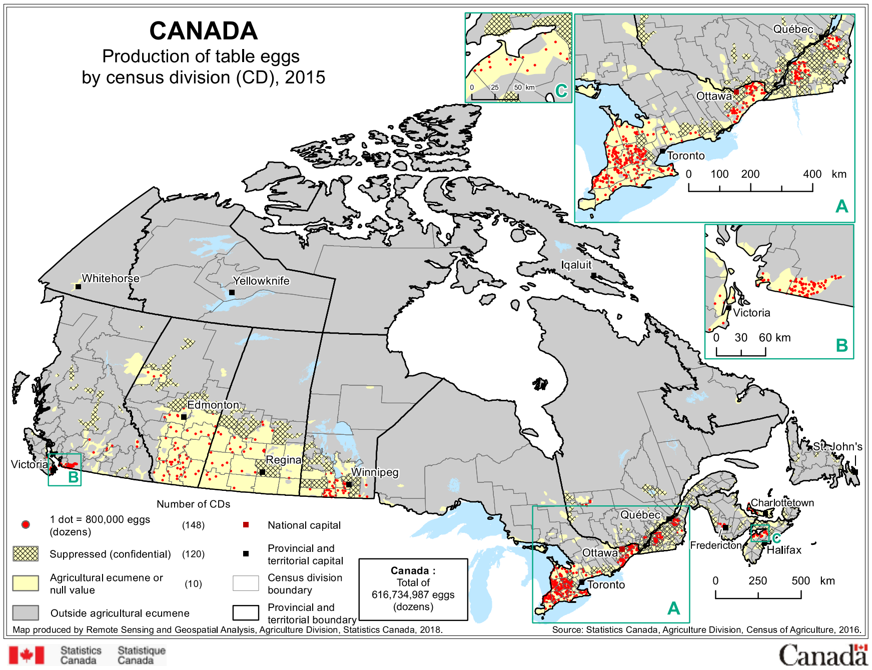


Figure 2. 1 A map of Canada showing the intensity of table egg production in Canada across various provinces (S. C. Government of Canada, 2018a).

For Canada and Alberta, three revenue categories (all-revenue-classes, medium, and large) will be simulated, while for BC, ON, and QC, medium farms and large farms will be simulated owing to the considerable amount of time it requires to set up and run simulations for multiple scenarios for each revenue category.

Table 2. 1 The numbers of poultry farms in Canada and four provinces for different revenue classes.

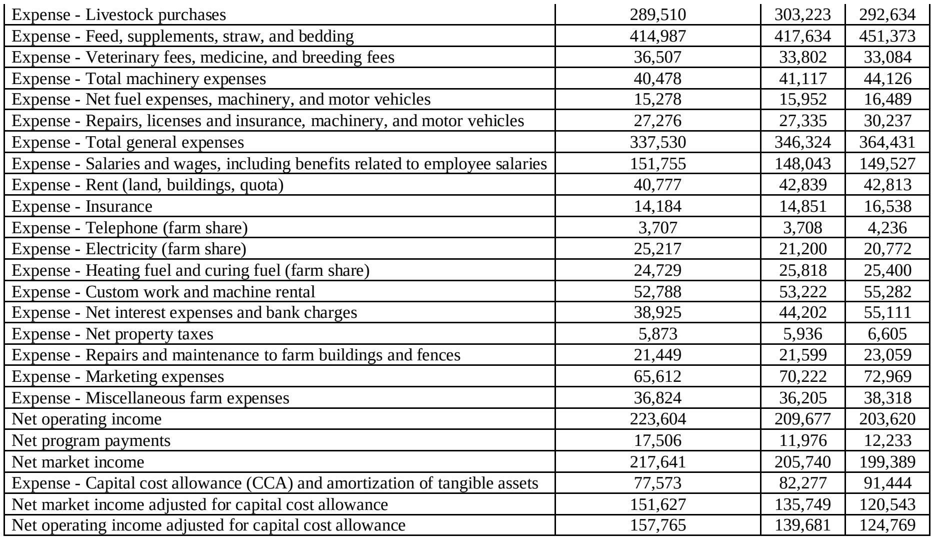
Revenue category	All revenue classes					Medium farms					Large farms				
Geography	CAN	BC	AB	ON	QC	CAN	BC	AB	ON	QC	CAN	BC	AB	ON	QC

No. of poultry farms	4,903	1,220	373	1,816	875	480	75	30	215	95	905	170	65	360	205

2.9 Data sources and input variables selected for simulations

Data for this research were gathered from the Statistics Canada website of the Agriculture and Agri-foods Canada, poultry industry reports (*e.g.*, annual reports and publications by provincial poultry associations, producer meetings, and conference proceedings), industry news (*e.g.*, market prices of eggs in different provinces), and published papers and reports of mortality, morbidity, incidence, and egg loss rates. I have included in the following an example of a data webpage for revenue and expenses of poultry farms for Canada, all revenue classes, based on averages computed per poultry farm reporting in the respective geographical area.

Geography	Canada		
	Poultry and egg production		
	All revenue classes		
	Average per farm reporting		
Estimates	2017	2018	2019
	Dollars		
Number of farms	..	..	..
Revenue - Total operating revenues	1,257,543	1,266,779	1,310,731
Revenue - Total crop revenues	145,295	168,907	167,616
Revenue - Total grain and oilseed revenues	204,095	225,463	228,324
Revenue - Wheat	72,018	83,505	82,120
Revenue - Oats	18,995	20,404	31,669
Revenue - Barley	43,783	42,956	49,486
Revenue - Canola (rapeseed)	145,684	140,124	159,156
Revenue - Soybeans	102,709	98,154	95,281
Revenue - Corn	125,685	135,418	146,976
Revenue - Mixed grains	13,793	79,536	106,053
Revenue - Other and non-specified grains and oilseeds	100,873	111,114	111,045
Revenue - Total other crop revenues	36,385	48,641	49,405
Revenue - Potatoes	16,915	31,815	25,099
Revenue - Fruits	48,420	67,658	45,786
Revenue - Vegetables (non-greenhouse)	41,223	40,866	57,468
Revenue - Greenhouse, nursery, and floriculture products	32,382	31,159	27,690
Revenue - Forage crops (including seeds)	29,021	41,570	43,974
Revenue - Other crops	17,353	29,004	30,852
Revenue - Total livestock and animal product revenues	1,149,775	1,152,283	1,192,133
Revenue - Cattle	56,164	41,624	39,465
Revenue - Swine	101,391	77,157	92,646
Revenue - Poultry and eggs	1,131,041	1,135,939	1,178,686
Revenue - Dairy products	268,330	298,142	310,514
Revenue - Sheep, lambs, and goats	5,653	4,760	9,088
Revenue - Other livestock and animal products	46,571	63,248	41,494
Revenue - Total other revenues	70,670	72,627	71,832
Revenue - Program payments and insurance proceeds	27,569	20,648	20,949
Revenue - Custom work and machine rental	56,904	56,978	65,710
Revenue - Miscellaneous revenues	39,565	45,261	38,930
Expense - Total operating expenses	1,034,197	1,057,341	1,107,343
Expense - Total crop expenses	57,519	61,150	68,309
Expense - Fertilizers and lime	39,054	39,244	47,145
Expense - Pesticides	16,212	19,146	22,139
Expense - Seeds and plants	30,750	32,854	35,868
Expense - Total livestock expenses	666,656	678,531	705,603



Expense - Livestock purchases	289,510	303,223	292,634
Expense - Feed, supplements, straw, and bedding	414,987	417,634	451,373
Expense - Veterinary fees, medicine, and breeding fees	36,507	33,802	33,084
Expense - Total machinery expenses	40,478	41,117	44,126
Expense - Net fuel expenses, machinery, and motor vehicles	15,278	15,952	16,489
Expense - Repairs, licenses and insurance, machinery, and motor vehicles	27,276	27,335	30,237
Expense - Total general expenses	337,530	346,324	364,431
Expense - Salaries and wages, including benefits related to employee salaries	151,755	148,043	149,527
Expense - Rent (land, buildings, quota)	40,777	42,839	42,813
Expense - Insurance	14,184	14,851	16,538
Expense - Telephone (farm share)	3,707	3,708	4,236
Expense - Electricity (farm share)	25,217	21,200	20,772
Expense - Heating fuel and curing fuel (farm share)	24,729	25,818	25,400
Expense - Custom work and machine rental	52,788	53,222	55,282
Expense - Net interest expenses and bank charges	38,925	44,202	55,111
Expense - Net property taxes	5,873	5,936	6,605
Expense - Repairs and maintenance to farm buildings and fences	21,449	21,599	23,059
Expense - Marketing expenses	65,612	70,222	72,969
Expense - Miscellaneous farm expenses	36,824	36,205	38,318
Net operating income	223,604	209,677	203,620
Net program payments	17,506	11,976	12,233
Net market income	217,641	205,740	199,389
Expense - Capital cost allowance (CCA) and amortization of tangible assets	77,573	82,277	91,444
Net market income adjusted for capital cost allowance	151,627	135,749	120,543
Net operating income adjusted for capital cost allowance	157,765	139,681	124,769

Figure 2. 2 Revenue and expenses data table for Canada all revenue classes exported from Statistics Canada webpage (S. C. Government of Canada, 2021a).

The key input variables chosen for simulation are listed in *Table 2. 2* below. I chose to include feed cost as a non-epidemiologic variable because it constitutes a significant portion of the operating expenses in a farm (Sumner *et al.*, 2011) and the impact due to variations in prices of grains such as corn, soybeans, oats, wheat, and oilseeds (Canada, 2018), can be huge. Therefore, I included it to see if it overwhelmed the epidemiologic variables or vice versa. Labour is another significant component of operating expenses in a layer farm. However, I did not include it in the simulations because the employee wages for the "workers in natural resources, agriculture, and related production" remained relatively constant if we look at data between 2014 and 2018 (Government of Canada, 2018).

Table 2. 2 Assumed probability distribution statistics for key input variables in scenario 5.

	Key input variables
1	Vaccine adoption (%)
2	Incidence rate of IB (%)
3	Vaccine efficacy (%)
4	Impact of the disease – abnormal production (%)
5	Impact of the disease – abnormal mortality rate (%)
6	Feed cost (percent of total expenses) (%)
7	Vaccine price (cents)

The epidemiologic factors of IB chosen as key variables were incidence, abnormal mortality, and abnormal production rates because, at higher rates, these variables can have a significant impact on the profitability of layer farms since IB is a very highly infectious disease, affecting the upper respiratory tract and the reproductive tracts, with some strains causing nephritis (Dave Cavanagh, 2007; David Cavanagh & Gelb, 2008; Winter *et al.,* 2006; Shahwan *et al.,* 2013). Abnormal mortality due to IB reaches 30%, and the drop in egg production can go up to 50%, while damages caused to the ovaries and fallopian tubes of infected birds can affect the quality of eggs, both internal and external (Dave Cavanagh, 2007; Jones, 2010; Amarasinghe *et al.,* 2018). Therefore, these epidemiological variables can phenomenally affect the economics of a layer farm. If incidence changes, it can have a ripple effect on almost all other factors, creating a huge impact.

Vaccines essentially provide protection due to the development of immunity that becomes effective in vaccinated birds at the flock and regional levels (Marangon & Busani, n.d.). Vaccination reduces transmission significantly due to a reduction in virus replication and excretion in birds, reducing R to less than 1 (de Wit *et al.,* 1998; De Jong & Kimman, 1994). The assumption of the efficaciousness of a vaccine is that a vaccinated population covered by an efficacious IB vaccine is protected against the infection and shedding of IB virus (Ali *et al.,* 2018). Good vaccination programs against IB and other control strategies can mitigate the negative impact and losses caused by a secondary bacterial infection (Sanei, 2018). Therefore, these factors associated with IB vaccine, namely vaccine adoption, vaccine efficacy, and vaccine price were chosen as input variables for simulations, as they significantly impact the outcome of generating profits in layer poultry farms.

2.10 Simulation

For inputs with unknown variability and values (lack of data), substituting them with probability distribution functions creates a stochastic model (in which probability distributions govern the values of a model) from a deterministic model (Frey & Pfeifer, 2013; Clemen, 2014). Therefore, Excel (Microsoft Excel, 2021) spreadsheets-based simulation models were prepared with @RISK add-in software that incorporates the effects of variability in disease incidence, mortality rate, productivity, vaccine adoption rate, vaccine efficacy, and production costs. The models simulated typical layer poultry farms in Canada and four provinces, namely Alberta (AB), British Columbia (BC), Ontario (ON), and Quebec (QC), to demonstrate how the costs of production, income, and revenue for their farms would react to IB outbreaks, vaccine adoption, and changes to production costs. The effects of changes to the disease status, vaccine adoption rate, and other variables will be seen without poultry producers having to experience it firsthand. By changing one or more attributes, their effects on the outcomes will be observed. Therefore, it becomes a robust prediction when we generate thousands of iterations to obtain a distribution that is characteristic of a particular outcome variable.

2.11 Monte Carlo Simulation

The operating principle of the Monte Carlo simulation is the process of drawing many random samples and observations to create a "pseudo-population" resembling the actual population in all aspects, by which the behaviour of a statistic is studied. It has properties for generating values similar to sample values drawn from the actual population, and several iterations or trials are done using this pseudo-population to investigate how a statistic behaves when the number of samples gets larger. Therefore, the Monte Carlo simulation stems from the concept of sampling distribution. A Monte Carlo simulation can be performed using Microsoft Excel (Microsoft

Excel, 2021; Frey & Pfeifer, 2013; Winston, 1999; Law *et al.*, 2000; Clemen, 2014).

For the input variables in this study, such as IB vaccine adoption rate, the efficacy of IB vaccines used, mortality rate, incidence rate, and feed cost change, I assumed normal probability density distribution (because many such natural phenomena are typically well represented by a normal distribution), symmetrically distributed about the mean with the graphical appearance of a bell curve. However, it was checked later for goodness-of-fit using the Kolmogorov-Smirnov test if the distributions of the input variables were a good fit with the normal distribution. The assumptions of the mean and standard deviations for each variable were based on the available figures in the literature.

2.12 Simulation set up

For the selected geographical regions, three revenue categories were chosen for Canada and Alberta, namely the all-revenue-classes category, the medium-farms category, and the large-farms category, to capture medium and large farms and the overall picture. For ON, BC, and QC, two revenue categories, namely the medium and large farms, were selected to capture layer poultry farms' upper and lower spectra in each geographical area. There were twelve revenue categories across the four selected provinces (and the overall Canada picture) covering major intensive poultry-producing regions.

The all-revenue-classes category represented the overall average of all layer farms from the smallest to the largest revenue classes, the medium farms category consisted of layer producers generating annual revenues between $250,000 and $499,000, and the large-farms category consisted of layer farms with annual revenues between $1000,000 and $1,999,000, as reflected in table 3.3 below.

Table 2. 3 The table below shows 12 revenue categories for simulations.

Revenue category	All revenue classes		Medium farms: $250,000-$499,000					Large farms: $1000,000-$1,999,000				
Geography	CAN	AB	CAN	BC	AB	ON	QC	CAN	BC	AB	ON	QC

For each revenue category above, seven scenarios were generated for simulation. Thus, in total, there were 84 scenarios. Canada and AB had three revenue categories each, BC, ON, and QC had two revenue categories each, and there were seven scenarios in each revenue category).

2.13 Scenario analysis

Scenario analysis is defined as setting up several assumed and well-defined scenarios to examine some effect on them. I used the farm income model for scenario analysis – a quantitative analysis using a BCR calculation approach. This model examined the economic impact of IB using simulated scenarios. The goal of models is to take advantage of insight into the optimization of welfare and benefits (Frey & Pfeifer, 2013; Clemen, 2014). The key input variables chosen were feed cost, IB epidemiologic variables (incidence, abnormal mortality, and abnormal production), and variables associated with IB vaccine (efficacy, adoption, and cost). I incorporated changes in key factors across options, comparing different values of the input variables for different scenarios.

Changes in the probability distributions of the input variables for different scenarios were specified according to the specific setup of each scenario. Five scenarios for each of the revenue categories were set up as follows:

2.13.1 Scenario 1 - Baseline

This scenario was the baseline where there was no outbreak of IB, nor an additional cost associated with vaccination against IB. The values were unpopulated for all the chosen input variables except for the feed cost. It represented an ideal scenario with no IB infection, and the birds in this scenario were not vaccinated. Typically, this scenario was unrealistic because IBV is ubiquitous, affecting poultry farms all over Canada. Nevertheless, to get the picture of an ideal situation, with no outbreak, no additional vaccination cost, and no change in feed prices, the consideration of this baseline situation was essential to understand the full impact of economic damages that IB could potentially cause when outbreaks happened on a farm.

Therefore, baseline assumptions were considered for calculating revenues, costs, and income in this scenario. This was the scenario that served as the comparator – the scenario to which all others were compared (because it was the baseline scenario that assumed no treatment or intervention).

The input variables were assumed to be normally distributed, as with many phenomena in nature. Other distributions were also considered and discussed under the Kolmogorov-Smirnov (KS) goodness-of-fit test. The normal mortality rate was assumed to be 2% (Richard M. Fulton, 2017), and it was computed monthly, meaning, at the start of the following month, the total number of birds would be 2% lesser than the previous month, *ceteris paribus*. The incidence rate of IB was assumed to be zero (no IB outbreak), which meant that abnormal production and abnormal mortality rates were non-existent as well. Next, vaccine adoption was assumed to be at zero percent because there was no IB, and vaccination was not practiced. Non-adoption of vaccines meant that vaccine efficacy and additional costs incurred due to vaccines were non-existent. Additional revenue generated from the sale of stewing hens (spent layer birds culled and sold for meat) was incorporated at the end of each cycle.

2.13.2 Scenario 2 – Disease with no vaccination

This scenario assumed there was an outbreak of IB, and birds were not vaccinated to prevent IB. The scenario represented an actual situation of farms that did not adopt vaccination for whatever reason. I chose to simulate this scenario so that the impact of IB outbreaks in unvaccinated farms was estimated in order to compare it with the potential benefits of the vaccinated farms. Among the input variables, feed cost percent was assumed to remain unchanged. This portrayed a typical outbreak scenario for unvaccinated farms. The parameters of IB outbreaks assumed were normal means that are characteristic of the existing strains of IB according to reported outbreak cases and available data in Canada and the world over.

Table 2. 4 Assumed probability distribution statistics for input variables in scenario 2.

	Key variables	**Assumed normal mean**	**Assumed standard deviation**
1	Vaccination (% adoption)	0%	0%
2	Incidence rate of IB (%)	35%	0.035 (10% of the mean)
3	Vaccine efficacy (%)	NA	NA
4	Impact of disease – abnormal production (%)	30%	0.03 (10% of the mean)
5	Impact of disease – abnormal mortality rate (%)	15%	0.015 (10% of the mean)
6	Feed cost (percent of total expenses) (%)	49%	0.049 (10% of the mean)
7	Vaccine price (cents)	NA	NA

As shown in *Table 2. 4*, the input variables were assumed to take the normal distribution, as with many natural phenomena. Other distributions were also considered and discussed under the KS goodness-of-fit test. The incidence rate of IB outbreaks was assumed to be 35%, with a standard deviation of 0.035 (10% of the mean). Although the incidence of birds in a barn can be 100% (Ignjatović & Sapats, 2000c), the assumption of 35% incidence is for farms (Derksen *et al.*, 2018). The abnormal mortality rate was assumed to be 15% which may go up to 70% with a secondary infection (Jackwood, 2012; Smith *et al.*, 2015; Jackwood & de Wit, 2013) with a standard deviation of 0.015 (10% of the mean) and an abnormal production rate of 30% with a standard deviation of 0.03 (10% of the mean). The feed cost was assumed to remain unchanged at 49% of the total expense (Sumner et al., 2011). There was no additional vaccination or vaccine cost incurred as vaccination was not done. The normal mortality rate in a farm was assumed to be 2%, and it was computed on a monthly basis besides the abnormal mortality rates, which were also calculated monthly. These assumptions were taken into account for calculating revenues, costs, and income in this scenario.

Table 2. 5 Monthly cash flow statement template showing different cohorts for the scenarios with IB (with or without vaccination).

	12 months													
	1	2	3	4	5	6	7	8	9	10	11	12	Total	
Birds in a farm (start of the month)														
1. Exposed														1. Exposed
Birds in cohort for the month														Avg birds in cohort annual
Cost for cohort for the month														Cost for cohort annual
Vax cost for the month														Vax cost annual
Eggs laid for cohort for the month														Eggs laid annual
Revenue for cohort for the month														Revenue for cohort annual
Profit for cohort for the month														Profit/loss for cohort annual
2. Unexposed														2. Unexposed
Birds in cohort for the month														Avg birds in cohort annual
Cost for the cohort for the month														Cost for the cohort annual
Vax cost for the month														Vax cost annual
Eggs laid for cohort for the month														Eggs laid total for cohort annual
Revenue for cohort for the month														Revenue for cohort annual
Profit for cohort for the month														Profit/loss for cohort annual
Eggs laid total for the month														Eggs laid total for cohort annual
Revenues														
Revenue (eggs) for the month														Revenue (eggs) annual
Revenue (spent hens) for the month														Revenue (spent hens) annual
Revenue total for the month														Revenue total annual
Revenue cumulative total														
Costs														

Chicks for the month														Chick cost annual
Feed for the month														Feed cost annual
Housing for the month														Housing cost annual
Labour for the month														Labour cost annual
Additional costs for the month														Additional cost annual
Costs (per bird basis) for the month														Costs (per bird basis) per farm annual
Costs cumulative total														
Cost per bird for the month														Cost per bird (annual)
Profit for the month														Profit per farm annual
Profits cumulative total														
Normal mortality for the month														Normal mortality annual
Abnormal mortality (15%) for the month														Abnormal mortality annual
Birds in a farm (end of month)														Average no. of birds in a farm (annual)

From *Table 2. 5*, the cohorts identified for this scenario were two in number, namely the exposed and unexposed groups. The number of eggs laid, revenue, costs, and income for each cohort were calculated monthly for each of the two cohorts separately, and the total amounts for the farm worked out for each month until the end of the cycle. The presence of the disease was assumed to be uniformly spread throughout the cycle, and monthly abnormal mortality was computed for the exposed cohort. Normal mortality, which happens ubiquitously in all the farms irrespective of IB outbreak or vaccination status, was incorporated into monthly bird mortality. The total number of birds carried over to the beginning of the following month in the cash flow statement thus reflects the reduction in the number of layer birds adjusted for normal mortality.

2.13.3 Scenario 3 – Disease with vaccination

I assumed there was an outbreak of IB in this scenario, and layer poultry producers chose to adopt vaccination to prevent IB. This scenario represented a real-life situation of layer farms that adopted vaccination to estimate the potential benefits of vaccination, and it would show the mitigating impact of vaccination on farms affected by IB outbreaks. It represented a typical outbreak scenario for vaccinated farms, and the parameters of IB outbreaks assumed were normal means of the existing strains of IB according to the available sources referenced wherever necessary.

Table 2. 6 Assumed probability distribution statistics for key input variables in scenario 3.

	Key variables	**Assumed normal mean**	**Assumed standard deviation**
1	Vaccination (% adoption)	80%	0.80 (10% of the mean)
2	Incidence rate of IB (%)	35%	15%
3	Vaccine efficacy (%)	90%	0.90 (10% of the mean)
4	Impact of disease – abnormal production (%)	30%	0.30 (10% of the mean)
5	Impact of disease – abnormal mortality rate (%)	15%	0.15 (10% of the mean)
6	Feed cost (percent of total expenses) (%)	49%	No change
7	Vaccine price (cents)	5 cents	25%

As shown in *Table 2. 6*, the input variables were assumed to take the normal distribution. The incidence rate of outbreaks of IB of 35% with a standard deviation of 0.035 (10% of the mean), the abnormal mortality rate of 15% with a standard deviation of 0.015 (10% of the mean), and the abnormal production rate of 30% assuming moderate mortality with presence of secondary bacterial infection which may go up to 70% per (Jackwood, 2012; Smith *et al.,* 2015; Jackwood & de Wit, 2013) with a standard deviation of 0.03 (10% of the mean), were assumed. The additional vaccination and vaccine costs incurred were incorporated into the total costs. The vaccine adoption rate of 80% with 0.08 standard deviation (10% of the mean), vaccine efficacy of 90% (De Wit *et al.,* 2010) with 0.09 (10% of the mean) standard deviation, and direct vaccine price of 5 cents per dose per bird (Zoetis Animal Health, 2020), were assumed. The feed cost was assumed to remain unchanged at 49% of the total expense. The normal mortality rate was assumed to be 2%, and it was computed monthly, similar to that of the abnormal mortality rate.

Table 2. 7 The table below shows different cohorts for the scenario with IB (with vaccination).

Cohort	**Cohort specifics**
1. Vaccinated exposed - Vax effective	Vaccinated, exposed, vaccine efficacious, normal production, and normal mortality
2. Vaccinated exposed - Vax ineffective	2.1 Vaccinated, exposed, vaccine inefficacious, abnormal production, and abnormal mortality
	2.2 Vaccinated, exposed, vaccine inefficacious, normal production, and normal mortality
3. Vaccinated unexposed	Vaccinated, unexposed, vaccine efficacious, normal production, and normal mortality + Vaccinated, unexposed, vaccine inefficacious, normal production, and normal mortality
4. Unvaccinated exposed	4.1 Unvaccinated, exposed, abnormal production, and abnormal mortality
	4.2 Unvaccinated, exposed, normal production, and normal mortality
5. Unvaccinated unexposed	Unvaccinated, unexposed, normal production, and normal mortality

From *Table 2. 7*, for this scenario with the presence of IB and vaccine adoption, five cohorts were identified. The number of eggs, revenue, costs, and income were calculated monthly for each of the five cohorts separately, and total amounts for the farm were worked out for each month. Similar to earlier scenarios, this scenario also assumed the constant presence of IB outbreaks throughout the cycle, and monthly abnormal mortality due to IB was computed for all the exposed cohorts. Normal mortality was incorporated into the monthly mortality and subtracted from the total number. There were additional costs incurred due to vaccination labour costs and direct vaccine costs in addition to the existing costs. It would also lead to a significant increase in the benefits due to averted losses due to IB outbreaks if vaccination were not adopted.

2.13.4 Scenario 4 – New strains of IBV with no vaccination

This scenario assumed an emergence or entry of new virulent strains of IBV, causing outbreaks, and birds were not vaccinated. This scenario represented a hypothetical situation of layer farms where layer poultry producers chose not to adopt vaccination to prevent IB, and there were outbreaks with the new IBV strains. This scenario would estimate the full-scale potential impact of new strains as vaccination was not adopted. The parameters of IB outbreaks assumed were supposed to be normal means of the new strains of IBV that are highly virulent, causing more damage than the existing strains.

As shown in table 3.8 in the following, the input variables were assumed to take the normal distribution. The incidence rate of outbreaks of 50% with a standard deviation of 0.05 (10% of the mean), the abnormal mortality rate of 35% with a standard deviation of 0.035 (10% of the mean), and the normal production rate of 50% with a standard deviation of 0.05 (10% of the mean), were assumed. The feed cost was assumed to remain unchanged at 49% of the total expense. No additional vaccination and vaccine costs were incurred, as vaccination was not adopted. The normal mortality rate of 2% was incorporated, and the abnormal mortality rate was also calculated monthly.

Table 2. 8 Assumed probability distribution statistics for key input variables in scenario 4.

	Key variables	**Assumed normal mean**	**Assumed standard deviation**
1	Vaccination (% adoption)	0%	0%
2	Incidence rate of IB (%)	50%	15%
3	Vaccine efficacy (%)	NA	NA
4	Impact of disease – abnormal production (%)	50%	0.05 (10% of the mean)
5	Impact of disease – abnormal mortality rate (%)	35%	0.035 (10% of the mean)
6	Feed cost (percent of total expenses) (%)	49%	No change
7	Vaccine price (cents)	NA	NA

Similar to scenario 3, this scenario had five cohorts identified, as shown in *Table 2. 8*, with the presence of both IB outbreaks and vaccine adoption. The calculations for the number of eggs, revenue, costs, and income for each cohort were done on a monthly basis for the five cohorts separately. The scenario assumed the constant presence of IB outbreaks due to new IBV strains throughout the cycle. The monthly abnormal mortality due to IB was computed for all the exposed cohorts, and the normal mortality was incorporated into the monthly total mortality for all cohorts. There were no additional costs incurred due to vaccination labour and direct vaccine costs, as vaccination was not adopted.

2.13.4 Scenario 4 – New strains of IBV with vaccination

This scenario was similar to scenario 4 (unvaccinated) except that it assumed layer producers vaccinated their birds in this scenario. Therefore, the same assumptions were made with the emergence or entry of new virulent strains of IBV but with vaccination. The scenario also represented a hypothetical situation of layer farms where layer poultry producers chose to adopt vaccination, and there were outbreaks of IB with new strains. Due to the high virulence of the new strains, the assumption was that there would be very minimal cross-protective immunity, leading to very low vaccine efficacy while causing higher abnormal mortality and abnormal production.

This scenario would estimate the benefits of vaccinating during the event when there is a full-blown impact of new strains of IBV. The assumptions for the parameters of IB outbreaks were the same as that of scenario 4 (unvaccinated). Although there were damages caused due to high virulence of the new strains, very minimal cross-protective immunity leading to very low vaccine efficacy, higher abnormal mortality, and higher abnormal production, there would still be potential benefits associated with vaccination in this scenario.

Table 2. 9 Assumed probability distribution statistics for key input variables in scenario 4.

	Key variables	**Assumed normal mean**	**Assumed standard deviation**
1	Vaccination (% adoption)	80%	0.08 (10% of the mean)
2	Incidence rate of IB (%)	50%	0.05 (10% of the mean)
3	Vaccine efficacy (%)	65%	0.065 (10% of the mean)
4	Impact of disease – abnormal production (%)	50%	0.05 (10% of the mean)
5	Impact of disease – abnormal mortality rate (%)	35%	0.035 (10% of the mean)
6	Feed cost (percent of total expenses) (%)	49%	No change
7	Vaccine price (cents)	5 cents	25% of 5 cents

As shown in *Table 2. 9*, the input variables were assumed to take the normal distribution, as with many natural phenomena. Comparison with other distributions for goodness-of-fit was done and reported under the KS test elsewhere in this document. The incidence rate of outbreaks of IB of 50% with a standard deviation of 0.05 (10% of the mean), abnormal mortality rate of 35% with a standard deviation of 0.035 (10% of the mean), and abnormal production rate of 50% with a standard deviation of 0.05 (10% of the mean) were assumed. The vaccine adoption rate of 80% with 0.08 (10% of the mean) standard deviation, vaccine efficacy of 65% with 0.065 (10% of the mean) standard deviation, and direct vaccine price of 5 cents was assumed. The feed cost was assumed to remain unchanged at 49% of the total expense. The normal mortality rate of 2% was incorporated, and it was computed on a monthly basis. The abnormal mortality rate was also calculated on a monthly basis.

This scenario also had five cohorts identified, as shown in table 3.8, involving both IB outbreaks and vaccine adoption. Cohort classification was the same because it was classified based on the vaccine adoption rate, efficacy, and disease exposure status. The calculations for the number of eggs, revenue, costs, and income for each cohort were done on a monthly basis for each of the five cohorts separately, similar to the previous scenarios. All the scenarios with the disease assumed the uniform presence of IB outbreaks due to new IBV strains throughout the cycle. The monthly abnormal mortality due to IB was computed for all the exposed cohorts, and normal mortality was incorporated into the monthly mortality for all cohorts.

2.13.5 Scenario 5 – New strains IBV and feed price rise with no vaccination

This scenario assumed an emergence or entry of new virulent strains of IBV causing outbreaks, birds were not vaccinated, and there was a rise in the feed price. It represented a hypothetical situation where layer poultry producers chose not to adopt IB vaccination, but there were outbreaks due to the new strains and changes in feed price. This scenario would estimate the potential impacts of new strains of IBV compounded by feed price changes (increase). The parameters of IB outbreaks assumed were supposed to be normal means of the new strains of IBV that were highly virulent, causing more damage than the existing strains similar to that of scenario 4, except that it was made worse by feed cost fluctuations.

As shown in Table 2. 10, the input variables were assumed to take the normal distribution, as with many natural phenomena. Comparison with other distributions for goodness-of-fit was done and reported under the KS test elsewhere in this document. The incidence rate of outbreaks of IB of 50% with a standard deviation of 0.05 (10% of the mean), abnormal mortality rate of 35% with a standard deviation of 0.035 (10% of the mean), and abnormal production rate of 50% with a standard deviation of 0.05 (10% of the mean) were assumed. The increase in the feed cost was assumed to be 10%, making it constitute 59% of the total expenses with a standard deviation of 0.059 (10% of the mean). No additional vaccination and vaccine costs were incurred as vaccination was not adopted. As with the previous scenarios, the normal mortality rate of 2% was computed monthly. The abnormal mortality rates due to outbreaks caused by new strains of

IBV were also computed monthly.

Table 2. 10 Assumed probability distribution statistics for key input variables in scenario 5.

	Key variables	**Assumed normal mean**	**Assumed standard deviation**
1	Vaccination (% adoption)	0%	0%
2	Incidence rate of IB (%)	50%	15%
3	Vaccine efficacy (%)	NA	NA
4	Impact of disease – abnormal production (%)	50%	0.05 (10% of the mean)
5	Impact of disease – abnormal mortality rate (%)	35%	0.035 (10% of the mean)
6	Feed cost (percent of total expenses) (%)	59%	0.059 (10% of the mean)
7	Vaccine price (cents)	NA	NA

This scenario also had five cohorts identified, shown in table 3.8, with no vaccine adoption, but the new strains caused outbreaks. Cohort classification was the same because it was classified based on the vaccine adoption rate, efficacy, and disease exposure status. This scenario assumed the constant presence of IB outbreaks due to new IBV strains throughout the cycle. The calculations of revenue, costs, and income were done on a monthly basis for each of the five cohorts separately. The monthly abnormal mortality due to IB was computed for all the exposed cohorts, while normal mortality was incorporated into the monthly mortality for all cohorts. There were no additional costs incurred for this scenario due to vaccination labour cost and direct vaccine costs as vaccination was not adopted.

2.13.6 Scenario 5 – New strains IBV and feed price rise with vaccination

This scenario assumed an emergence or entry of new virulent strains of IBV, causing outbreaks along with the rise in feed price, but birds were vaccinated. It represented a hypothetical situation where layer poultry producers chose to adopt IB vaccination and outbreaks due to the new strains and changes in feed price. This scenario would estimate the potential benefits of adopting vaccination despite the severe impacts of new strains of IBV compounded by feed price changes. The parameters of IB outbreaks assumed were supposed to be normal means of the new strains of IBV that were highly virulent, and feed cost fluctuations worsened it, but layer producers adopted vaccination.

As shown in *Table 2. 11*, the input variables were assumed to take normal distribution while comparing with other distributions for goodness-of-fit was done and reported under the KS test elsewhere in this document. The incidence rate of outbreaks of IB of 50% with a standard deviation of 0.05 (10% of the mean), abnormal mortality rate of 35% with a standard deviation of 0.035 (10% of the mean), and abnormal production rate of 50% with a standard deviation of 0.05 (10% of the mean) were assumed. The increase in the feed cost was assumed to be 10%, making it constitute 59% of the total expenses with a standard deviation of 0.059 (10% of the mean). The vaccine adoption rate of 80% with 0.08 (10% of the mean) standard deviation, vaccine efficacy of 65% with 0.065 (10% of the mean) standard deviation, and direct vaccine price of 5 cents was assumed. As with the previous scenarios, the normal mortality rate of 2% was computed monthly. The abnormal mortality rates due to outbreaks caused by new strains of IBV were also computed monthly.

Table 2. 11 Assumed probability distribution statistics for key input variables in scenario 5.

	Key variables	**Assumed normal mean**	**Assumed standard deviation**
1	Vaccination (% adoption)	80%	0.08 (10% of the mean)
2	Incidence rate of IB (%)	50%	0.05 (10% of the mean)
3	Vaccine efficacy (%)	65%	0.065 (10% of the mean)
4	Impact of disease – abnormal production (%)	50%	0.05 (10% of the mean)
5	Impact of disease – abnormal mortality rate (%)	35%	0.035 (10% of the mean)
6	Feed cost (percent of total expenses) (%)	59%	0.059 (10% of the mean)
7	Vaccine price (cents)	5 cents	25% of 5 cents

This scenario also had five cohorts identified. There were outbreaks caused by the new strains and feed price changes, but layer producers chose to adopt vaccination. Cohort classification was the same because it was classified based on the vaccine adoption rate, efficacy, and disease exposure status. Similarly, the constant presence of IB outbreaks due to new IBV strains was assumed throughout the cycle. Monthly calculations of revenue, costs, and income were done for each of the five cohorts separately. The abnormal mortality due to IB was computed monthly for all exposed cohorts, and normal mortality was considered for all the cohorts, exposed or otherwise.

Seven scenarios were considered for each of the twelve revenue categories, and simulations were performed. The impact of changes in the key input variables in the different scenarios was analyzed from the findings and outputs of the simulations in terms of profits generated/losses incurred, profitability ratios, benefit-cost ratios, and tornado charts would be used for the assessment of the impacts of various input variables.

2.14 Tests of significance - Kolmogorov-Smirnov test

To test the goodness-of-fit for the fitted results of the distributions for input variables, I chose Kolmogorov-Smirnov statistics from among many other popular options of “Best Fit Selection” statistics such as AIC – Akaike information criteria (Akaike, 1998), BIC – Bayesian Information Criteria (Marwala *et al.*, 2016), AvLogL – Average Log-Likelihood (Chan & Walther, 2014; Rivera & Walther, 2013), ChiSq – Chi-squared Statistic (The Design of Experiments, 1974; Cochran, 1952), and AD – Anderson-Darling (Anderson & Darling, 1952). I chose Kolmogorov-Smirnov statistics because KS statistics as a goodness-of-fit test is widely used and easily understood by many stakeholders and researchers alike.

KS test is used to compare the one-dimensional probability distribution of a sample with a reference distribution if they are equal or the distributions of two samples, and it is a nonparametric test that can be used to compare all the percentiles simultaneously (Kolmogorov–Smirnov Test, 2021; Wilcox, 2011). The distribution of this statistic is arrived at under the null hypothesis that the distribution of a sample belongs to the reference distribution (Kolmogorov–Smirnov Test, 2021). A critical value is very important, as it is used to reject the null hypothesis. We reject the hypothesis when a KS statistic is greater than or equal to the critical value (Wilcox, 2011). (Formulae to calculate KS statistics and critical value are included in the discussion section.)

For a KS test, let $\hat{F}_1(x)$ be, for group 1, the proportion of observations that are less than or equal to x, and let $\hat{F}2$ (x) be the proportion for group 2.

Let $U_i = |\hat{F}_1(X_{i1}) - \hat{F}_2(X_{i1})|$, (1)

$i = 1,\ldots,n1$. That is, for the ith observation in group 1 (X_{i1}), we calculate the proportion of observations in group 1 that are less than equal to X_{i1}, and same is done for group 2, then take the absolute value of the difference and label the result U_i. Repeat it for observations in group 2 and label the results

$V_i = |\hat{F}_1(X_{i2}) - \hat{F}_2(X_{i2})|$, (2)

$i = 1,\ldots,n2$. The Kolmogorov-Smirnov test statistic is

$KS = max\{U_1,\ldots,U_{n1},V_1,\ldots,V_{n2}\}$, (3)

the largest of the pooled U and V values. For large sample sizes, an approximate critical value when $\alpha = 0.05$ is

$$1.36\sqrt{\frac{n1+n2}{n1n2}}, \quad (4)$$

2.15 Revenues and costs

The revenues and expenses per poultry farm reporting were combined figures for layer farms, broiler farms, and hatcheries. Therefore, I used data for production, disposition, and farm value of poultry meat and that of production and disposition of eggs from Statistics Canada on revenues generated by eggs and by poultry meat to calculate a percentage of revenue that is contributed by layers for each selected province as well as for Canada (Government of Canada, 2021c; Government of Canada, 2021b). The ratios were calculated for five fiscal years from 2011 to 2016, and they were found to be very consistent over the five years. Thus, for this study, I used the ratios calculated using the data from the year 2016 to split revenue and expenses between layer revenue and otherwise.

Partial budget analysis was also done, meaning not all the revenues and benefits of the farm but those that concerned layer birds and those impacted by IB outbreaks and vaccination, which involved incorporating the value of profits or losses, revenues, expenses, additional costs incurred due to vaccines, and quantification of the economic consequences of adopting or not adopting vaccine against IB in farms (Dijkhuizen, 1995; Stadig *et al.,* 2020; Partial Budgeting, n.d.). It also captured fluctuations in the vaccine price and other epidemiologic factors of IB, along with feed cost price changes for scenario 5. The breakdown of the cost of production contribution for layers reared in a cage system by various constituent costs, namely chick price, feed, labour, and additional costs, were done according to (Sumner *et al.*, 2011), and calculations were done to arrive at several important figures required to set up the best simulation model. I used the prices for chickens for different provinces (Branch, 2008) to calculate the average number of layer birds each farm would have in a one-year cycle for all the selected provinces.

I chose to simulate egg production over one cycle of production only (a twelve-month cycle) because production decreases as the age advances, and it is counterproductive to keep birds for the second cycle, for instance, in White Leghorn layer poultry birds (Tazari, 2006). A monthly cash flow statement was worked out for a 12-month cycle (55-week-cycle). It entailed taking stock of a total number of birds at the beginning of a month, eggs laid during a month, revenue generated through the sale of eggs, revenue from the sale of stewing hen at the end of a cycle, costs incurred due to chicks/pullets (one-off expense at the start of a cycle), feed, labour, housing, vaccines, income for the month, and cumulative computing of monthly totals throughout the cycle. I developed a realistic and comprehensive income model with maximum resemblance to the settings of an actual layer farm working out monthly details, accounting for monthly bird loss due to normal and abnormal mortality rates when there was an outbreak of IB and the monthly cost of the vaccine (the month of a cycle in which birds are vaccinated).

To capture all the impact of the disease on the layer poultry farms in the form of direct effects such as abnormal mortality and abnormal production, and indirect effects such as additional costs due to vaccination and foregone profits (Penson *et al.,* 2017), different cohorts were identified for scenarios involving presence or absence of IB outbreaks and vaccination. Calculation of revenues, costs, and income were done separately for each of the cohorts in all scenarios in a similar fashion, incorporated into Excel codes for the models to compute consequences of various uncertainties and changes in variable values altogether.

Five cohorts were identified for the scenario with IB and vaccine adoption. Vaccine adoption and exposure of the population of layer birds to the disease (incidence) were the two important variables that influenced cohort classification and vaccine efficacy. The number of eggs laid, revenue, costs, and income were calculated monthly for cohorts, and total values for the farm were computed monthly. The presence of the disease was assumed to be uniformly spread throughout the cycle, and monthly abnormal mortality was computed for exposed cohorts in the scenario. Additionally, vaccine costs (vaccination labour and direct vaccine cost) were added to the existing operating costs for each cohort to make the models more robust and realistic. Normal mortality of layer birds was accounted for in the monthly cash flow statement as birds dying due to normal mortality in a month were subtracted from the total for the month, which leaves an exact number of birds alive and laying eggs at the start of the following month. It would preclude over-accounting of egg production if only an annual average of the birds were worked out and only an annual figure for the number of birds that died due to normal mortality was discounted. Cumulative revenues and cumulative costs were calculated for the whole farm across 12 months on a monthly basis.

2.16 Benefits, profitability ratios, and BCRs

The benefits of a project are the value of extra income made and costs averted (Campbell & Brown, 2015). The benefits of vaccinating in this study were the value of income generated by vaccination and losses avoided if outbreaks occurred in farms where birds were not vaccinated. Income was generated when total revenues for a farm exceeded total costs incurred over a period, which happened to be one year in this context. Income (pre-tax) was calculated for all the sub-cohort and cohorts in each scenario every month, and cumulative totals for the whole cycle are worked out, meaning there were skewed incomes at the beginning and the end of the cycle due to one-off chick cost at the start and one-off revenue from stewing hens at the end.

Finally, the net monthly income (pre-tax) for the whole farm, the cumulative total for the cycle, and then the net annual income for the farm were computed. Net income for different scenarios could then be used for calculating profitability ratios.

A profitability ratio is the ratio of net income generated after vaccination to the net income in the unvaccinated scenario. This ratio provides essential information on how much net income is made in the different scenarios. More income in the vaccinated scenario may indicate that the intervention in the form of vaccination is beneficial, but it does not provide the specifics about how beneficial it is to adopt such mitigating interventions. Therefore, benefit-cost ratios are helpful to look into that aspect of farm economics.

BCRs are calculated as the ratio of the net present value of the benefits of vaccination (increase in total revenues due to vaccination) to the net present value of costs (increase in total costs of production due to adopting vaccination). If the value of a BCR is greater than one, the value of benefits is more than that of costs. It is an indication that vaccination is favourable and beneficial in the scenario concerned, primarily when it is understood that this benefit would go to the producers that comprise the referent group in this context (Campbell & Brown, 2003).

2.17 Net present value, discount rates

A discount rate is defined as the rate of return applied in order to discount future cash flows in terms of their present value. It is also used to account for the time value of money and riskiness of an investment; it represents an opportunity cost for a firm; it acts as a hurdle rate for investment decisions; and it makes different investments more comparable. Higher discount rates give greater value to costs and benefits that occur more quickly, and projects that yield delayed benefits relative to costs will have lower net returns. It would allow us to consider both long-term and short-term costs and benefits. The present value of a future amount is the maximum amount one would be willing to pay to receive that amount in the future. If one does not include a discount for future values, it would artificially inflate the value of that option.

In order that one assesses and accounts for the time value of money, discount rates are applied and discounted for each future annual amount to get the net present value over a period in the future or at any given point of time in the future (Campbell & Brown, 2015; Greene, 2005; Hausman & Wise, 1978).

Net Present Value (net returns):$\sum_i [\frac{B_i - C_i}{(l+r)^i}]$ (5)

B – benefits

C – costs

i – time period (years)

r – discount rate

$$NPV = NR_0 + \frac{NR_1}{(1+r)^1} + \frac{NR_2}{(1+r)^2} + \cdots + \frac{NR_t}{(1+r)^t} \qquad (6)$$

or

$$NPV = \sum_0^T \left[\frac{NR_t}{(1+r)^t}\right] \qquad (7)$$

Appropriate discount rates need to be accounted for when looking at cash flows for scenarios that involve more than one year (NPV brings it back to year one), but I did not need to discount in this study since I was looking at a one-year time shot notwithstanding, and the effective discount rate was thus incorporated in this work.

The incorporation of a discount rate is helpful if we were to look at a four- to a five-year scenario. In Canada and the US, the conventional social discount rates are usually between two to three percent, and the conventional government discount rate in Canada was 4.80% (www.otpp.com, Jan 1, 2020). Generally, it should be less than the private market savings rate, and it typically follows government savings bond rates (*i.e.*, the cost of borrowing at virtually no risk). The social discount rate is the discount rate of time preference. The greater the social discount rate, the greater the social value of consumption today relative to consumption in the future.

2.18 Sample size calculation

The appropriate sample size is the minimum number of samples one needs to estimate the true population parameters with the required relative precision and confidence levels, meaning it is a theoretical lower limit for getting a statistically significant parameter estimate for that parameter (Dohoo *et al.*, 2003). As mentioned earlier, the data for this study came from 4903 poultry layer producers in Canada. I created farm income models for 12 select revenue categories and 84 scenarios in total. The probability distributions were defined for each scenario for different input variables depending on the scenario setup. Random values were drawn according to the probability distribution for different input variables when a simulation was run, and outcomes were calculated. One iteration of a simulation involves a single round of drawing new values and calculating consequences (Frey & Pfeifer, 2013; Clemen, 2014). It depends on models and the number of input variables to ascertain how many iterations are necessary for achieving reliable results. For this study, I chose to perform 50,000 iterations because the models set up were reasonably complex and incorporated many variables and uncertainties. Therefore, a large sample size (higher number of iterations) was important to achieve reliable findings (Clemen, 2014).

Chapter 3

Results and discussion

3.1 Results

3.1.1 Profits in scenarios 1-3

Table 3. 1 The table below shows profits, profit ratios, and BCRs for scenarios 1-3.

	Scenario 1: Baseline	Scenario 2: Disease with disease (no vaccine)	Scenario 3: Disease with vaccine (abnormal mortality 15%, abnormal production 30%, vaccine efficacy 90%, incidence 35%, and feed 49% of expenses)		
Geography	Profit ($)	Profit ($)	Profit ($)	Profit ratio	BCRs of vax
All Canada	65,177.89	11,685.84	53,912.73	4.61	8.25
Canada medium	16,093.05	840.89	12,881.00	15.32	8.10
Canada large	74,990.25	17,879.46	62,961.64	3.52	8.34
All Alberta	68,485.52	12,272.65	56,593.58	4.61	7.92
Alberta medium	49,093.89	28,300.28	44,689.35	1.58	9.04
Alberta large	71,035.63	14,102.59	58,990.94	4.18	7.95
Ontario medium	18,381.29	3,567.73	15,266.65	4.28	8.39
Ontario large	76,004.77	22,927.24	64,842.30	2.83	8.58
BC medium	6,172.29	(9,009.45)	2,985.44	0.33	7.72
BC large	76,533.40	17,209.25	64,066.88	3.72	8.50
QC medium	13,442.96	2,247.71	11,090.31	4.93	8.39
QC large	65,436.03	15,345.28	54,908.25	3.58	8.50

The results of the analyses and simulations from scenarios 1 to 3 were summarized and presented in Figure 3. 1 below. For Canada, an average layer farm would lose up to $42,226.89 (if not otherwise stated, all figures are in Canadian dollars) annually ($53,912.73-$11,685.84 from scenarios 3 and 2 respectively for all-Canada revenue category from table 3.1 above). Overall, taking into account the existing number of layer farms in Canada, the total impact of IB on the Canadian poultry industry for all 4903 layer farms would be $207,038,442 ($42,226.89*4903 farms). I present the most salient trends and features in each scenario in the following.

3.1.1.1 Scenario 1 - Baseline

For the all-revenue-classes category in the base scenario, AB medium layer producers made an average income of $68,485.52 per farm (all figures in CAD) in a year compared to $65,177.89 per farm for Canada in the same revenue category.

In this scenario, the largest profit makers were large layer farms in BC with an average annual income of $76,533.40 per farm, compared to the smallest annual average profit of $6,172.29 per farm for medium farms in BC.

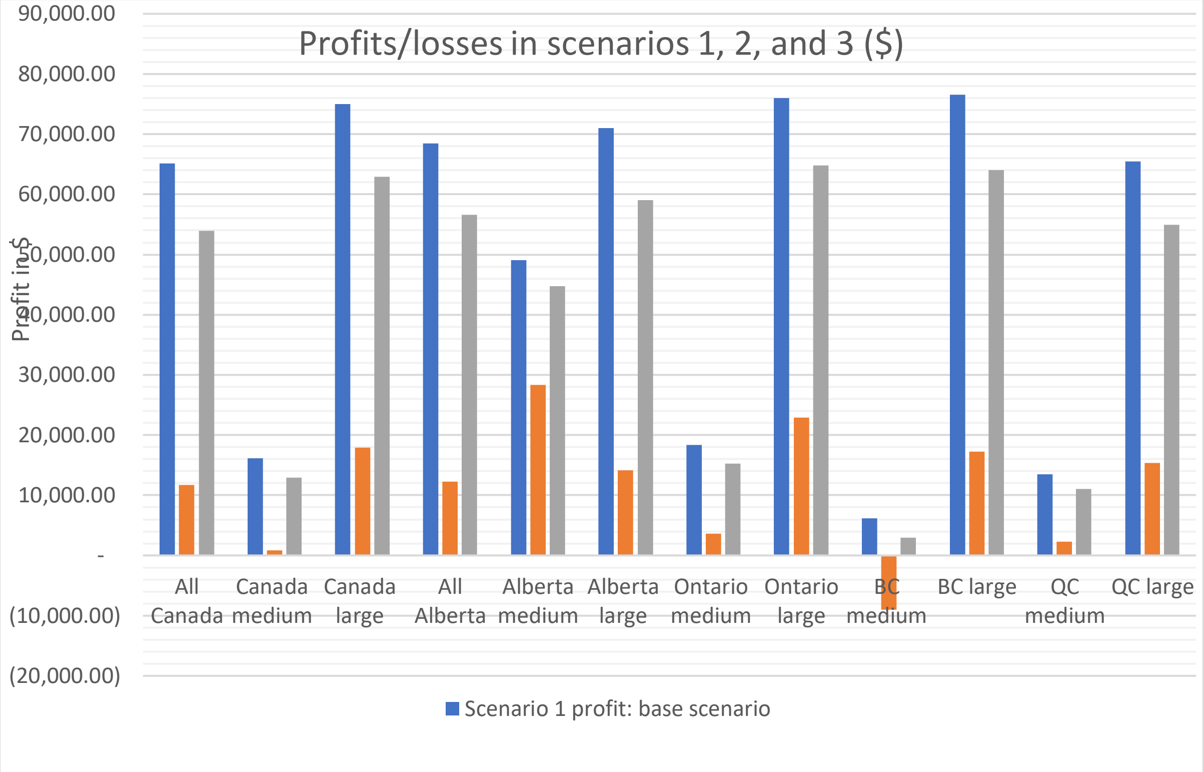
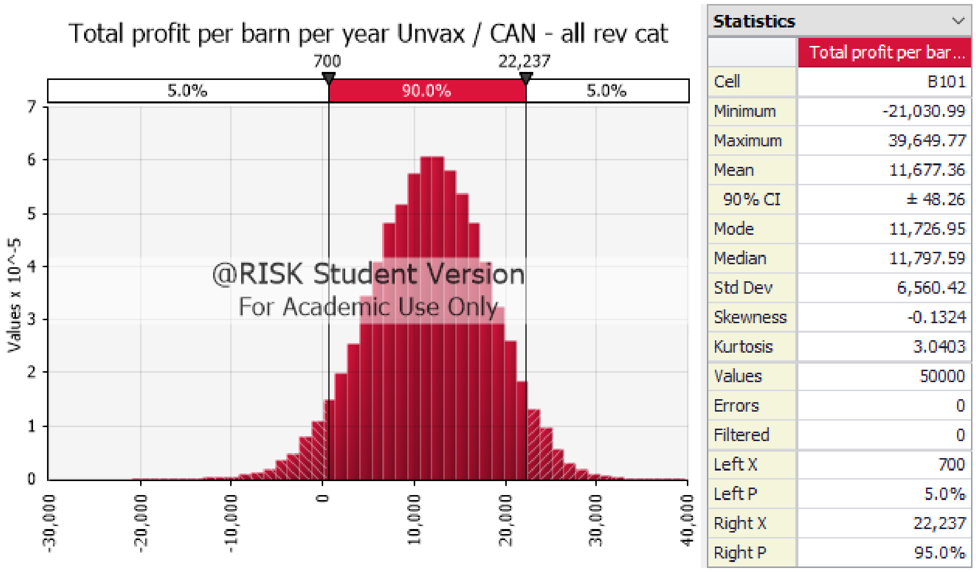


Figure 3. 1 A bar chart of profits/losses for various revenue categories in scenarios 1, 2, and 3.

3.1.2 Scenario 2 - IB in farms with no vaccination

Overall (for the all-revenue-classes category), in scenario 2, AB layer farms made an annual average income of $12,272.65 per farm while that of Canada was $11,685.84 per farm.

The largest profit makers in scenario 2 were ON large layer farms with an average annual income of $22,927.24 generated per farm compared to BC medium farms in the same scenario, which made the lowest, with a loss of $9,009.45 per farm on average annually.



	Total profit per bar...
Cell	B101
Minimum	-21,030.99
Maximum	39,649.77
Mean	11,677.36
90% CI	± 48.26
Mode	11,726.95
Median	11,797.59
Std Dev	6,560.42
Skewness	-0.1324
Kurtosis	3.0403
Values	50000
Errors	0
Filtered	0
Left X	700
Left P	5.0%
Right X	22,237
Right P	95.0%

Figure 3. 2 A bar chart showing probability density distribution of profits for scenario 2 for all-revenue-classes category for Canada (exported from @RISK analytical software).

Figure 3. 2 shows that, for the all-revenue-class category in scenario 2 (unvaccinated birds) in Canada, farms generated a mean annual income of $11,677.36 per farm with a standard deviation of $6,560.42 per farm.

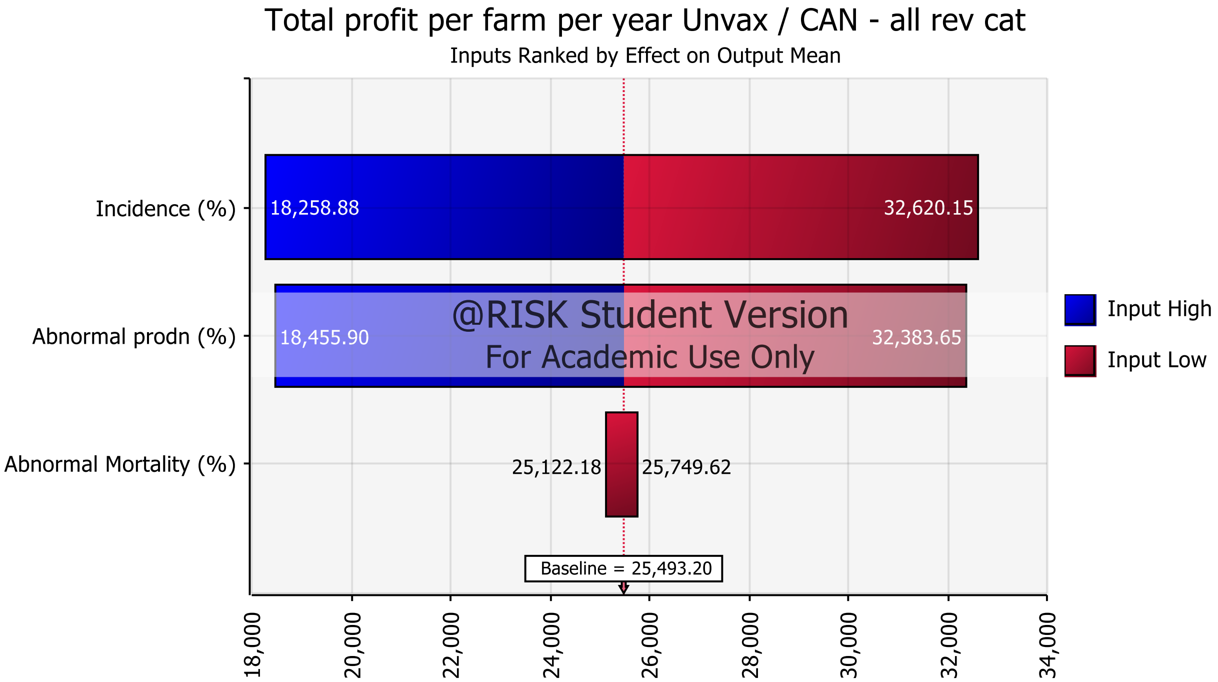
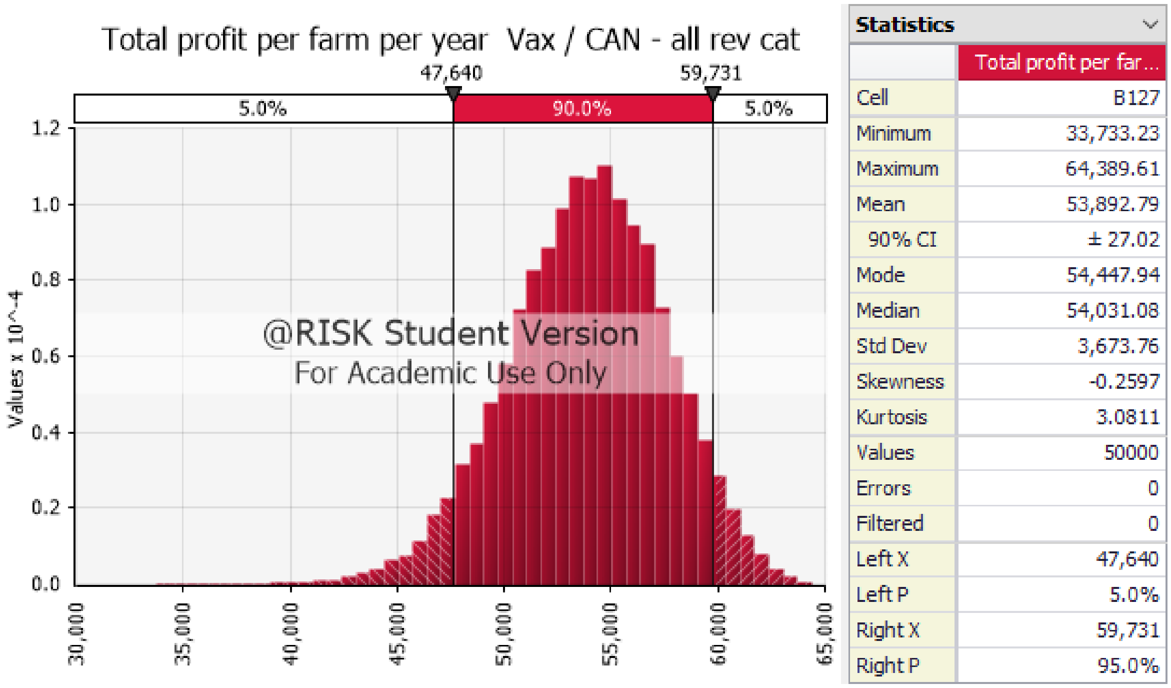


Figure 3. 3 A tornado chart showing the impact of input variables on mean profit in scenario 2 (exported from @RISK analytical software).

From figure 3.3, the incidence rate had, by far, the greatest impact on profit (output). When the incidence rate was very high, profit made was at $18,258.88 per farm, and when incidence race was minimum, profit went up to $32,620.15 per farm. Abnormal production rate due to IB had the second-largest impact on mean annual income, and there was the least impact on profit by abnormal mortality rate.

3.1.3 Scenario 3 - IB in farms with vaccination

For all revenue classes category in scenario 3, AB layer farms made an annual average income of $56,593.58 per farm compared to $53,912.73 per farm for Canada in the same revenue category. In scenario 3, the largest profit makers were ON large layer farms with an average annual income of $64,842.30 per farm compared to an average annual income of $2,985.44 per farm for BC, the lowest in the scenario.



	Total profit per far...
Cell	B127
Minimum	33,733.23
Maximum	64,389.61
Mean	53,892.79
90% CI	± 27.02
Mode	54,447.94
Median	54,031.08
Std Dev	3,673.76
Skewness	-0.2597
Kurtosis	3.0811
Values	50000
Errors	0
Filtered	0
Left X	47,640
Left P	5.0%
Right X	59,731
Right P	95.0%

Figure 3. 4 A bar chart showing probability density distribution of profits in scenario 3 (exported from @RISK analytical software).

Figure 3. 4 above shows that in the all-revenue-class category in scenario 3 (vaccinated farms), farms in Canada generated a mean annual income of $53,892.79 per farm with a standard deviation of $3,673.76 per farm.

3.1.4 Impact of input variables on mean profit (output) in Scenario 3

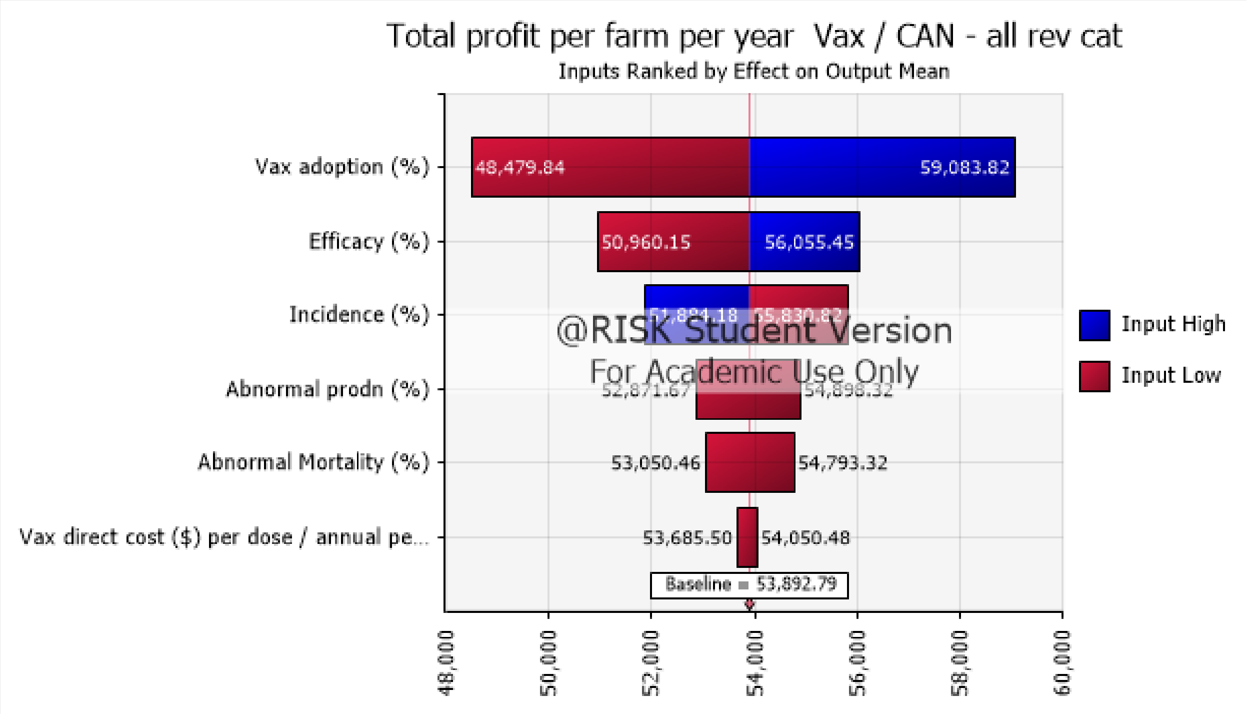


Figure 3. 5 A tornado chart showing the impact of inputs on profit in scenario 3 (exported from @RISK analytical software).

From the tornado chart above, the vaccine adoption rate had the greatest impact on profit in scenario 3. When the vaccine adoption rate was minimum, profit made was $48,479.84 per farm, while profit went up to $59,083.82 per farm when the adoption rate was maximum.

The efficacy of IB vaccines had the second most significant impact on mean annual income, followed by incidence, abnormal production, and mortality rates, in that order. The least impact on profit was by the direct costs of purchasing vaccines.

3.1.5 Profits in scenarios 4 and 5

Table 3. 2 Profits/losses for scenarios 4 and 5 for various revenue categories.

	Scenario 4: New virulent IBV strain (abnormal mort:35%, abnormal production 50%, vaccine efficacy 65%, incidence 50%, and feed 49% of expenses)				Scenario 5: New virulent IBV with feed cost rise (abnormal mortality 35%, abnormal production 50%, vaccine efficacy 65%, and incidence 50% with feed cost up 10%)			
Geography	Unvaccinated Profit ($)	Vaccinated Profit ($)	Profit ratio	BCR of vax	Unvaccinated ($)	Vaccinated ($)	Profit ratio	BCR of vax
All Canada	(61,590.50)	22,665.69	(0.37)	7.12	(92,067.94)	(9,174.73)	0.10	6.48
Canada medium	(20,018.28)	3,974.86	(0.20)	6.96	(28,969.47)	(5,376.64)	0.19	6.33
Canada large	(60,428.93)	29,594.59	(0.49)	7.22	(92,401.68)	(3,808.02)	0.04	6.57
All Alberta	(65,075.92)	23,608.09	(0.36)	7.00	(80,827.68)	7,151.89	(0.09)	6.68
Alberta medium	(635.99)	32,462.69	(51.04)	8.38	(10,037.64)	22,640.59	(2.26)	7.66
Alberta large	(64,259.78)	25,581.10	(0.40)	7.03	(80,127.39)	9,003.86	(0.11)	6.71
Ontario medium	(16,697.80)	6,627.08	(0.40)	7.19	(20,772.06)	(2,692.01)	0.09	5.47
Ontario large	(88,244.75)	14,028.25	(0.16)	5.99	(100,054.28)	924.14	(0.01)	5.63
BC medium	(28,955.56)	(4,961.65)	0.17	6.50	(38,861.24)	(15,310.32)	0.39	5.90
BC large	(63,920.27)	29,486.12	(0.46)	7.27	(80,191.76)	12,486.95	(0.16)	6.93
QC medium	(13,049.37)	4,569.52	(0.35)	7.16	(19,443.65)	(2,110.72)	0.11	6.51
QC large	(53,171.58)	25,726.03	(0.48)	7.27	(81,205.00)	(3,562.09)	0.04	6.61

The results of the analyses and simulations from scenarios 4 and 5 were summarized and presented in Table 3. 2 above. I present the most important trends and features in each scenario in the following.

3.1.6 Scenario 4 – New IBV strains with no vaccination

The presence of disease in this scenario had a considerable impact on the income of layer poultry farms in Canada. In the all-revenue-classes category in unvaccinated scenario 4, AB layer farms lost $65,075.92 per farm annually, while Canada's loss stood at $61,590.50 per farm on average annually for the same revenue category.

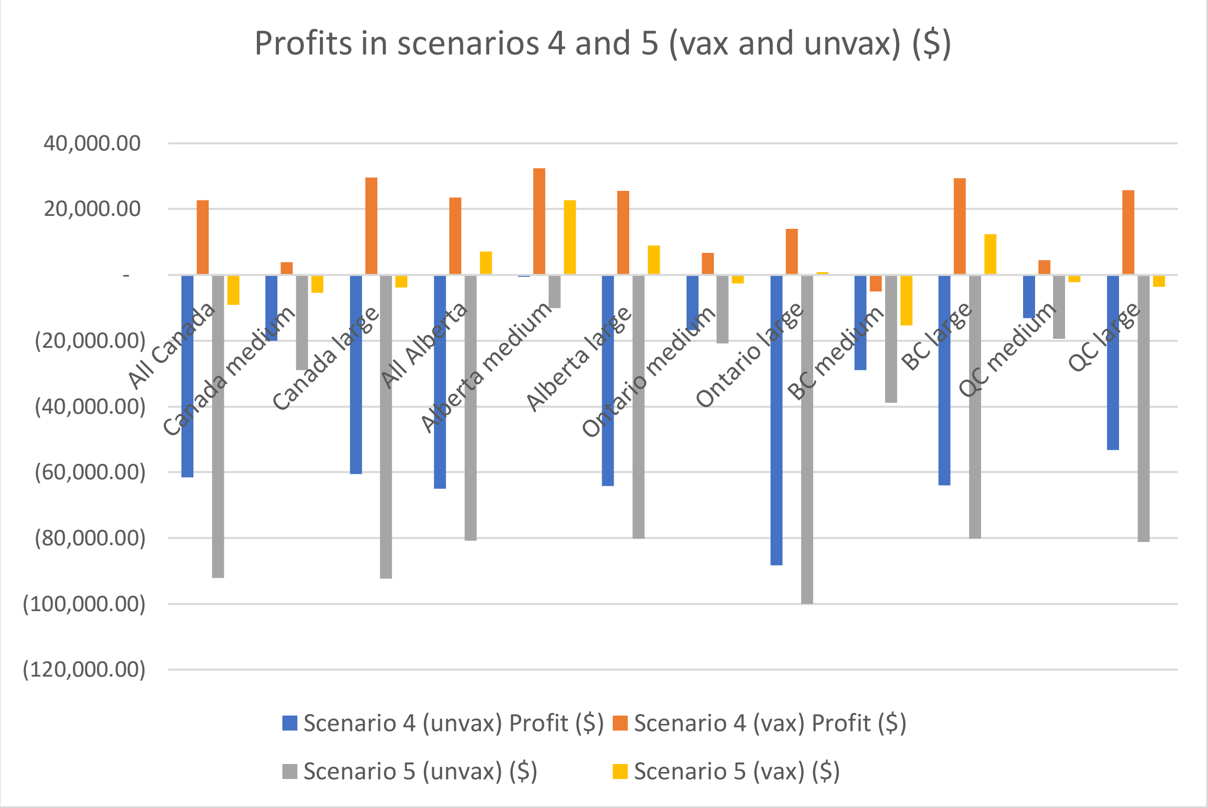
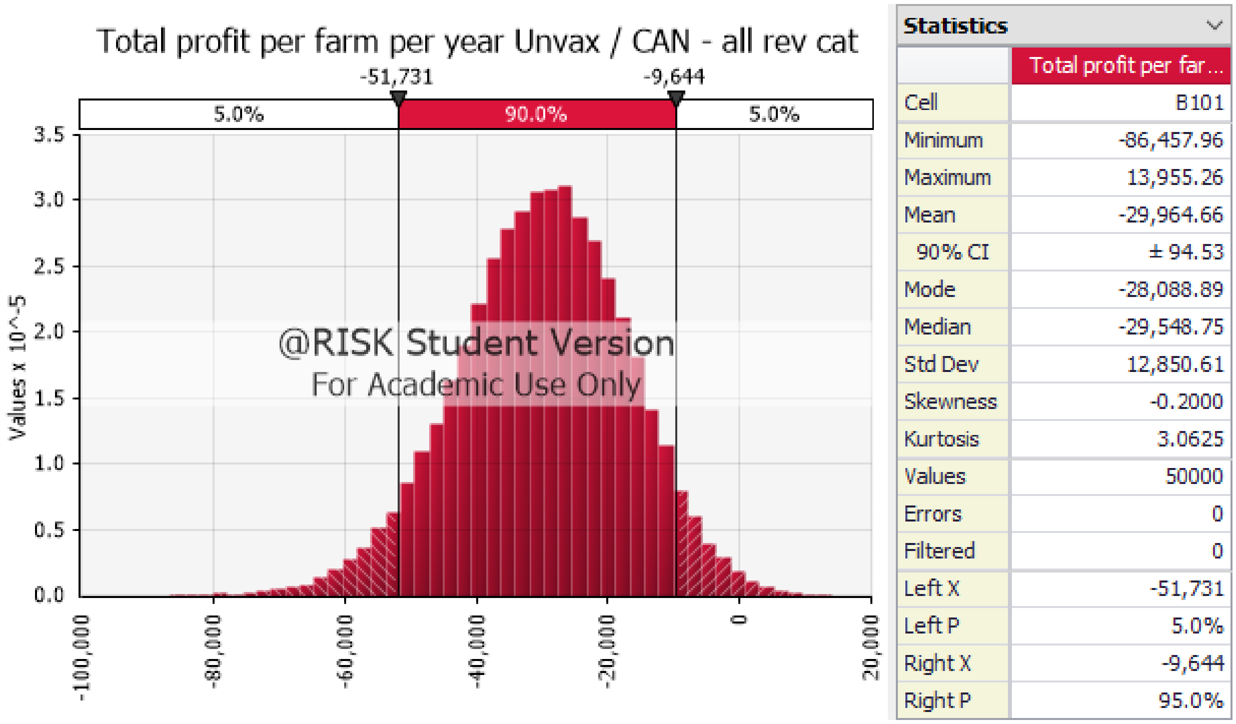


Figure 3. 6 The bar chart shows profits/losses for scenarios 4 and 5 for various revenue categories.

For the medium layer farms category in unvaccinated scenario 4, BC layer farms lost the most, at $28,955.56 on average per farm annually, while AB medium farms in the same scenario lost $8,918.05 per farm on average annually.

In the large layer farms category in unvaccinated scenario 4, ON farms lost the most at $88,244.75 per farm annually, while QC had the smallest loss of $53,171.58per farm for the same category.



Statistics	Total profit per far...
Cell	B101
Minimum	-86,457.96
Maximum	13,955.26
Mean	-29,964.66
90% CI	± 94.53
Mode	-28,088.89
Median	-29,548.75
Std Dev	12,850.61
Skewness	-0.2000
Kurtosis	3.0625
Values	50000
Errors	0
Filtered	0
Left X	-51,731
Left P	5.0%
Right X	-9,644
Right P	95.0%

Figure 3. 7 A bar chart showing probability density distribution of profits in unvaccinated scenario 4 (exported from @RISK analytical software).

From the probability density distribution chart above, it is evident that all-revenue-class farms in scenario 4 (for unvaccinated farms) in Canada ran into a loss of $ -29,964.66 per farm mean annual income with a standard deviation of $12,850.61 per farm in unvaccinated farms in scenario 4.

3.1.7 Impact of input variables on profit in unvaccinated farms in scenario 4

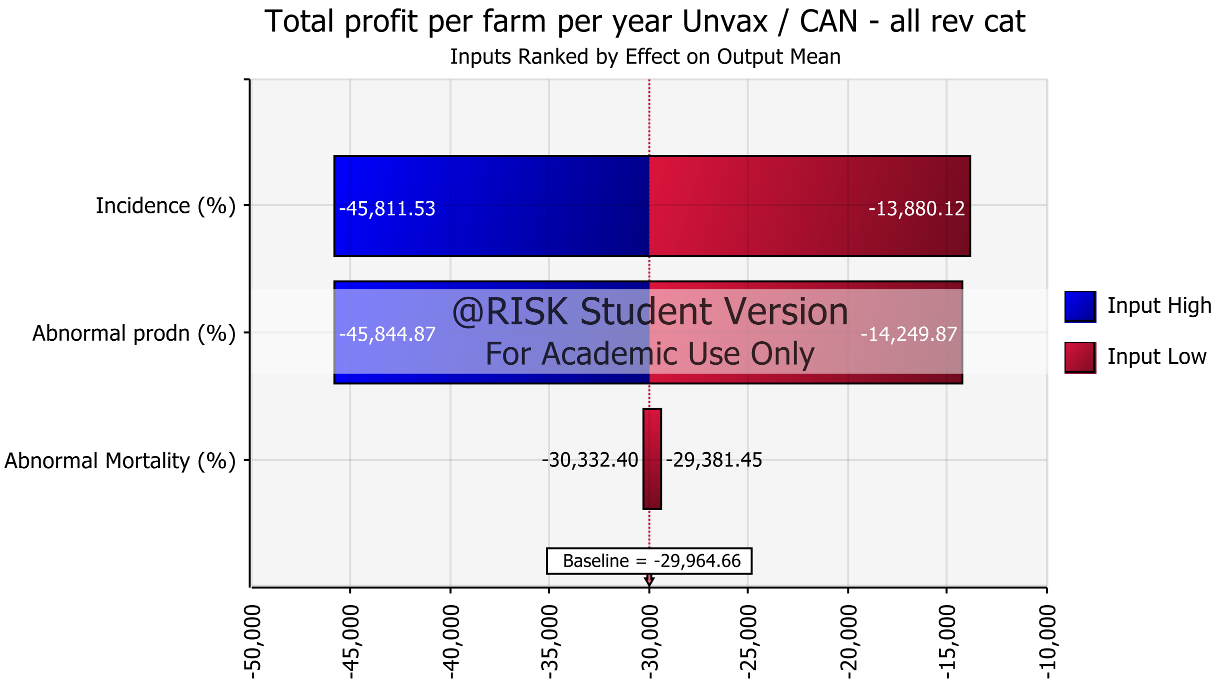


Figure 3. 8 A tornado chart of the impact of inputs on profit in scenario 4 (exported from @RISK analytical software).

From the tornado chart above, the incidence rate had the greatest influence on the mean profit in unvaccinated farms in scenario 4. When the incidence rate was at its maximum, a mean annual income decreased to $-45,811.53 per farm, while it reached $-13,880.12 per farm when the incidence rate was at a minimum. Abnormal production rate due to IB had the second greatest impact on mean annual income, and there was minimal impact by abnormal mortality rate.

3.1.8 Scenario 4 – New IBV strains with vaccination

AB layer farms made an annual average income[5] of $23,608.09 per farm in the all-revenue-classes category in scenario 4 (vaccinated farms), while an average annual income for Canada for the same revenue category was $22,665.69 per farm.

In the medium layer farms category in vaccinated scenario 4, AB layer farms made the largest

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[5] Income here is defined as revenue minus costs (also known as simple profit).

profit with an average annual income of $23,863.01 per farm, while BC medium farms made the least in the same scenario with a loss of $4,961.65 per farm on average annually.

In the large layer farms category in vaccinated scenario 4, BC large farms generated the largest profit with an average annual income of $29,486.12per farm while ON large farms have the smallest average annual income of $14,028.25 per farm for the same revenue category.

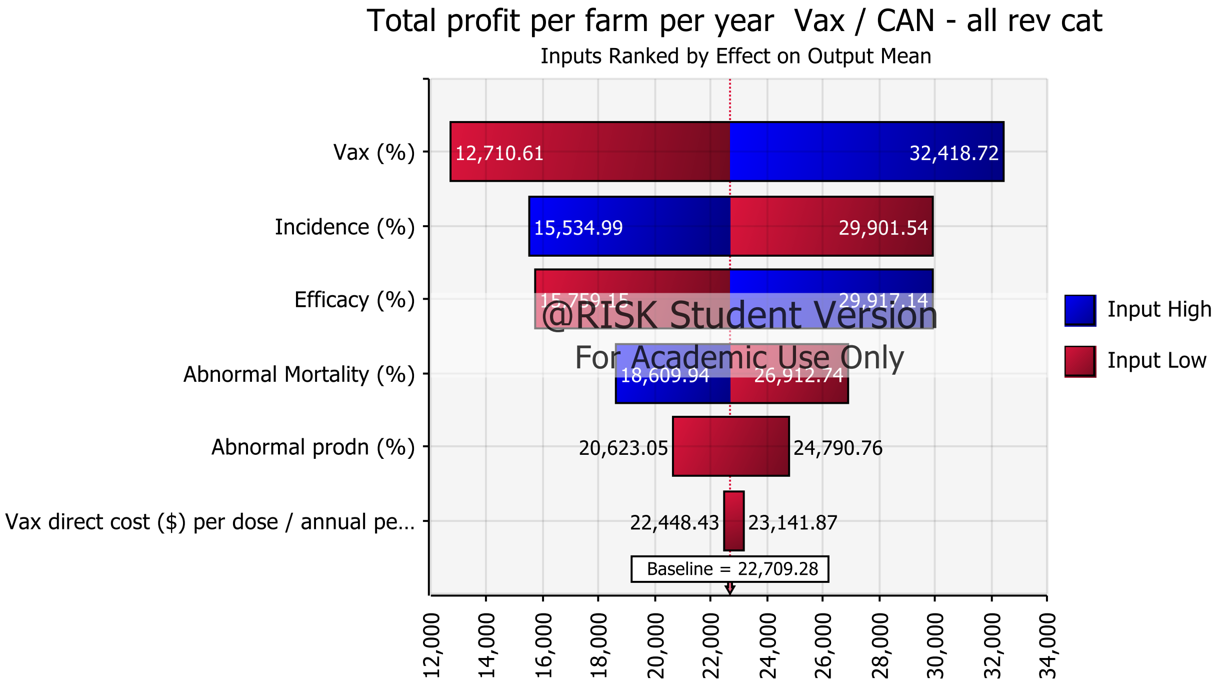


Figure 3. 9 A tornado graph showing the impact of inputs on the profit for vaccinated farms in scenario 4, (exported from @RISK analytical software).

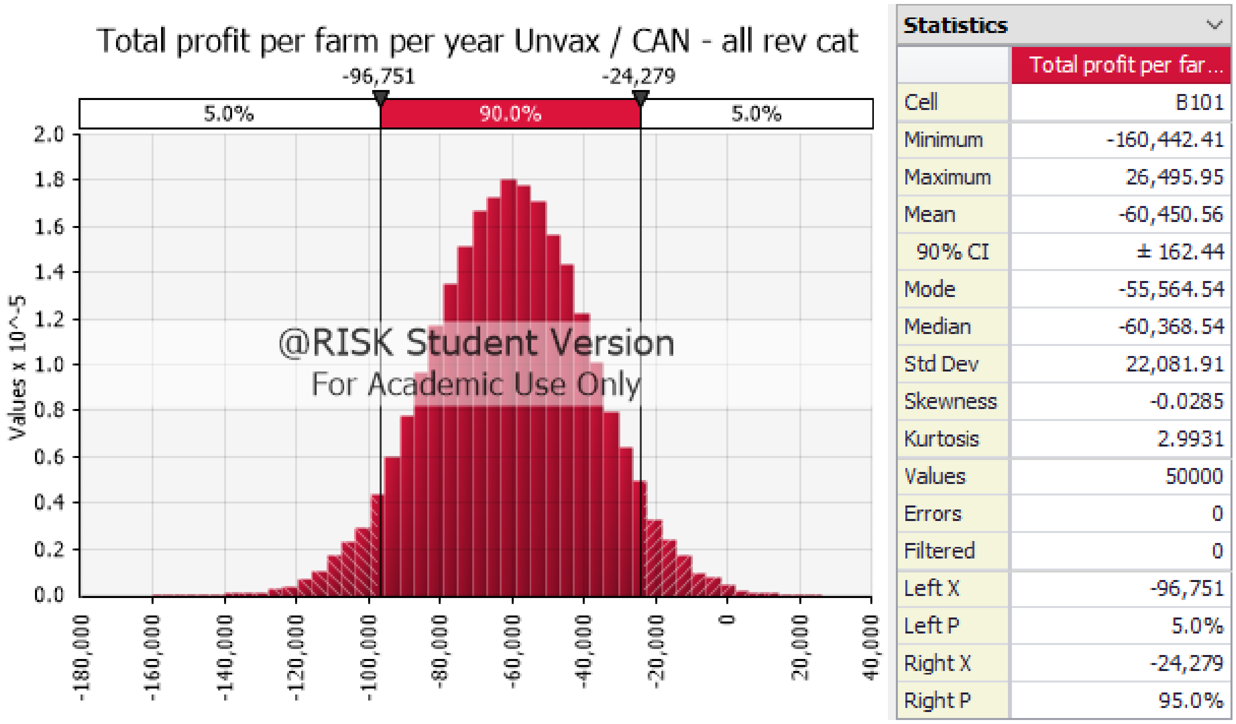
3.1.9 Scenario 5 (unvaccinated farms)

The presence of disease in this scenario with a change in feed price had a devastating impact on Canadian layer producers' income. In the all-revenue-classes category in scenario 5 (unvaccinated), AB layer farms incurred a loss of $80,827.68 per farm on average in a year, while Canada had a loss of $76,521.40 per farm on average for the same revenue category.

For the medium layer farms category, BC layer farms suffered the largest loss at $38,861.24 per farm on average annually, while AB medium farms in the same scenario lost the least income at

$10,037.64 per farm on average annually.

In the large layer farms category in scenario 5 with unvaccinated birds, ON large farms were the worst affected with a loss of $100,054.28 per farm annually, while AB had the smallest loss of $80,127.39 per farm for the same category.



	Total profit per far...
Cell	B101
Minimum	-160,442.41
Maximum	26,495.95
Mean	-60,450.56
90% CI	± 162.44
Mode	-55,564.54
Median	-60,368.54
Std Dev	22,081.91
Skewness	-0.0285
Kurtosis	2.9931
Values	50000
Errors	0
Filtered	0
Left X	-96,751
Left P	5.0%
Right X	-24,279
Right P	95.0%

Figure 3. 10 A bar chart showing the probability density distribution of profits per farm in scenario 5 (unvaccinated), (exported from @RISK analytical software).

The probability density distribution chart above shows that all-revenue-class farms (for unvaccinated farms in scenario 5) in Canada ran into loss with a mean annual income of $ -60,450.56 per farm and standard deviation of $22,081.91 per farm in unvaccinated farms in scenario 5.

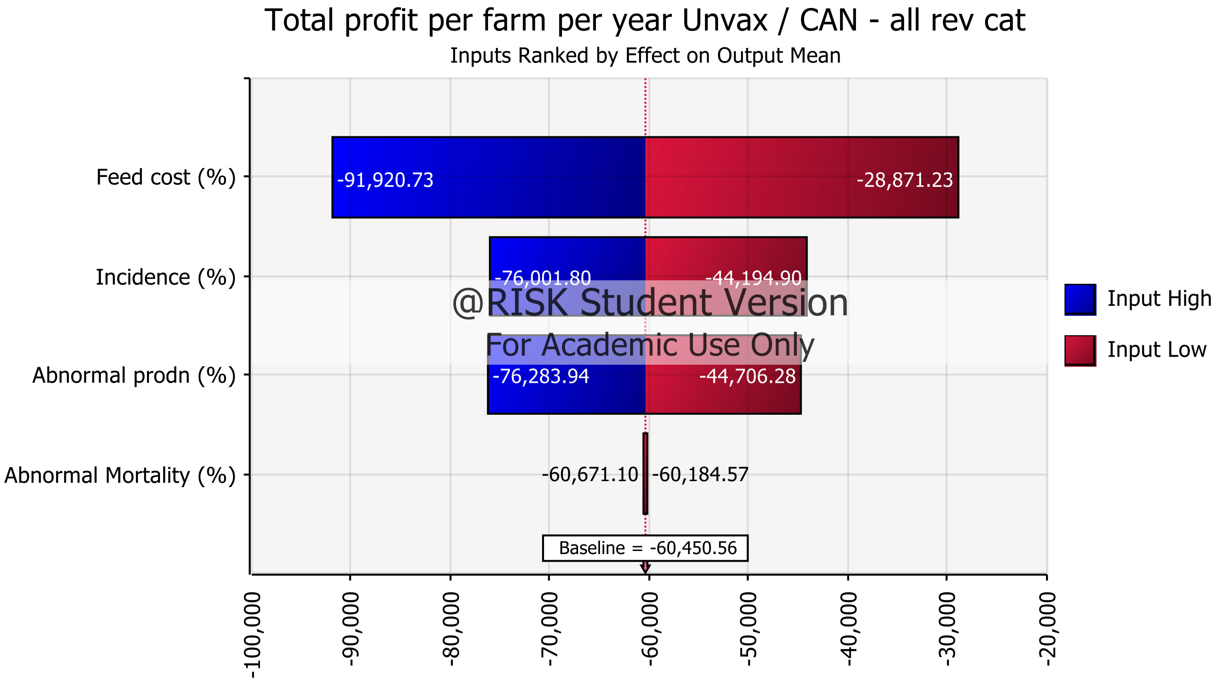


Figure 3. 11 A tornado graph showing the impact of inputs on the profit in scenario 5 (unvaccinated), (exported from @RISK analytical software).

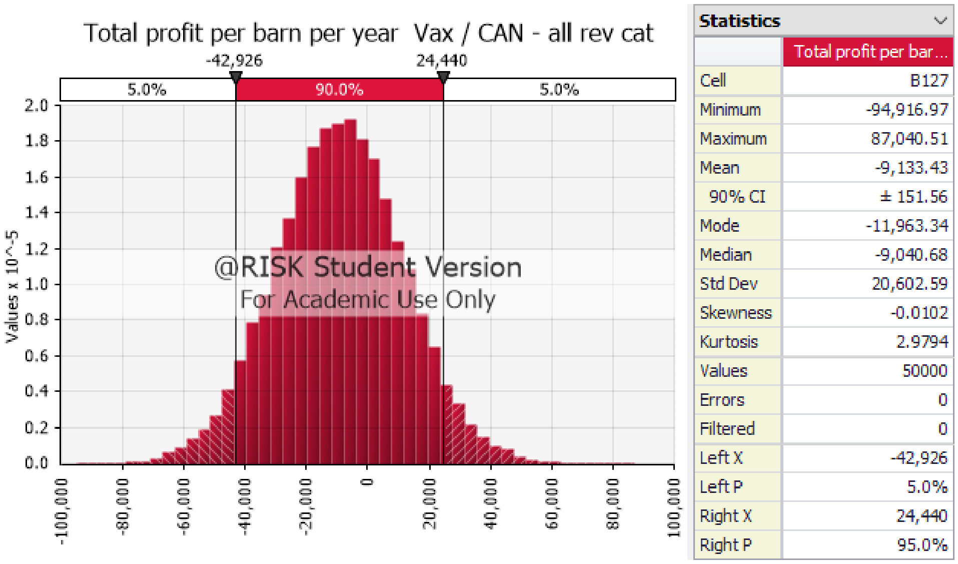
The tornado chart above shows that the feed cost changes had the greatest influence on mean profit in scenario 5 (unvaccinated). When feed cost was at its maximum, a loss incurred was at high as $-91,920.73 per farm, and when the feed cost rise was at a minimum, farms in this scenario made a profit with a mean annual income of $-28,871.23 per farm. Incidence rate had the second-largest impact on mean annual income followed by abnormal production and abnormal mortality rates.

3.1.10 Scenario 5 (vaccinated farms)

AB layer farms made an annual average income of $7,151.89 per farm in the all-revenue-classes category in scenario 5 (vaccinated), while an average annual income for Canada for the same revenue category was $7,067.07 per farm.

For medium layer farms category in vaccinated scenario 5, AB layer farms were the greatest profit makers with an average annual income of $22,640.59 per farm, while BC medium farms make the least in the same scenario as they suffered a loss of $15,310.32 per farm on average in a year.

For the large layer farms category in vaccinated scenario 5, BC large farms generated the largest profit with an average annual income of $12,486.95 per farm, while QC large farms had the smallest average annual income (a loss of $3562.09 per farm) for the same revenue category.



	Total profit per bar...
Cell	B127
Minimum	-94,916.97
Maximum	87,040.51
Mean	-9,133.43
90% CI	± 151.56
Mode	-11,963.34
Median	-9,040.68
Std Dev	20,602.59
Skewness	-0.0102
Kurtosis	2.9794
Values	50000
Errors	0
Filtered	0
Left X	-42,926
Left P	5.0%
Right X	24,440
Right P	95.0%

Figure 3. 12 A bar chart showing probability density distribution of profits for vaccinated scenario 5 (exported from @RISK analytical software).

The probability density distribution chart above shows that all-revenue-class farms (for vaccinated farms in scenario 5) in Canada ran into loss with a mean annual income of $ -9,133.43 per farm and standard deviation of $20,602.59 per farm in the vaccinated farms in scenario 5.

2.1.11 Impact of inputs on profit in vaccinated scenario 5

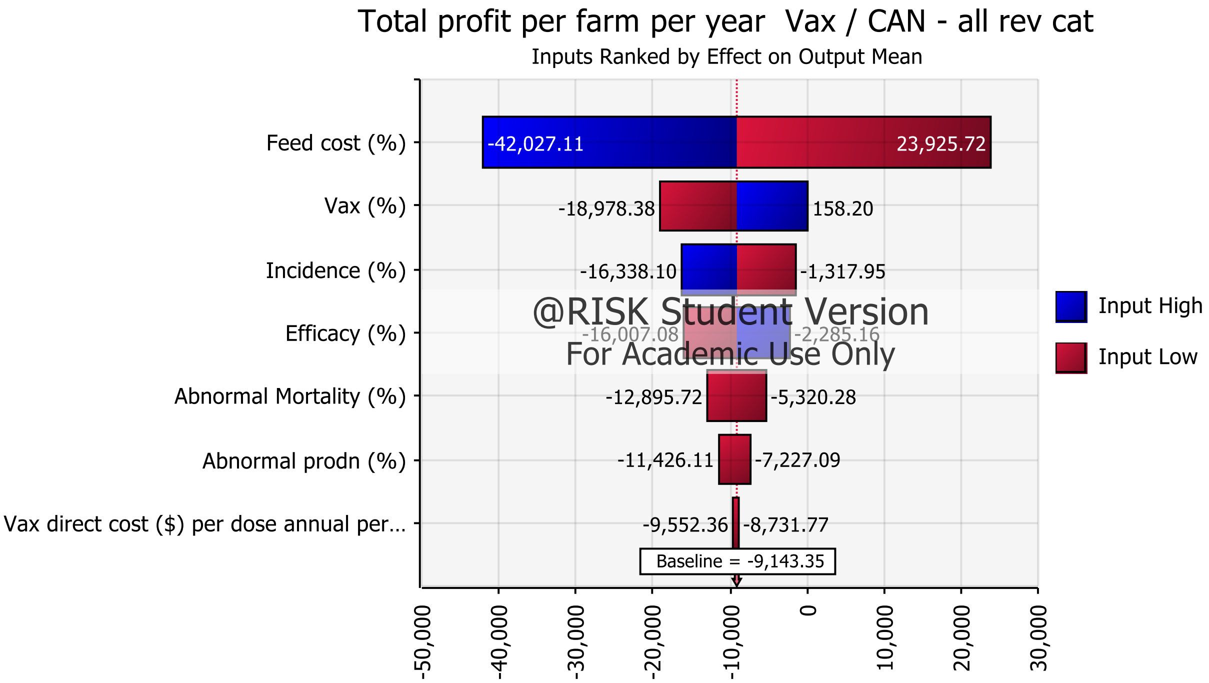


Figure 3. 13 A tornado chart showing the impact of various inputs on profit in vaccinated scenario 5 (exported from @RISK analytical software).

The tornado chart above shows that the feed cost changes had the greatest influence on mean profit in scenario 5. When feed cost was at its maximum, a loss incurred was $-42,027.11 per farm, and when the feed cost rise was at a minimum, farms in this scenario made a profit with a mean annual income of $23,925.72 per farm.

Vaccine adoption rate had the second-largest impact on mean annual income followed closely by incidence, vaccine efficacy, abnormal mortality, and abnormal production rates, in that order. As seen in the earlier scenarios, there was minimal impact on mean profit by direct cost of vaccines.

3.2 Benefit-cost analyses and BCR results

3.2.1 BCRs for scenarios 3

In scenario 3, IB caused abnormal mortality of 15%, abnormal production of 30%, vaccine efficacy of 90%, incidence rate of 35%, and feed remained unchanged at 49% of total operating expenses. Layer poultry producers in Canada vaccinated against IB, BCRs of vaccination to prevent IB in layer farms in all the revenue categories generally were very high, ranging from 7.72 in the BC medium farms category to 9.04 in the AB medium farms category.

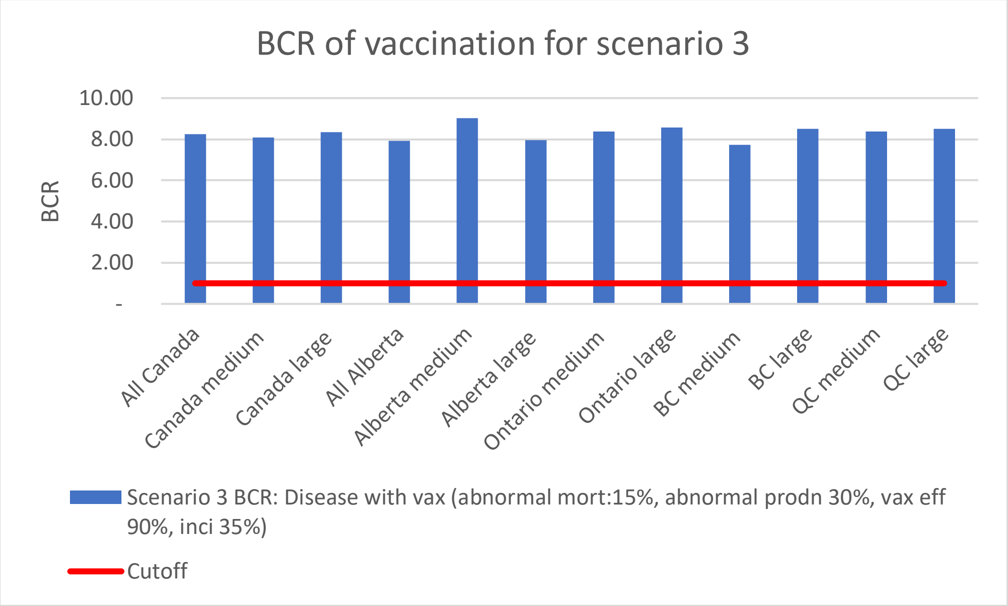


Figure 3. 14 A bar chart showing BCRs of IB vaccination in various revenue categories in Canada and the four provinces in scenario 3.

3.2.2 Impact of inputs on BCR in scenario 3

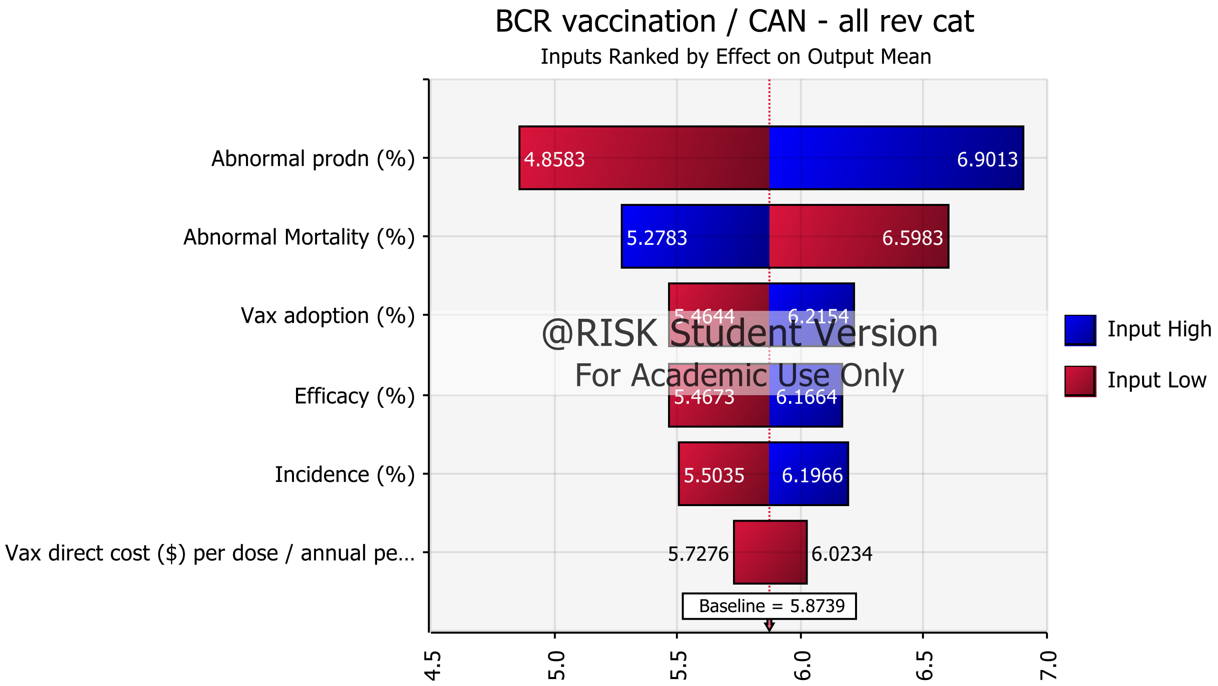


Figure 3. 15 A tornado chart showing the impact of inputs on BCR in scenario 3 (exported from @RISK analytical software).

From the tornado chart above, the abnormal production rate had the greatest influence on mean BCRs of vaccination in scenario 3. When the abnormal production rate was at its maximum, meaning that the production rate dropped to its lowest, it became most advantageous for producers to vaccinate because drop in egg production had the largest impact on the farm profitability, and thus, the BCR of vaccination was maximum for this scenario at 6.9.

It was followed by abnormal mortality as most impactful on BCRs of vaccination, then vaccine adoption rate, vaccine efficacy, and incidence.

3.2.3 BCRs of vaccination in scenario 4

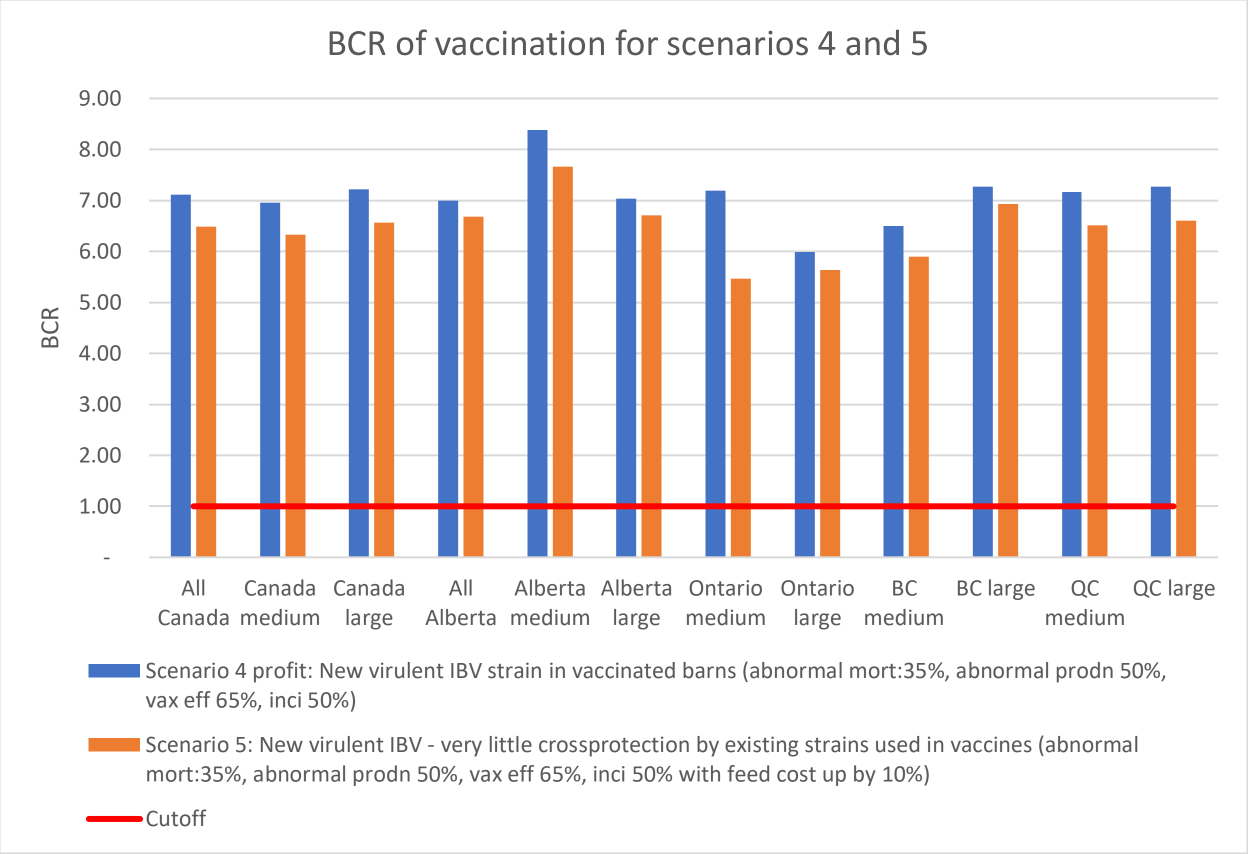
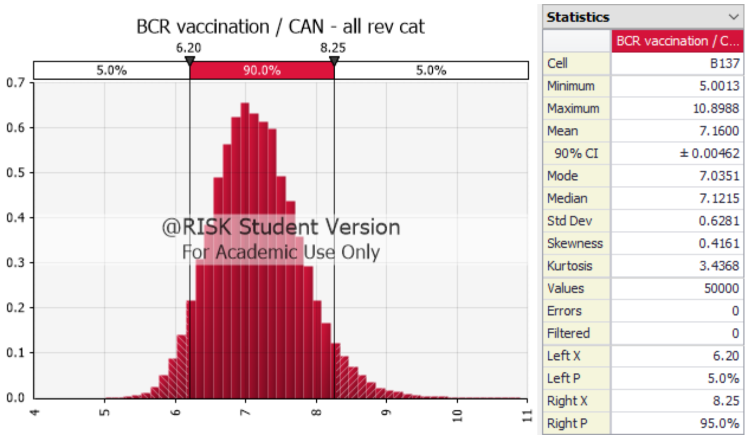


Figure 3. 16 A bar chart showing BCRs of vaccination in various revenue categories in Canada and the four provinces in scenarios 4 and 5.

In scenario 4, even though layer poultry producers vaccinated their birds against IB, new circulating strains of IBV caused an abnormal mortality rate of 35%, abnormal production of 50%, vaccine efficacy declined from 90% to 65%, incidence rate went up from 35% to 50%, and feed cost did not change at 49% of the total operating expenses. BCRs of vaccination in all the revenue categories in this scenario ranged from 5.99 in the ON large farms category to 8.38 in the AB medium farms category.



Statistics	BCR vaccination / C...
Cell	B137
Minimum	5.0013
Maximum	10.8988
Mean	7.1600
90% CI	± 0.00462
Mode	7.0351
Median	7.1215
Std Dev	0.6281
Skewness	0.4161
Kurtosis	3.4368
Values	50000
Errors	0
Filtered	0
Left X	6.20
Left P	5.0%
Right X	8.25
Right P	95.0%

Figure 3. 17 A bar chart showing the distribution of BCR of vaccination in scenario 4 (exported from @RISK analytical software).

The probability density distribution chart of BCRs of vaccination in scenario 4 for all-revenue-class farms in Canada shows that the mean BCR of vaccination was 7.16, with a standard deviation of 0.628.

3.2.4 Impact of various inputs on BCRs in scenario 4

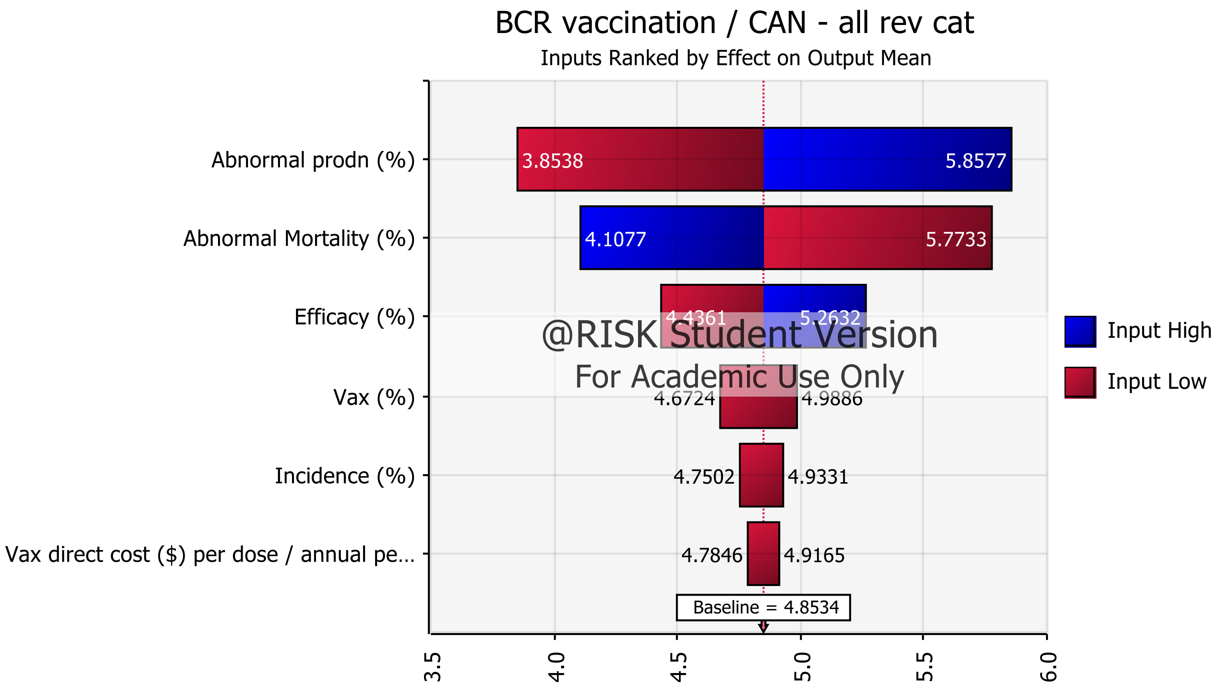


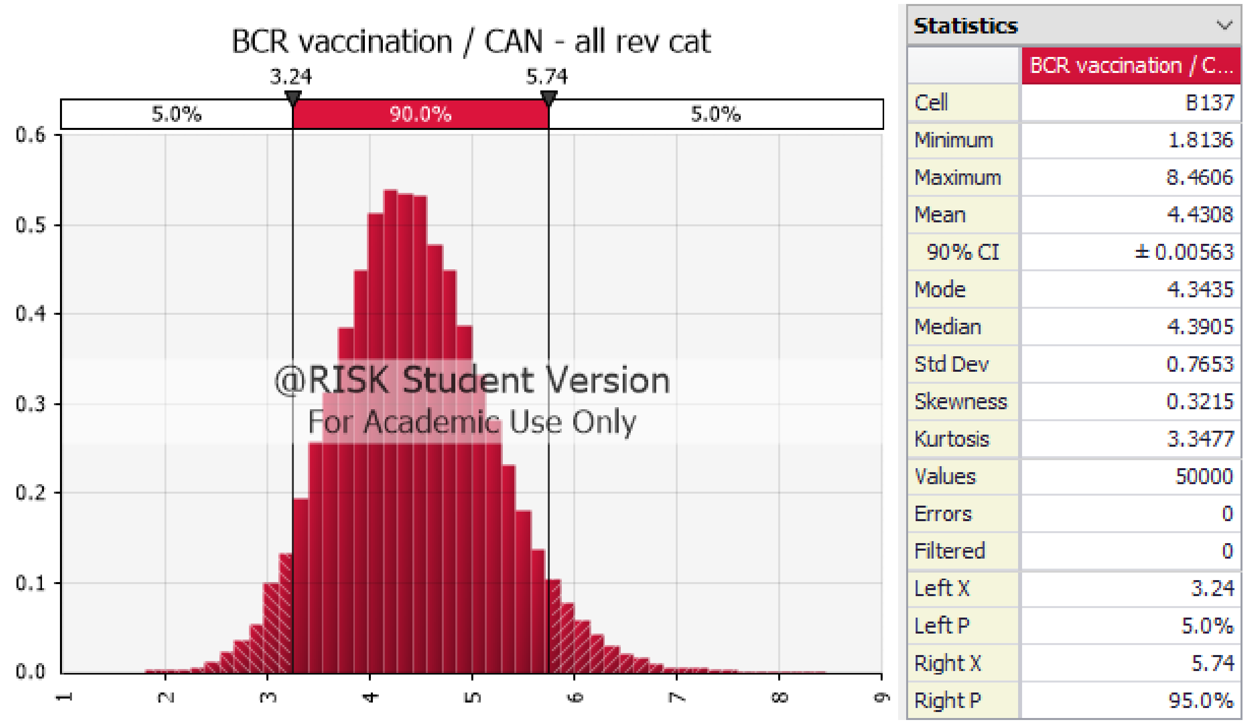
Figure 3. 18 A tornado chart showing the impact of various inputs on BCRs of vaccination in scenario 4 (exported from @RISK analytical software).

From the tornado chart above, the abnormal production rate had the greatest influence on the mean BCRs of vaccination in scenario 4. When the abnormal production rate was at its highest, it became most advantageous for farms to vaccinate, and thus, the BCR of vaccination was maximum for this scenario at 5.86.

It was followed by abnormal mortality rate as most impactful on the mean BCRs of vaccination, then vaccine efficacy, vaccine adoption rate, incidence, and vaccine direct cost, in that order.

3.2.5 BCRs in scenario 5

In scenario 5, there was an increase in feed cost, and concurrently, there were new strains of IBV that caused abnormal mortality of 35%, abnormal production of 50%, vaccine efficacy of 65%, and incidence rate of 50% while vaccine adoption rate remains unchanged. When layer poultry producers in Canada vaccinated against IB in this scenario, BCRs of vaccination ranged from 5.47 in the ON medium farms category to 7.48 in AB medium farms category.



	BCR vaccination / C...
Cell	B137
Minimum	1.8136
Maximum	8.4606
Mean	4.4308
90% CI	± 0.00563
Mode	4.3435
Median	4.3905
Std Dev	0.7653
Skewness	0.3215
Kurtosis	3.3477
Values	50000
Errors	0
Filtered	0
Left X	3.24
Left P	5.0%
Right X	5.74
Right P	95.0%

Figure 3. 19 A bar chart showing probability density distribution of BCRs of vaccination in scenario 5 for Canada all-revenue-classes category (exported from @RISK analytical software).

The probability density distribution chart shows that the mean BCR of vaccination for all-revenue-class farms in Canada is 4.43 for scenario 5, with a standard deviation of 0.7653.

3.2.6 Impact of inputs on BCRs in scenario 5

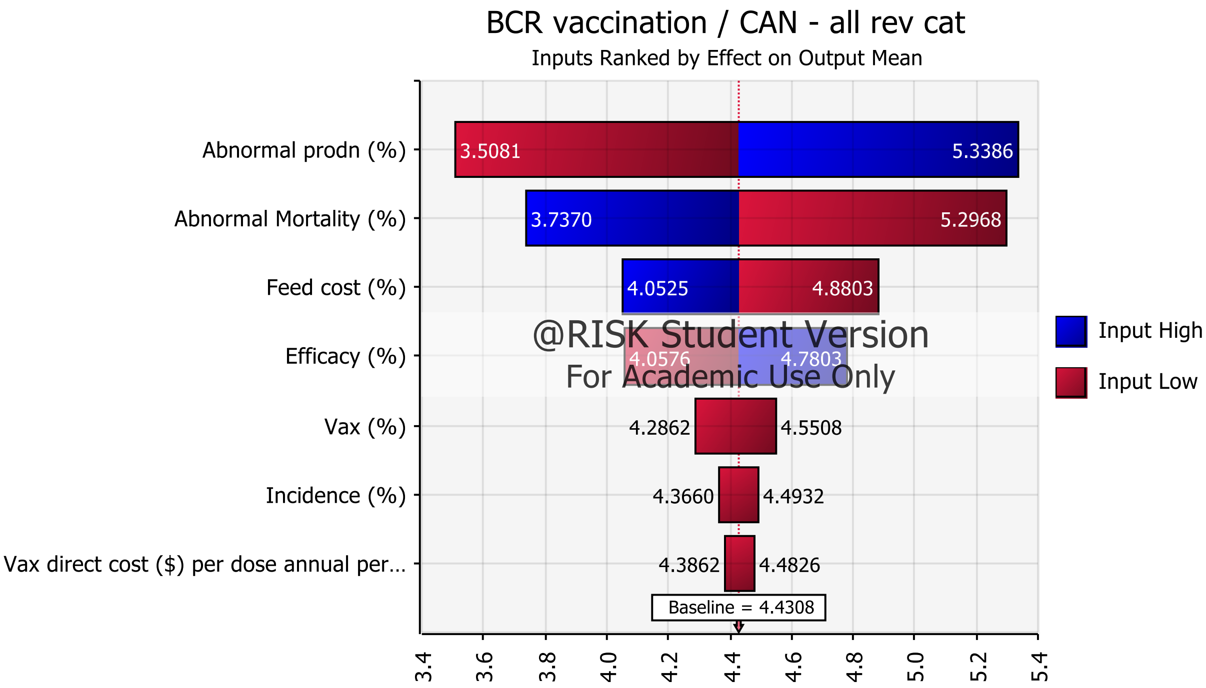


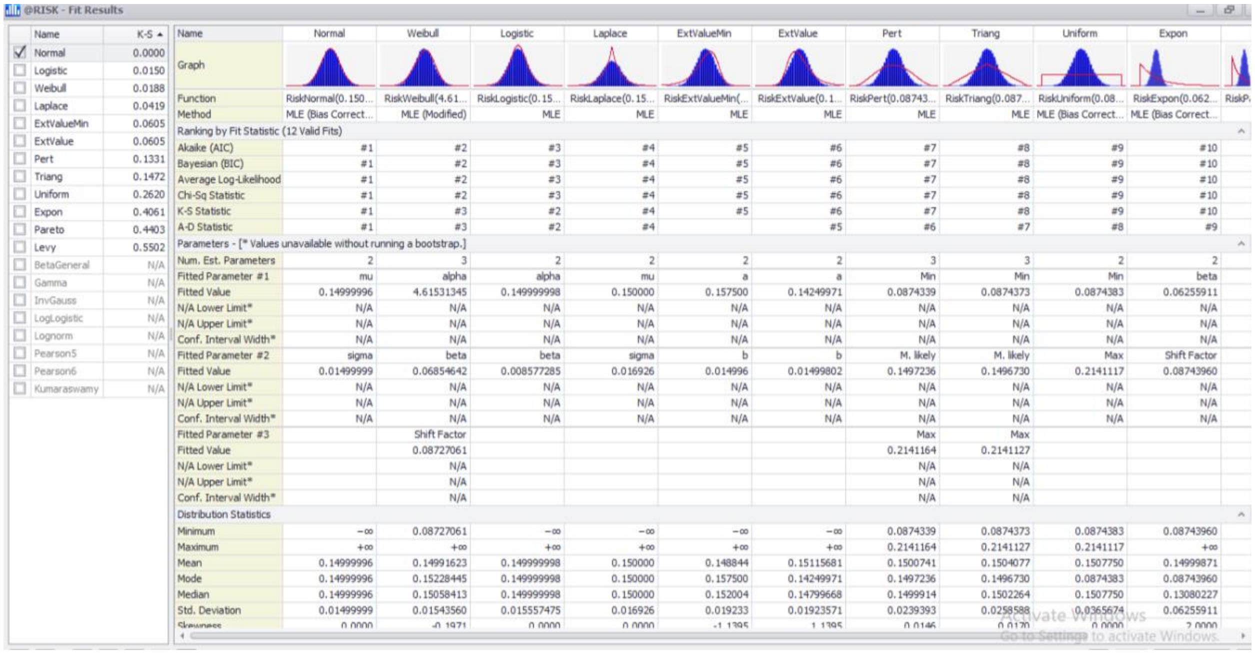
Figure 3. 20 A tornado chart showing the impact of various inputs on BCRs of vaccination in scenario 5 (exported from @RISK analytical software).

From the tornado chart above, the abnormal production rate had the greatest influence on mean profit in scenario 5. Abnormal mortality rate had the second greatest influence on mean BCR. When the feed cost was minimum, BCR was high at 7.19.

The increase in feed cost had the third greatest impact on mean BCRs of vaccination followed by vaccine efficacy, vaccine adoption rate, and incidence rate, in that order. There was the least impact on mean BCRs of vaccination by direct vaccine cos

3.3 Goodness-of-fit for input distributions (Kolmogorov-Smirnov test)

3.3.1 Abnormal mortality rate



	Name	K-S ▲
☑	Normal	0.0000
☐	Logistic	0.0150
☐	Weibull	0.0188
☐	Laplace	0.0419
☐	ExtValueMin	0.0605
☐	ExtValue	0.0605
☐	Pert	0.1331
☐	Triang	0.1472
☐	Uniform	0.2620
☐	Expon	0.4061
☐	Pareto	0.4403
☐	Levy	0.5502
☐	BetaGeneral	N/A
☐	Gamma	N/A
☐	InvGauss	N/A
☐	LogLogistic	N/A
☐	Lognorm	N/A
☐	Pearson5	N/A
☐	Pearson6	N/A
☐	Kumaraswamy	N/A

Name	Normal	Weibull	Logistic	Laplace	ExtValueMin	ExtValue	Pert	Triang	Uniform	Expon
Graph										
Function	RiskNormal(0.150...	RiskWeibull(4.61...	RiskLogistic(0.15...	RiskLaplace(0.15...	RiskExtValueMin(...	RiskExtValue(0.1...	RiskPert(0.08743...	RiskTriang(0.087...	RiskUniform(0.08...	RiskExpon(0.062...
Method	MLE (Bias Correct...	MLE (Modified)	MLE	MLE	MLE	MLE	MLE	MLE	MLE (Bias Correct...	MLE (Bias Correct...
Ranking by Fit Statistic (12 Valid Fits)										
Akaike (AIC)	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10
Bayesian (BIC)	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10
Average Log-Likelihood	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10
Chi-Sq Statistic	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10
K-S Statistic	#1	#3	#2	#4	#5	#6	#7	#8	#9	#10
A-D Statistic	#1	#3	#2	#4		#5	#6	#7	#8	#9
Parameters - [* Values unavailable without running a bootstrap.]										
Num. Est. Parameters	2	3	2	2	2	2	3	3	2	2
Fitted Parameter #1	mu	alpha	alpha	mu	a	a	Min	Min	Min	beta
Fitted Value	0.14999996	4.61531345	0.149999998	0.150000	0.157500	0.14249971	0.0874339	0.0874373	0.0874383	0.06255911
N/A Lower Limit*	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
N/A Upper Limit*	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Conf. Interval Width*	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Fitted Parameter #2	sigma	beta	beta	sigma	b	b	M. likely	M. likely	Max	Shift Factor
Fitted Value	0.01499999	0.06854642	0.008577285	0.016926	0.014996	0.01499802	0.1497236	0.1496730	0.2141117	0.08743960
N/A Lower Limit*	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
N/A Upper Limit*	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Conf. Interval Width*	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Fitted Parameter #3		Shift Factor					Max	Max		
Fitted Value		0.08727061					0.2141164	0.2141127		
N/A Lower Limit*		N/A					N/A	N/A		
N/A Upper Limit*		N/A					N/A	N/A		
Conf. Interval Width*		N/A					N/A	N/A		
Distribution Statistics										
Minimum	−∞	0.08727061	−∞	−∞	−∞	−∞	0.0874339	0.0874373	0.0874383	0.08743960
Maximum	+∞	+∞	+∞	+∞	+∞	+∞	0.2141164	0.2141127	0.2141117	+∞
Mean	0.14999996	0.14991623	0.149999998	0.150000	0.148844	0.15115681	0.1500741	0.1504077	0.1507750	0.14999871
Mode	0.14999996	0.15228445	0.149999998	0.150000	0.157500	0.14249971	0.1497236	0.1496730	0.0874383	0.08743960
Median	0.14999996	0.15058413	0.149999998	0.150000	0.152004	0.14799668	0.1499914	0.1502264	0.1507750	0.13080227
Std. Deviation	0.01499999	0.01543560	0.015557475	0.016926	0.019233	0.01923571	0.0239393	0.0258588	0.0365674	0.06255911
Skewness	0.0000	-0.1971	0.0000	0.0000	-1.1395	1.1395	0.0146	0.0170	0.0000	2.0000

Figure 3. 21 Goodness-of-fit of the distribution of abnormal mortality rate with reference distributions (exported from @RISK analytical software).

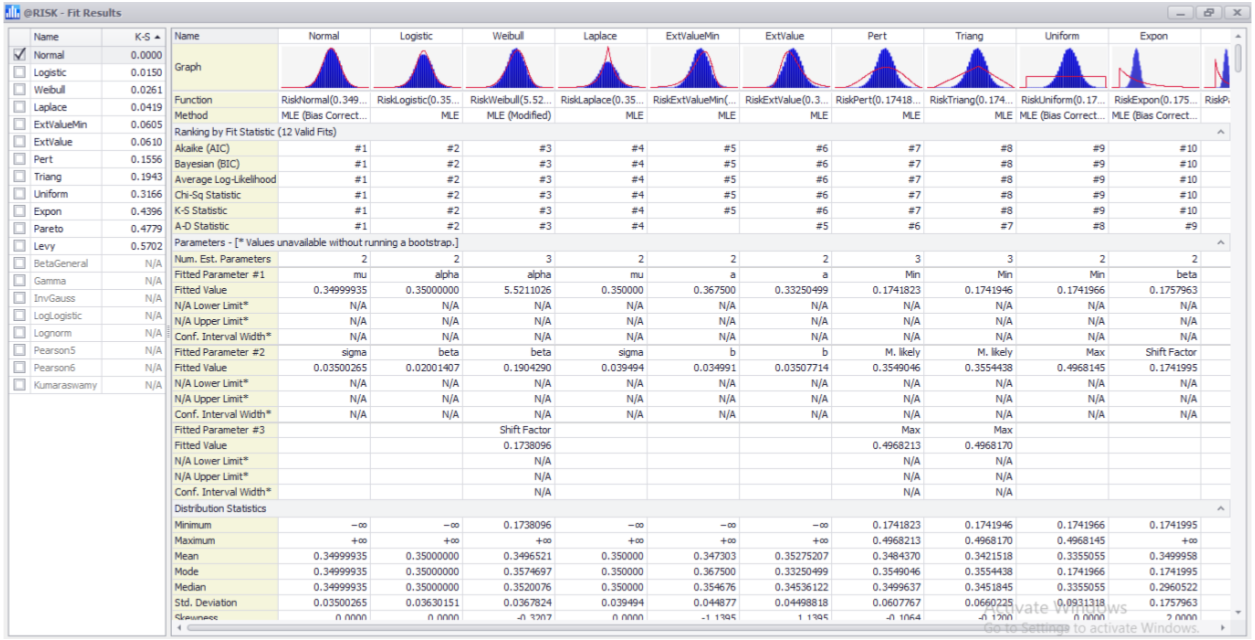
From Figure 3. 21 above, the normal distribution had a KS statistic of 0.0000, which was the lowest among all the reference distributions. Therefore, it was ranked first. The other reference distributions such as Logistic, Weibull, Laplace (Marwala *et al.*, 2016), ExtValueMin, ExtValue, and Pert were ranked in that order after the normal distribution.

According to every other fit selection method such as AIC, BIC, Chi-Sq, AvLogL, and A-D statistics, the normal distribution came on top as the best fit for the probability density distribution of abnormal mortality rate.

3.3.2 Abnormal production rate

From igure 3. 22 below, the goodness-of-fit KS statistic for normal distribution was 0.0000 for probability density distribution of abnormal production rate of eggs, the lowest among all the reference distributions, thereby making it the best fit among the reference distributions. The other reference distributions such as Logistic, Weibull, Laplace, ExtValueMin, ExtValue, and Pert were ranked in that order after the normal distribution.

Normal distribution was the best fit for abnormal production rate according to every other fit selection method such as AIC, BIC, Chi-Sq, AvLogL, and A-D statistics.



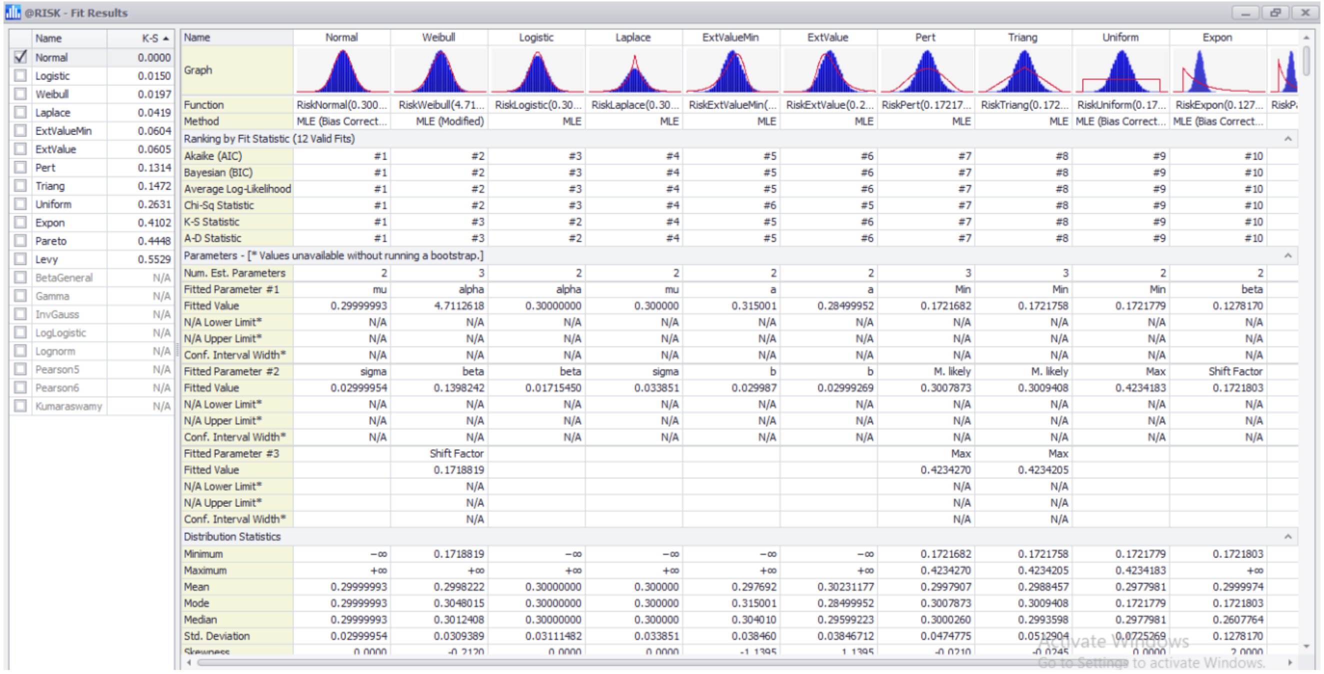
@RISK - Fit Results

	Name	K-S ▲
☑	Normal	0.0000
☐	Logistic	0.0150
☐	Weibull	0.0261
☐	Laplace	0.0419
☐	ExtValueMin	0.0605
☐	ExtValue	0.0610
☐	Pert	0.1556
☐	Triang	0.1943
☐	Uniform	0.3166
☐	Expon	0.4396
☐	Pareto	0.4779
☐	Levy	0.5702
☐	BetaGeneral	N/A
☐	Gamma	N/A
☐	InvGauss	N/A
☐	LogLogistic	N/A
☐	Lognorm	N/A
☐	Pearson5	N/A
☐	Pearson6	N/A
☐	Kumaraswamy	N/A

Name	Normal	Logistic	Weibull	Laplace	ExtValueMin	ExtValue	Pert	Triang	Uniform	Expon
Graph										
Function	RiskNormal(0.349...	RiskLogistic(0.35...	RiskWeibull(5.52...	RiskLaplace(0.35...	RiskExtValueMin(...	RiskExtValue(0.3...	RiskPert(0.17418...	RiskTriang(0.174...	RiskUniform(0.17...	RiskExpon(0.175...
Method	MLE (Bias Correct...	MLE	MLE (Modified)	MLE	MLE	MLE	MLE	MLE	MLE (Bias Correct...	MLE (Bias Correct...
Ranking by Fit Statistic (12 Valid Fits)										
Akaike (AIC)	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10
Bayesian (BIC)	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10
Average Log-Likelihood	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10
Chi-Sq Statistic	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10
K-S Statistic	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10
A-D Statistic	#1	#2	#3	#4		#5	#6	#7	#8	#9
Parameters - [* Values unavailable without running a bootstrap.]										
Num. Est. Parameters	2	2	3	2	2	2	3	3	2	2
Fitted Parameter #1	mu	alpha	alpha	mu	a	a	Min	Min	Min	beta
Fitted Value	0.34999935	0.35000000	5.5211026	0.350000	0.367500	0.33250499	0.1741823	0.1741946	0.1741966	0.1757963
N/A Lower Limit*	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
N/A Upper Limit*	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Conf. Interval Width*	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Fitted Parameter #2	sigma	beta	beta	sigma	b	b	M. likely	M. likely	Max	Shift Factor
Fitted Value	0.03500265	0.02001407	0.1904290	0.039494	0.034991	0.03507714	0.3549046	0.3554438	0.4968145	0.1741995
N/A Lower Limit*	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
N/A Upper Limit*	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Conf. Interval Width*	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Fitted Parameter #3			Shift Factor				Max	Max		
Fitted Value			0.1738096				0.4968213	0.4968170		
N/A Lower Limit*			N/A				N/A	N/A		
N/A Upper Limit*			N/A				N/A	N/A		
Conf. Interval Width*			N/A				N/A	N/A		
Distribution Statistics										
Minimum	−∞	−∞	0.1738096	−∞	−∞	−∞	0.1741823	0.1741946	0.1741966	0.1741995
Maximum	+∞	+∞	+∞	+∞	+∞	+∞	0.4968213	0.4968170	0.4968145	+∞
Mean	0.34999935	0.35000000	0.3496521	0.350000	0.347303	0.35275207	0.3484370	0.3421518	0.3355055	0.3499958
Mode	0.34999935	0.35000000	0.3574697	0.350000	0.367500	0.33250499	0.3549046	0.3554438	0.1741966	0.1741995
Median	0.34999935	0.35000000	0.3520076	0.350000	0.354676	0.34536122	0.3499637	0.3451845	0.3355055	0.2960522
Std. Deviation	0.03500265	0.03630151	0.0367824	0.039494	0.044877	0.04498818	0.0607767	0.0660225	0.0931318	0.1757963
Skewness	0.0000	0.0000	-0.3207	0.0000	-1.1395	1.1395	-0.1064	-0.1200	0.0000	2.0000

Figure 3. 22 Goodness of fit of the distribution of incidence rate with other reference distributions (exported from @RISK analytical software).

3.3.3 Vaccine adoption rate



@RISK - Fit Results

	Name	K-S ▲
☑	Normal	0.0000
☐	Logistic	0.0150
☐	Weibull	0.0197
☐	Laplace	0.0419
☐	ExtValueMin	0.0604
☐	ExtValue	0.0605
☐	Pert	0.1314
☐	Triang	0.1472
☐	Uniform	0.2631
☐	Expon	0.4102
☐	Pareto	0.4448
☐	Levy	0.5529
☐	BetaGeneral	N/A
☐	Gamma	N/A
☐	InvGauss	N/A
☐	LogLogistic	N/A
☐	Lognorm	N/A
☐	Pearson5	N/A
☐	Pearson6	N/A
☐	Kumaraswamy	N/A

Name	Normal	Weibull	Logistic	Laplace	ExtValueMin	ExtValue	Pert	Triang	Uniform	Expon
Graph										
Function	RiskNormal(0.300...	RiskWeibull(4.71...	RiskLogistic(0.30...	RiskLaplace(0.30...	RiskExtValueMin(...	RiskExtValue(0.2...	RiskPert(0.17217...	RiskTriang(0.172...	RiskUniform(0.17...	RiskExpon(0.127...
Method	MLE (Bias Correct...	MLE (Modified)	MLE	MLE	MLE	MLE	MLE	MLE	MLE (Bias Correct...	MLE (Bias Correct...
Ranking by Fit Statistic (12 Valid Fits)										
Akaike (AIC)	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10
Bayesian (BIC)	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10
Average Log-Likelihood	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10
Chi-Sq Statistic	#1	#2	#3	#4	#6	#5	#7	#8	#9	#10
K-S Statistic	#1	#3	#2	#4	#5	#6	#7	#8	#9	#10
A-D Statistic	#1	#3	#2	#4	#5	#6	#7	#8	#9	#10
Parameters - [* Values unavailable without running a bootstrap.]										
Num. Est. Parameters	2	3	2	2	2	2	3	3	2	2
Fitted Parameter #1	mu	alpha	alpha	mu	a	a	Min	Min	Min	beta
Fitted Value	0.29999993	4.7112618	0.30000000	0.300000	0.315001	0.28499952	0.1721682	0.1721758	0.1721779	0.1278170
N/A Lower Limit*	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
N/A Upper Limit*	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Conf. Interval Width*	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Fitted Parameter #2	sigma	beta	beta	sigma	b	b	M. likely	M. likely	Max	Shift Factor
Fitted Value	0.02999954	0.1398242	0.01715450	0.033851	0.029987	0.02999269	0.3007873	0.3009408	0.4234183	0.1721803
N/A Lower Limit*	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
N/A Upper Limit*	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Conf. Interval Width*	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Fitted Parameter #3		Shift Factor					Max	Max		
Fitted Value		0.1718819					0.4234270	0.4234205		
N/A Lower Limit*		N/A					N/A	N/A		
N/A Upper Limit*		N/A					N/A	N/A		
Conf. Interval Width*		N/A					N/A	N/A		
Distribution Statistics										
Minimum	−∞	0.1718819	−∞	−∞	−∞	−∞	0.1721682	0.1721758	0.1721779	0.1721803
Maximum	+∞	+∞	+∞	+∞	+∞	+∞	0.4234270	0.4234205	0.4234183	+∞
Mean	0.29999993	0.2998222	0.30000000	0.300000	0.297692	0.30231177	0.2997907	0.2988457	0.2977981	0.2999974
Mode	0.29999993	0.3048015	0.30000000	0.300000	0.315001	0.28499952	0.3007873	0.3009408	0.1721779	0.1721803
Median	0.29999993	0.3012408	0.30000000	0.300000	0.304010	0.29599223	0.3000260	0.2993598	0.2977981	0.2607764
Std. Deviation	0.02999954	0.0309389	0.03111482	0.033851	0.038460	0.03846712	0.0474775	0.0512904	0.0725269	0.1278170
Skewness	0.0000	-0.2120	0.0000	0.0000	-1.1395	1.1395	-0.0210	-0.0245	0.0000	2.0000

Figure 3. 23 Goodness of fit of the distribution of vaccine adoption rate with normal and other reference distributions (exported from @RISK analytical software).

Normal distribution had a goodness-of-fit KS statistic of 0.0077 for the probability density distribution of vaccine adoption rate, which was the lowest among all the reference distributions, from Figure 3. 23 above, ranking it first among the reference distributions. According to every other fit selection method such as AIC, BIC, Chi-Sq, AvLogL, and A-D statistic, the normal distribution came on top as the best fit for the probability density distribution of vaccine adoption rate.

3.4 Correlation results

Table 3. 3 The table below shows the results of correlation analysis (exported from @RISK analytical software).

@RISK Correlations	Incidence	Vax	Abnormal Mortality	Abnormal prodn	Efficacy	Feed cost
Incidence	1.000					
Vax	0.000	1.000				
Abnormal Mortality	0.000	0.000	1.000			
Abnormal prodn	0.000	0.000	0.000	1.000		
Efficacy	0.000	0.000	0.000	0.000	1.000	
Feed cost	0.000	0.000	0.000	0.000	0.000	1.000

The results presented in Table 3. 3 show that there was no correlation between any two input variables as far as this study is concerned.

3.5 Discussion and interpretation

I set out to study what impact IB would have on layer poultry farms with and without vaccination and the potential impact of new virulent strains of IBV that render existing vaccines ineffective. The existing strains used in the current vaccines would not protect due to a lack of cross-protection among emerging and different strains (Jackwood & de Wit, 2017; Torres, 2021). I used multiple scenario framework and benefit-cost ratios calculations to see the impacts of various inputs such as vaccine cost, feed cost, IB incidence, abnormal mortality rate, vaccine adoption rate, abnormal production rate, and vaccine efficacy on income generated in each scenario and BCRs of vaccination in those scenarios. My results demonstrate that I was able to do that. This section discusses relevant findings from the analyses as evidence of that and interpretations of those results and findings.

3.5.1 Farm demographics

Table 3. 4 Numbers of poultry farms and the average number of layers in each farm in Canada and the four provinces in different revenue categories.

Revenue category	**All revenue classes**					**Medium farms: $250K-$499K**					**Large farms: $1000K -$1,999K**				
Geography	**CAN**	**BC**	**AB**	**ON**	**QC**	**CAN**	**BC**	**AB**	**ON**	**QC**	**CAN**	**BC**	**AB**	**ON**	**QC**
No. of poultry farms	4,903	1,220	373	1,816	875	480	75	30	215	95	905	170	65	360	205
Total number of layers	8,265	6,578	8,363	7,237	9,833	2,363	2,157	3,038	2,390	1,783	8,811	8,313	8,466	8,536	7,967

I conducted simulations for five geographical regions, namely Canada, AB, BC, ON, and QC. Comments on most of the farms in Canada are, Ontario had the highest number of poultry farms in Canada, with 1816 farms overall, because it has the highest quality farmland and is the most populated province (Ontario, 2021) while Alberta had the least number of poultry farms with 373 farms; the majority of large farms are contributed to by Hutterite farming colonies (Evans, 2019). Overall, Canada had 4903 poultry farms in the year 2016.

The provincial approach was used, and three revenue categories were simulated to examine the impact of IB on the layer farms in Alberta and Canada, because it was Alberta research and assessing the impact on egg production in the province was instrumental, while it was also important to see how IB and new strains impacted layer producers on the national scale, in Canada. BC, ON, and QC were chosen for simulations to see the impact of IB and new strains, among others, were the largest poultry-producing provinces.

3.5.2 Scenarios 1-3: Baseline, IB, and vaccination

For the all-revenue-classes category in the base scenario, a poultry layer producer in AB made a mean annual income of $68,485.52 per farm compared to per farm, which was slightly more than Canada's all-revenue-classes category in the base scenario at $65,177.89 per farm. It indicated that medium farms in AB invested more in poultry and eggs compared to other provinces. This right skew in favour of AB is due to the contribution by Hutterites, with some hundreds of colonies distributed across five states and four Canadian provinces. The contribution of Hutterite colonies to agriculture in AB is about 80 percent of the province's eggs, and this productivity is premised upon a relatively large labour force and the willingness to adopt modern technology, well complemented by the establishment of good links with marketing chains (Evans, 2019). Overall, in the other revenue categories, large farms made more profits, while the smaller farms made smaller profits.

The presence of IB in farms in scenario 2 had a substantial negative impact on the income of producers in general. AB layer farms made an annual average income of $12,272.65 per farm, compared to Canada's at $11,685.84 per farm for the all-revenue-classes category. Even though it appeared that AB farms made more profits compared to the Canadian average despite the impact of IB outbreaks, Ab farms lost more in terms of forgone profits as they made $68,000 per farm in the base scenario, meaning AB lost a greater percentage of potential profits due to the sheer average size of the layer farms in AB where the epidemiology of IB did the larger scale of damage. BC medium farms lost the most, with an annual average loss of $9,009.45 per farm because they were small farms, with a small profit margin in the baseline scenario also. The profits plummeted due to the impact of IB and sent them into a loss.

However, in scenario 2 overall, ON large farms lost the most despite having made an average annual income of $22,927.24 per farm. ON large farms lost the most amount of money in terms of forgone profits as they had made $76,533.40 per farm with no outbreak.

The incidence rate of IB had a greater impact on profit in scenario 2 because when there was a high incidence rate of IB, the number of birds dying due to IB would be high, and so would the number of affected birds by abnormal production, resulting in reduced egg output and reduced income. Moreover, the pathological damage caused by the IB virus to the upper respiratory tracts, especially the trachea, predisposes birds to subsequent bacterial infections such as colibacillosis, resulting in greater damage and condemnations (Sanei, 2018) that would contribute to more birds getting impacted by abnormal production.

In scenario 3, even though IB outbreaks affected the farms, layer producers mitigated the damage by vaccinating their birds against IB. In the medium layer farms category in scenario 3, the largest profit makers (AB layer farms) were able to generate profits almost twice as much as they made in scenario 2, at $$44,689.35 per farm, while the least income earners, BC medium farms made a profit of $2,985.44 per farm (they had lost close to $9,000 annually without vaccination). The vaccination protected birds, resulting in the reduction of the number of birds dying due to abnormal mortality caused by IB and the number of birds affected by abnormal production. Due to this mitigating effect of vaccines, the total income for the farms increased compared to scenario 2. Similarly, for the large layer farms category, the largest profit makers were ON large farms, which made close to three times as much profit, compared to scenario 2 ($ 64,842.3 per farm, from barely $23,000 per farm annually). Furthermore, large layer farms in QC, with the smallest average annual income of $ 54,908.25 per farm in the category, made four times as much as they made in scenario 2. ON large layer farms were making more profits because the farms were larger in size than the rest in the same category, and they were investing more in poultry and eggs comparatively. It indicated that the profits increased manifold for larger farms due to vaccination. It could be explained by the fact that vaccination exerted its mitigating impact on multiple fronts, namely the reduction of abnormal mortality and abnormal production, with a very minimal increase in production costs incurred for vaccines and vaccination labor. It is evident from the impact analysis of input variables that showed vaccine adoption rate had the greatest impact on a mean annual profit of the layer farms in scenario 3. When the adoption rate was at its lowest, the profit plummeted to $48,421.05 per farm, while it was $59,068.78 per farm when the vaccine adoption rate was at its highest. At an individual bird level, vaccines reduce both susceptibility and infectivity. Vaccines protect the entire poultry population due to herd immunity that becomes effective in vaccinated birds at two critical levels: flock level and country/region level (Marangon & Busani, n.d.). Proper vaccination against IB, along with other mitigating strategies, has been observed to reduce the negative impact and losses caused by a secondary bacterial infection (Sanei, 2018).

Therefore, the vaccine adoption rate had a domino effect, reducing the number of birds dying due to abnormal mortality and the number of birds affected by abnormal production due to IB. As the adoption rate went up, more birds were protected and the total count of birds dying due to abnormal mortality decreased. The greater the number of birds that get vaccinated, the greater the number of birds protected by the vaccine, and hence, fewer birds will be affected by abnormal production with the resultant increase in profits. The significant impact of vaccination was because vaccines reduced both the susceptibility and infectivity of individual birds and herd immunity at the flock level for a specific region or country (Marangon & Busani, n.d.). It also helped lessen the negative impact caused by potential secondary bacterial pathogens (Sanei, 2018). In effect, vaccine adoption decreased birds dying due to abnormal mortality and birds affected by abnormal production due to IB.

The efficacy of IB vaccines had the second greatest impact on mean annual income because when the efficacy increases, the percentage of birds that are effectively protected by the vaccine increases and thereby reducing both the numbers of birds in abnormal mortality and abnormal production cohorts. R is the mean number of new infections caused by one typical infectious individual bird during its entire infectious period. Generally, the reproduction ratio is the basic reproduction ratio for an unvaccinated population or R_0 (Jong & Diekmann, 1992). If R is less than one, the infection will (eventually) fade out, resulting in a low percentage of infected birds (minor outbreak). If R among birds within a flock is greater than 1, minor and major outbreaks can occur. The probability and the size of a major outbreak increase as R increases. Thus, vaccination preferably should not only reduce transmission significantly, but it should also reduce R to less than 1 (de Wit *et al.,* 1998; De Jong & Kimman, 1994). The assumption of the efficacy is for all farms and not individual farms. The vaccinated population covered by an efficacious IB vaccine would be protected against infection (manifestation of clinical signs of IB infection) and shedding of IB virus (Ali *et al.,* 2018).

The impact on mean profit by incidence, abnormal production, and mortality rates was minimal because these variables are primarily influenced by vaccine adoption and vaccine efficacy. The least impact on mean profit by the direct costs of purchasing vaccines, and it was because the price of IB vaccines (and that of all poultry vaccines in general) is very low (Green, 1962).

In scenario 3, BCRs of vaccination in all the revenue categories in Canada and the four provinces were very high, ranging from 7.72 in the BC medium farms category to 9.04 in the AB medium farms category, which meant that it was very beneficial for farms to vaccinate against IB and that the increase in costs due to vaccination was compensated for by the manifold increase in the revenue in this scenario. The abnormal production rate had the greatest influence on the mean BCRs of vaccination in scenario 3 as the BCR of vaccination reached the maximum at 9.08 when the abnormal production rate was at its highest. A high abnormal production rate (a greater number of birds were producing a smaller number of eggs per day on average due to IB infection) could have a devastating impact on the farms if birds were not vaccinated. Therefore, the benefits of vaccinating were high (as much as nine times) when the abnormal production rate was high, as vaccination would protect birds from the massive impact of having many birds producing at an abnormal production rate.

Interestingly, the vaccine adoption rate had a minimal impact on BCRs of vaccination while it influenced the income the most. When the vaccine adoption rate increased, there was an increase in vaccine cost and vaccination labour cost also, and therefore, it not only increased the income but also the costs. Since BCRs are essentially calculated based on the changes in benefits and costs (Campbell & Brown, 2015), the vaccine adoption rate did not seem to impact BCRs as much as abnormal production did.

3.5.3 Scenario 4: New IBV strains and vaccination

In this scenario 4 with no vaccination, new strains of IBV affected the layer birds to a great extent. The severity of clinical signs and impact of the disease is influenced by the IBV strain(s) involved and, *inter alia*, the presence of secondary or co-infections (Jackwood & de Wit, 2013). There are several emerging, heterologous IBV variants that affect vaccinated flocks due to a lack of cross-protective immunity because new strains are serotypically different from the ones used in vaccines (Ignjatović & Sapats, 2000a; Awad *et al.*, 2014). AB layer farms, on average, lost $65,075.92 per farm annually in this scenario compared with that of Canada average at $61,590.50 per farm annually for the same revenue category. It indicated that Alberta farms, with larger farm sizes, lost more compared to Canada's average because of the directly proportional impact of the epidemiology of the new IBV strains on the scale of production. Similarly, in the large layer farms category in scenario 4 (unvaccinated), ON farms lost the most because of the epidemiology of IB infections and the economies of scale, as ON had the largest average size of farms.

Interestingly, in the medium layer farms category, BC layer farms lost the most at $28,955.56 on average per farm annually compared to AB medium farms, at $635.99 per farm annually. It could be due to Hutterite colonies, as discussed elsewhere in this document, that rely on the brethren's collective labour force, which is mostly unaccounted for in the cash flows, or cheap at best. While labor should always be valued by the producer, it is often not. This is true for smaller, independent operators as well where they show their "profits" but do not include what they have paid to themselves as labor before calculating profit.

The incidence rate of new and virulent IBV strains had the greatest and most devastating impact on mean profit for unvaccinated farms in scenario 4 because it directly influenced the abnormal mortality and abnormal production rates, which effectively impacted the total egg output and hence, income.

In scenario 4 with vaccination, there was an apparent impact of vaccination where AB layer farms made a turn-around to make an annual average income of $23,608.09 per farm, up from a loss of $65,075.92 per farm annually in unvaccinated scenario 4. Similarly, layer farms across Canada made profits, indicating that the detrimental impact of IB on profit in this scenario 4 (unvaccinated) was mitigated due to vaccination. Even though new strains caused higher abnormal mortality rate and abnormal production rate along with lower vaccine efficacy, IB vaccination was able to protect birds, thereby reducing the number of birds dying due to abnormal mortality caused by IB and the number of birds affected by abnormal production rate. When the impact of these two input variables was minimized, the total income for farms increased. The profits in scenario 4 with vaccination were lesser than that in scenario 3 (due to new strains that were highly virulent), not to mention the baseline scenario, regardless, the adoption of vaccines to protect their birds against IB salvaged the situation by not only averting losses but also being able to make some profits.

High BCRs of vaccination in all the revenue categories in Canada in scenario 4 evinced that it was highly beneficial to vaccinate against IB, as the increase in total revenues for the farms after vaccination was at least six times as much as the increase in total costs incurred due to vaccination. It pulled farms out from running in loss and generated profits for most layer farms. Therefore, by investing in vaccines (and associated costs) for your layer birds, the returns in the form of revenue would be at least six times as much, even if outbreaks were to occur either due to existing or new strains of IBV.

No other input variable influenced BCRs more than the abnormal mortality rate in scenario 4, because when abnormal mortality is low, the number of birds that die due to IB is small, implying that a greater number of birds will remain alive and produce more eggs and hence, more income, and vice versa. It was followed by abnormal production as the most impactful on mean BCRs of vaccination. When the abnormal production rate is high, many birds would be affected by it, producing a smaller number of eggs, and if these birds are vaccinated, the income will be higher compared to a slight increase in costs for vaccines and vaccination.

There was the least influence on BCRs by direct vaccine cost because vaccine prices and vaccination labour costs are relatively minimal, as noted elsewhere in this document.

3.5.4 Scenario 5: New IBV strains with feed price rise and vaccination

In scenario 5 with no vaccination, there were outbreaks due to new and virulent strains of IBV and feed cost increased to 59% (from 49%) of total operating expenses, creating a devastating impact on the profitability of Canadian layer producers. ON large farms lost the most, with a loss of $100,054.28 per farm on average annually, while AB medium farms in the same scenario lost the least, with a loss of $10,037.64 per farm on average annually, because the average number of layer birds for ON large farms is significantly larger, and therefore, the increase in feed cost and the outbreaks of IB infection hugely impacted farm revenue and income negatively, making producers lose thousands of dollars. As noted earlier, the epidemiology of the disease affected farms proportionately with the scale of production. Moreover, with the increase in the feed cost, the total production cost increased substantially while revenue generation was crippled by IB outbreaks, resulting in a maximum loss for the largest farms such as ON large farms.

In scenario 5 with vaccination, the general trend was that many farms were able to mitigate losses to a great extent, but AB medium layer farms were able to make some profit as well, at $22,640.59 per farm, while BC medium farms made the least, with a loss of $15,310.32 per farm. Despite high feed cost, epidemiology of IB, and low vaccine efficacy, AB medium farms managed to generate some profit, which was an anomaly, and it could be attributed to the Hutterite farming colonies that largely under-account for labour (Evans, 2019). Conversely, farms with the largest numbers of birds ran into huge losses because of the feed cost rise and having a larger number of birds to feed only made it worse, besides the full-blown impact of the new, virulent strains of IBV. BC medium layer farms had very small flock size, and as it is, they were losing close to $3900 in the unvaccinated scenario 5. However, when they adopted IB vaccination, although they still ended up with the greatest loss in that category in scenario 5 (vaccinated), they made a considerable improvement over scenario 5 with no vaccination.

The changes in the feed cost had the greatest influence on the mean profit in scenario 5. Feed costs constitute 49% of operating expenses; a 10% change in the feed cost would significantly impact the farm revenue and cost structure. Additionally, when new strains affected birds, their productivity was affected, while total expense due to feed consumption increased. Therefore, when the feed cost was highest, the farms all over Canada (all revenue classes) were losing the most and vice versa. The vaccine adoption rate had the second greatest impact on income because the number of birds affected by abnormal mortality and abnormal production rates, among other things, depended on the vaccine adoption rate. When a higher percentage of the population was vaccinated, more birds were protected, and hence, more income was generated. In this scenario 5, high BCRs of vaccination were observed when layer poultry producers in Canada vaccinated against IB, indicating that investing in the vaccination of layer birds in Canada would be beneficial. The increase in revenue due to vaccination against IB would be almost six times the increase in total production costs in terms of vaccinating labour cost and the vaccine price.

The abnormal mortality rate had the greatest impact on mean profit in scenario 5. Interestingly enough, the impact of abnormal mortality was more than that of feed cost because the incidence rate was high (with increased abnormal mortality rate) due to new strains of IBV, which affected the profitability of farms more than any other input variable. It meant that a greater number of birds were exposed (high incidence of 50%) with the result that a greater number of birds among the exposed died due to a high abnormal mortality rate, leaving only a smaller number of birds in production, from which certain percent would be affected by abnormal production caused by IB. If the abnormal mortality rate was the lowest, the number of birds dying due to IB could be tiny, but birds may be affected by abnormal production due to the infection regardless. Therefore, the two extremes of abnormal mortality massively impacted the profitability of layer farms.

The findings from all scenarios made it clear that we need to understand and know more about IB and its impact on the poultry industry in Canada. The profitability of the layer farms depended on how much damage a strain of IBV can cause on the farms. Many poultry producers routinely vaccinate all the different types of chickens in most countries, with live and inactivated IBV vaccines (Bande *et al.,* 2015), but have we considered the impact of new strains of IBV affecting the poultry? If we were to go by the findings of the simulations done in this study, the implications of new, virulent strains of IBV affecting the poultry could be nothing short of devastating. New variants of IBV continue to emerge, making it difficult to identify this virus and even more challenging to control, posing challenges to poultry industries and vaccine developers worldwide (Jackwood, 2012b; Awad *et al.,* 2014). It changes by both spontaneous mutation and genetic recombination because it is a single-stranded RNA virus (Cavanagh, 2007; Wood *et al.,* 2009) and there is a lack of cross-protective immunity, leading to outbreaks in vaccinated flocks also (Ignjatović & Sapats, 2000a; Awad *et al.,* 2014).

IB is an OIE-listed poultry disease recognized the world over for its economic impact on poultry production and global trade due to the risk of spreading among multiple countries (Colvero *et al.*, 2015), Ontario Animal Health Network (OAHN) reported an increasing number of IBV cases in December 2016 in Ontario from different poultry sectors, and some new strains distinct from earlier reports were identified (OAHN Special IB Report, 2016). In Canada, there are many strains of IBVs that fall into nine genotypes belonging to four groups based on similarities in their S gene sequences (Martin *et al.*, 2014). There are over seventy two known genotypes of gamma-coronavirus worldwide (Jackwood, 2012a; Snyder *et al.*, 1983; Bande *et al.*, 2016). Canadian IBVs are divided into nine genotypes belonging to four groups based on similarities in their S gene sequences: "Canadian variant virus, strain Qumv; the classic, vaccine-like viruses, Connecticut and Massachusetts; US variant-like virus strains, California 1734/04, California 99, CU82792, Pennsylvania 1220/98 and Pennsylvania Wolg/98; and non-Canadian, non-US virus, strain 4/91" (Martin *et al.*, 2014).

The emergence of QX variant has reinforced the virulence of some IBV strains in damaging reproductive tracts of breeder and layer birds, causing a delay in the onset of production, poor egg production peak, a high proportion of false-layers, and deteriorated quality of eggs (Ganapathy, 2009; Jones, 2010; David Cavanagh & Gelb, 2008). Sometimes, it can be associated with male infertility and enteritis (Villarreal *et al.,* 2007) and potential vertical transmission of IBV (Pereira *et al.*, 2016; Gallardo *et al.,* n.d.). A recent complete genomic sequence analysis in Canada revealed evidence of recombination of at least three different IBV strains (Hassan *et al.*, 2019) while using live attenuated vaccines also impacts the genetic profile of similar IBV variants in the field (Jackwood & Lee, 2017). Moreover, there has been evidence of a wider host range of IBV than was previously thought (Cavanagh, 2007). Many of these wild birds connect all parts of the world because of the annual migration, unhindered by country or continental borders (Wille & Holmes, 2020) while some migrate between Canada and the US (McConnell, 2021).

Wille & Holmes, (2020) revealed the multi-host nature and host range of gamma-coronaviruses at the genus and species levels using genome sequence and ecological data. They concluded that it was challenging to infer and assess viral diversity and ecology because of major limitations in generating complete genome sequences, which creates a limitation in understanding more about the cross-species transmission within and between wild and domestic birds, and most importantly, at domestic-wild-mammal bird interface.

Therefore, consistent with the above information (or lack thereof) in the literature on current strains and emerging ones, there is a very high possibility of new strains of IBV emerging due to the mixing strains of gamma-coronavirus across the wild bird-poultry interface, with potentially huge socio-economic ramifications. Then, the big unknown is, how much damage can these new strains cause to the world poultry trade in general and Canadian poultry in particular?

3.5.5 BCR calculation

BCA is thought to have been derived in principle in France in the early 1800s (McConnell, 2021) or even earlier in the UK by Sir William Petty, 1665 (Petty, 1662) in his book “A treatise of taxes and contributions”. In summary, BCA is a systematic process to estimate the strengths and weaknesses of alternatives by comparing and calculating the costs and benefits of a project for 1) determining if the project is a viable and justifiable investment, and 2) studying how it compares with alternatives either by ranking them or by assigning priority. It has widespread use in making policy decisions and project investments. The U.S. Securities and Exchange Commission, for instance, is required to conduct BCA while instituting regulations (University of California, Berkeley, 2008). CBA is now a requirement for many government agencies and international organizations, including the US EPA, Inter-American Development Bank, and the World Bank (US EPA Guidelines for Preparing BCA, n.d. ; IADB, n.d.). BCA was applied in estimating the use of water resources efficiently while managing natural resource sustainability (Carlson *et al.,* 1993).

Simulated models in this study replicated typical layer poultry farms in Canada and four provinces to demonstrate how the changes to vaccine adoption rate, vaccine efficacy, abnormal mortality rate, abnormal production rate, the incidence rate of IB, and costs of production (mainly feed) affect the annual income and revenue for their farms. The effects of these changes on the input variables will be understood without having (for poultry producers) to experience them firsthand. By changing one or more attributes, their effects on the outcomes will be seen. This becomes a robust prediction when we generate thousands of iterations to obtain a characteristic distribution of a particular outcome variable (Frey & Pfeifer, 2013; Clemen, 2014). A strength of BCA is that it can combine its rigour with comprehensiveness (incorporation of productivity impacts, elasticities of input variables, costs, vaccine adoption data, and discount rates), while its weakness is that it requires robust data and substantial analytical skills (Zerbe & Bellas, 2006; Campbell & Brown, 2015). BCRs can convert the absolute benefits and costs into a simple ratio that many stakeholders can understand. It makes easier the comparison of different scenarios, investments, or projects as alternatives to current ventures with better profitability. BCRs make it understandable to interpret the risk of forecasted net cash flows and assess if it is profitable. Moreover, BCRs equate the value of cash flows with respect to the period in which it occurs.

The BCRs used as a basis for comparison cannot adequately indicate the liquidity or profitability with analyzed scenarios and options because this option may involve huge investments to start up with little returns but produces more returns much later. Besides, the assumptions for other factors such as discount rate, residual value, and cash flow statements can significantly influence the BCRs because these parameters have inherent insecurities that BCA may not need to consider (Campbell & Brown, 2015).

I could find no reference in the literature on BCA applied to study the impact of IB either in Canada or elsewhere in the world. BCA has been used to estimate the impact of diseases in other animal species as well, including FMD in cattle. A benefit-cost analysis of costs of outbreak and surveillance for poultry HPAI H5N1 was done in Nigeria (Fasanmi *et al*., 2018) to determine surveillance as an alternative intervention to a response where the results showed that the cost-effectiveness of surveillance for HPAI was 68 times that of doing nothing and despite HPAI surveillance appearing to be expensive, it actually had economic benefits. It was similar to this study in which adopting IB vaccines appeared to increase the production costs, but the results of BCA showed that it was indeed beneficial to vaccinate.

I also present more examples and comparisons of benefit-cost analyses from in literature in the simulation section, as many such studies were conducted using Monte Carlo and other simulation methods.

3.5.6 Simulation and Monte Carlo simulations

Simulation is a process of getting random outcomes, like rolling some dice in a casino, where uncertain values for input variables are chosen at random under a specified probability distribution. The outcome values are computed based on randomly chosen input values, and probability distribution for these outcomes is generated to understand the profile of an outcome variable (Frey & Pfeifer, 2013; Clemen, 2014). Simulation programs run efficiently because they function on a simple mathematical theorem that states that if the probability values are chosen uniformly, the sample values will approximately have the expected distribution (Frey & Pfeifer, 2013; Clemen, 2014).

Simulation has been gaining widespread usage and application because it allows us to analyze and make complex decisions involving many uncertainties. Simulation models with just one uncertainty can also give many interesting insights. It also allows the modelling of each uncertainty with a probability distribution that is chosen for it. We can use probability distribution for unknown inputs to transform a deterministic model into a stochastic or probabilistic model to capture the effects of variability of independent variables. Therefore, the values generated by the MC simulation model are governed by probability distributions, which makes the model more realistic (Frey & Pfeifer, 2013; Winston, 1999; Law *et al.*, 2000; Hyde & Engel, 2002). It is regarded as a very flexible framework, and the ability for the models to incorporate risk and interactions (Frey & Pfeifer, 2013) of input variables or components is a significant upside.

Critical weaknesses of simulation include the requirement of enormous analytical skills and problem definition can be not so clear as it involves setting up models to analyze "what-if" scenarios (Frey & Pfeifer, 2013; Clemen, 2014). Simulations may not be realistic if data are poorly representative of the population, and the application of results will be irrelevant. If we use data that are not robust (complete data from reliable sources), it will yield unrealistic results, and reasonable estimates of input variables should be available along with means and standard deviations, thus, making a thorough knowledge of systems under study very essential (Frey & Pfeifer, 2013; Clemen, 2014; Heady *et al.*, 1978). I had access to robust estimates and means for input variables from reliable data sources such as Statistics Canada, although they do not have standard deviations for means of many data and figures.

While assuming distribution for input variables, a wrong distribution would give irrelevant and wrong outputs and unrealistic results. For this study, I used goodness-of-fit tests inherently performed by the @RISK software for MC simulations which confirmed the assumptions of the normal distribution as the best fit reference distribution for input variables. I used KS statistics for best fit selection to assess the goodness-of-fit for the distributions.

Therefore, simulation modelling has a lot to offer and has often been used to analyze input-output relationships and, in BCA frameworks, provides factual information to solve problems, make decisions, and quantify costs and benefits to assess the impact (Clemen, 2014); historically, this was particularly so in the context of agricultural production (Heady *et al.,* 1978).

Monte Carlo simulation creates distributions of potential output values using probability distributions where each variable has a certain probability of various outcomes happening. It is because probability distributions are a very realistic approach to describing the uncertainty of variables in an analysis (Palisade, 2018; Korn *et al.,* 2010). The name Monte Carlo simulation came from the computer simulations done in the 1930s and 1940s for estimating the probability of the chain reactions required for an atom bomb to detonate with accuracy. Since the physicists working on this project, John von Neumann and Stanislaw Ulam, were big gambling fans, Monte Carlo was the code name they gave to the simulations. The term Monte Carlo refers to the administrative area of Monaco, popularly known as a place where European elites gamble (Harrison, 2010; Winston, 2016; Korn *et al.,* 2010; Palisade, 2018)

A Monte Carlo simulation can be performed using Microsoft Excel and a dice game. The Monte

Carlo simulation is a strategy of mathematics that uses random draws to solve complex problems. Today, it has widespread usage and has key roles in many fields such as finance, physics, chemistry, and economics (Winston, 2016). The principle of Monte Carlo simulation is to study the behaviour of statistics by drawing a large number of random samples and observing empirical procedures. The idea is to create a "pseudo-population" similar to the real population in all relevant respects. This pseudo-population contains mathematical procedures for generating sets of numbers that resemble data samples drawn from the true population. It is then used for multiple trials of a statistical procedure of interest to study the behaviour of that procedure across many samples. Thus, the Monte Carlo simulation has a simple concept that flows from the sampling distribution concept (Mooney, 1997).

It must be emphasized that the results presented in this study cannot be directly compared with other similar studies involving Monte Carlo simulations and benefit-cost analyses simply because there may be differences in the methodology, impact categories, functional units, scenario setup, and revenue categories.

Berentsen *et al.,* (1992) simulated the spread of FMD by building BCA epidemiological models and Markov chain models (that used a state-transition approach) for FMD control measures in the Netherlands and concluded that losses were resulting from export bans during outbreaks and FMD prophylactic vaccination costs. They considered cattle and pig farms as modelling units and all animals on each farm were assumed to be in the same state (susceptible, infectious, and immune being the three different states). The probability of transition from one state to another was simulated dynamically. It was different from this study in that the disease status of IB was assumed to be dependent on exposure status even within the same farm and barns, thereby leading to the formation of different cohorts even within the same barn. Similarly, Rasmussen *et* *al.,* (2021) simulated the spread of bovine paratuberculosis to estimate economic losses for affected farms and regional losses (by considering economic variables specific to selected, intensive dairy-farming regions) using a Monte Carlo Markov Chain approach. Saatkamp *et al.,* (2000) evaluated the economic impact of improved systems for national identification and recording on classical swine fever in the European Union, using a Markov-process-based simulation model.

Andrew *et al.,* (2019) conducted a study in Tanzania that assessed the impacts of agro-ecological parameters on the performance of newly introduced Sasso and Kuroiler chicken strains. A farm-level economic and nutrition analysis simulation model (FARMSIM) was developed to assess the economic viability of these strains in relation to local chickens. FARMSIM is a Monte Carlo Simulation Model that evaluates a baseline and an alternative option of farming or technology simultaneously. The data, similar to this study, were obtained through production and marketing data, historical data especially prices of both inputs and outputs, and from simulation exercises. The findings showed Sasso strain to be most economically viable in terms of NPV and the probability potential economic benefits. Kuroiler came second, followed by local chickens. FARMSIM model used was similar to the farm income model developed for my study that assessed the economic benefits of vaccinating layer birds in Canada, but the difference was that they studied the impact of agro-ecological parameters on the production performance of the new chicken strains, while this study assessed the impact of an intervention on the profitability of layer farms. They generated distributions for simulated outputs using 500 iterations, while this study used 50,000 iterations. They used a certain distribution called Gray-Richardson-Klose and Schuman (GRKS) for economic viability indicators, which uses minimum, mean, and maximum statistics (Richardson *et al.,* 2000), while the current study used normal distribution.

Kovacs *et al.*, (2007) applied Monte Carlo simulation combined with Bayes' statistics to examine the technological risk of a laying-hen stock breeding program with the data obtained from a company involved in breeding broiler parent stock. They used an improved version of the Monte Carlo technique, which allowed the comparison of the profitability of many stocks and evaluation of alternative decisions with more precision. They simulated distributions of outputs such as body mass for chickens as well as the number of fertile eggs produced, the rate of feed consumption, and production costs, which are important data concerning breeding stocks that explained and estimated technological risk and uncertainties. They applied normal distribution for modelling weekly body mass growth, similar to the reference distribution used for input variables in the current study, but they also used gamma hyper-distribution for survival rates and beta hyper-distribution for egg production and the rate of fertile eggs but had no information regarding the goodness-of-fit.

Kusnaman *et al.*, (2018) collated profit volatility and capital productivity of rice farming with layer poultry farming in Indonesia using probabilistic models and Monte Carlo simulation. The results showed that rice farming had better capital productivity as well as lesser profit volatility. This meant that farmers chose low-risk ventures such as rice farming, over high-risk businesses such as poultry layer farming, even if it meant making a lesser profit. Similar to the current study, they considered feed price fluctuations in the models and their respondents were poultry producers rearing about 2,000 birds, which corresponds to the medium Canadian layer farm category in the context of my study.

Leinonen *et al.*, (2012) quantified the environmental burdens caused by four popular egg production systems in the United Kingdom by applying the life cycle assessment method. While they used data from the UK egg industry (mechanistic sub-models for animal performance and crop production), they used Monte Carlo simulations to quantify the uncertainties in outputs and systems comparison. They used 5,000 iterations compared to 50,000 for this study. The results showed that the organic system required the highest number of birds to produce 1000 kg of eggs compared to the least number required for the cage system. Feed, processing, and transport had the greatest impacts on the environment due to the energy use and global warming potential followed by gas and oil. Manure had the biggest impact on the acidification potential due to the emission of ammonia gas. The mechanistic production sub-models they developed inherently incorporated correlation between any two variables. Similar to the current study where one cycle of production spanning twelve months was considered, they also used data on the farm activities from one year's operations.

Martinelli *et al.,* (2020) evaluated the eco-efficiency of systems of poultry production in Southern Brazil using lifecycle assessment (LCA) and economic value added from cradle to the gate. The findings indicated that animal feed production and electric energy usage by the equipment in large aviaries had the biggest impact on the environment. The organic egg production system showed the best eco-efficiency and the economic value added per kilogram of eggs produced, but with a slightly bigger impact on the environment. Much like the current study, they also assumed probability distributions for input variables and used the normal distribution (with assumptions made for the mean and standard deviation of input variables) as the reference. They used 10,000 iterations for simulations.

Purwaningsih *et al.,* (2018) assessed the business risk due to selling price fluctuation of live broiler birds in East Java province in Indonesia using the Monte Carlo simulation method. The results showed that feed cost was 74% of the total cost of production and broiler farms had a high probability of loss risk. They studied farms with 3000 broiler birds, that correspond to medium layer farms in the context of the current study. They used profit and loss probability from production cost and adjusted selling price data from 2014 to 2015, while my study used data from several sources to assume probability distributions for various input variables. They simulated the selling price of live broiler birds for a long duration using the Monte Carlo and value-at-risk methods to estimate the losses incurred, to arrive at a business risk decision. Similarly, the current study also used Monte Carlo simulations of profits and losses to estimate the impacts of IB infection and IB vaccine adoption (using BCRs of vaccination analysis) on the Canadian layer poultry production.

Sakomura *et al.,* (2019) developed a stochastic model in Brazil to simulate laying hens and broiler breeder populations to their response to dietary contents and optimize dietary nutrient contents, feed conversion efficiency, egg production, and feed cost. Similar to the current study, they assumed statistics for input parameters to build a stochastic model. Their findings represented the reality and were ideal for estimating the optimum economic regimen of calculating ration for the simulated flocks.

Yates *et al.,* (2007) constructed an economic model to study the economic viability of a broiler agroforestry system and investigated the sensitivity of economic performance to identify key variables that needed further research and managing, using Monte Carlo simulations and financial analyses. They used an internal rate of return (IRR) of 15.5% because the study analyzed data for a 120-year time frame, while the current study didn’t have to include IRR because it involved simulations over a twelve-month period. They allowed the models to simulate and observe a range of potential results from random variations applied to all parameters simultaneously using assumed probability distribution statistics, similar to the current study.

3.5.7 The probability distribution function for input variables

I assumed that my input variables for Monte Carlo simulations were normally distributed (for biological data, one usually assumes normality or binomial distribution), which would be tested using KS. The normal distribution is symmetrical and continuous probability distribution where most of the values cluster around the mean, with a central peak, and the probabilities for observations taper off evenly as tails on either side (Steel & Torrie, 1980). It is alternatively called the Gaussian distribution or the bell curve. In nature, many natural phenomena have a normal distribution (Steel & Torrie, 1980), and I too used normal distribution since we do not have data or samples of the distribution for input variables from some fifty thousand poultry producers.

3.5.8 Goodness-of-fit test for the distributions of input variables

The results of the simulation models showed that my choice of distributions was right and that my assumptions were correct as the simulated results of the distributions for all input variables conformed to the normal distribution. It naturally flows that the distributions for output variables did fit well with the normal distribution. To test the goodness-of-fit for the fitted results of the distributions for input variables, I chose Kolmogorov-Smirnov statistics from among many other popular options of "Best Fit Selection" statistics such as AIC – Akaike information criteria, Bayesian Information Criteria (BIC), Average Log-Likelihood (AvLogL), Chi-squared Statistic (ChiSq), and Anderson-Darling (AD).

3.5.8.1 Kolmogorov-Smirnov test

I chose Kolmogorov-Smirnov statistics because KS statistics as a goodness-of-fit test is widely used and easily understood by many stakeholders and researchers alike.

This test was named after Andrey Kolmogorov and Nikolai Smirnov. It is used to compare the one-dimensional probability distribution of a sample with a reference distribution or to compare probability distributions of two samples if they are equal, and it is a nonparametric test that can be used to compare all the percentiles simultaneously (Kolmogorov–Smirnov Test, 2021; Wilcox, 2011).

The KS statistic measures the distance between the cumulative distribution function of a reference and the empirical distribution function of a sample. For a two-sample test, it provides the distance between the empirical distribution functions of the samples.

The null hypothesis of a KS statistic states that the sample is drawn from the reference distribution in the case of one-sample fit test and that both the samples are drawn from the same distribution in the two-sample case (Kolmogorov–Smirnov Test, 2021). A two-sample KS test is one of the most useful nonparametric methods used to compare two samples because it is sensitive to variations in the shape and location of the empirical cumulative distribution functions of the samples compared. As a goodness-of-fit test, the KS test is used to test the distribution of a sample variable for normality of distribution, where samples are standardized to compare with a standard normal distribution. Thus, the mean and variance of a reference distribution need to be set equal to the estimates of a sample, and it changes the null distribution of the test statistic (Kolmogorov–Smirnov Test, 2022).

The use of the critical value is significant to reject the null hypothesis that the distribution of a sample belongs to the reference distribution. One rejects the hypothesis when a KS statistic is greater than or equal to the critical value. When there are no tied values, the KS test can have relatively high power, but with ties, its power can be relatively low (Wilcox, 2011)

The KS statistic outputs are given by @RISK for Monte Carlo simulations, and those reference distributions with higher KS statistics (that got rejected) were not included in the best fit ranking output.

3.5.8.2 Goodness-of-fit for input distributions (KS statistics) fitted results

3.5.8.2.1 Abnormal mortality

The normal distribution (reference) had a KS statistic of 0.0000, the lowest among all the reference distributions for abnormal mortality rate. Other reference distributions such as Logistic, Weibull, Laplace, ExtValueMin, ExtValue, and Pert were ranked after the normal distribution in that order. Therefore, normal distribution was ranked first for goodness-of-fit for the probability density distribution of the input variable, abnormal mortality rate.

Also, according to every other fit selection method such as AIC, BIC, Chi-Sq, AvLogL, and A-D statistics, normal distribution came on top as the best fit for the probability density distribution of abnormal mortality rate. It confirmed that the probability density distribution of abnormal mortality belonged to the normal distribution.

3.5.8.2.2 Abnormal production rate

The goodness-of-fit KS statistic (at 0.0000) for normal distribution was the lowest among all the reference distributions for probability density distribution of abnormal production rate of eggs, thereby making it the best fit among the reference distributions. The other reference distributions such as Logistic, Weibull, Laplace, ExtValueMin, ExtValue, and Pert were ranked after the normal distribution in that order. Normal distribution was the best fit for abnormal production according to other fit selection methods such as AIC, BIC, Chi-Sq, AvLogL, and A-D statistics.

It confirmed that the probability density distribution of abnormal production belonged to the normal distribution.

3.5.8.2.3 Vaccine adoption rate

Normal distribution had a goodness-of-fit KS statistic of 0.0077 for the probability density distribution of vaccine adoption rate, ranking first among the reference distributions. According to every other fit selection method such as AIC, BIC, Chi-Sq, AvLogL, and A-D statistic, normal distribution came on top as the best fit for the probability density distribution of vaccine adoption rate.

It confirmed that the probability density distribution of vaccine adoption rate belonged to the normal distribution.

Chapter 4

Conclusions

4.1 Gaps in the economic impact of IB in the literature

IB has a substantial economic impact on the global poultry industry in general, and IBV infections globally are considered the second most-damaging poultry disease after highly pathogenic avian influenza (HPAI) (World Bank, 2011). The impact of the disease may be influenced by IBV strain(s), environmental conditions, circumstances, age, type, immune status, and the presence of secondary or co-infections (Jackwood & de Wit, 2013). However, the economic impact of IBV infection on the Canadian poultry industry has not been well studied. Some work has been done on the impact of various poultry diseases or interventions in poultry.

Cook *et al.*, (2001) refer to IB as possibly the most economically significant viral respiratory disease in chickens. Therefore, there was a significant gap in the literature as far as the research on the economic impact of IB is concerned, be it in Canada or elsewhere in the world.

4.2 Multiple scenario framework and BCA

Therefore, I set out to perform simulations using multiple scenario frameworks and estimate the impact of IB on poultry farms using BCR calculations. I set up models that replicated typical layer poultry farms in Canada, AB, BC, ON, and QC to observe how IB outbreaks, vaccination, and other production costs (especially feed price changes) impacted revenues and costs. I generated 50,000 iterations to make predictions more robust and (Frey & Pfeifer, 2013) maintain that a large number of iterations are essential to obtaining a distribution that is characteristic of a particular variable.

BCRs of vaccination were calculated for income generation and profitability in the scenarios that vaccinated the birds in relation to scenarios that did not vaccinate against IB. BCR calculation entails incorporating the time value of benefits and present value calculation for multi-phased benefits crucial. However, since this study considered only one cycle of layer production (twelve months), present values were inherently incorporated into the benefits and costs calculated. Benefits of vaccination (present value of benefits) were therefore calculated as the increase in revenue for the farm in the scenario where birds were vaccinated in relation to revenue generated for the scenario that did not vaccinate, divided by the increase in the expenses and costs of production incurred for the farm due to adoption of IB vaccination concerning the scenario that did not vaccinate.

4.3 Findings from analyses (discussion and interpretation summary)

This study clarified the impact of IB on the Canadian poultry industry and the value of vaccinating to prevent IB as a mitigation strategy and a part of "insurance" for layer farms in Canada. I present in the following some overarching, important conclusions from this study.

4.3.1 BCA and MC simulation worked to model what I set out to model, despite dataset limitations.

I set out to model Canadian layer poultry farms in Canada and four provinces, namely AB, ON, BC, and QC. Three revenue categories, namely medium, large, and all-revenue-classes category were modelled. Multiple scenarios were set up to assess the impact of IB under a range of circumstances including potential new strains of IBV. I chose to see the impact of epidemiologic parameters of IBV (incidence, abnormal mortality, and abnormal production), vaccine parameters (adoption rate, efficacy, and costs including vaccination labor), and feed price. Assumptions were made for epidemiologic parameters of potential new strains of IBV and its impact on vaccine efficacy due to the lack of cross-protection among strains. Depending on the scenario setup, probability distribution statistics were assumed for various input variables. The impact of vaccination in each of those scenarios was assessed using benefit-cost ratios. Therefore, despite the dataset limitations such as the unavailability of comprehensive and exhaustive data on farm-level costs of production and revenues (disaggregated figures by species, farm type, and individual expenses such as feed cost, vaccine cost etc., with standard deviation and mean) of layer poultry farms in Canada and all the provinces (separately), MC simulations worked to successfully simulate the outcomes and impacts of vaccination in various scenarios set up under a range of IB infection situations, including feed price changes and new strains.

4.3.2 IB impact varies across the country, largely because of differences in the size of the industry per province.

The impact of IB on Canadian layer farms varied across the country depending on the size of the poultry industry in each province. ON and QC with a large poultry industry were the ones that usually made the largest profits in the baseline situation due to the larger size of the farms and consequently, when IB outbreaks happened, they lost the most. Even within the same province, larger farms were impacted more by IB compared to medium farms. The incidence rate of IB was the single disease parameter that had the greatest impact on profit in outbreak situations because when there is a high incidence rate of IB, the number of birds dying due to IB will be high as well as the number of affected birds by abnormal production, thereby resulting in reduced egg output and hence, reduced income for layer farms.

When new and virulent strains of IBV infected birds on their farms, producers lost more profits compared to outbreaks involving current strains because IBV strains in vaccines do not cross protect, resulting in greater losses for larger farms. When there was added effect of changes in feed price on top of IB outbreaks with new strains, the larger farms fared even worse, as the losses incurred on farms increased substantially.

4.3.3 IB vaccination seems to prevent substantial losses, but there may be more lost potential production capacity because of damage due to pre-lay IB infection.

The impact of IB vaccination appeared to be substantial in all the scenarios across the revenue categories. The vaccine adoption rate was key to the profitability of farms. BCRs of vaccination were very high for all the provinces and revenue classes but evidently, larger layer poultry farms reaped more benefits. The impact of IB vaccination only got emphasized and greater when there were potential new strains of IBV involved in outbreaks and poultry feed price fluctuation occurred. Therefore, the vaccination to prevent IB in Canadian layer poultry seemed to prevent substantial losses, but we don't know much about IBV etiology (only very recently, there have been studies that showed evidence of the extensive damage IB caused to the lymphatic system of birds, crippling their immunity (C. Faizal, personal communication, September 9, 2022). Thus, there may be more lost potential production capacity because of pre-lay damage caused by IBV when they affect the reproductive tracts of younger birds when outbreaks occur in chick and pullet stages.

4.3.4 We need to think more about an incursion of a wild type of virus or a more severe variant/strain.

There are several emerging heterologous IBV causing outbreaks in vaccinated flocks due to the lack of cross-protective immunity, resulting in significant production losses (Ignjatović & Sapats, 2000a; Awad *et al.,* 2014). There are many strains of IBV that are persistently emerging (Bande *et al.,* 2017) a study revealed evidence of recombination of at least three different IBV strains (Hassan *et al.,* 2019), and global poultry trade only engenders the risk of spread (Colvero *et al*., 2015), indicating that the likelihood of new strains either emerging or entering Canada is very high.

In summary, the findings of this study underscored the need to understand more about the impact of IB on the Canadian poultry industry, realizing how much damage it can cause. Many poultry producers routinely vaccinate, but the potential impact of new strains of IBV should be considered since new variants of IBV continue to arise due to mutation and recombination, making control strategies difficult (Cavanagh, 2007; Wood *et al.,* 2009).

We also need to think about IBV incursion from the wild, because the spread of IBV strains over the world might be attributed to other species of birds (Wit & Cook, 2019).

4.4 Implications

Transmitting the advantages and benefits of mitigation and control of IB requires a united approach and the willingness to vaccinate by Canadian layer poultry producers to benefit the whole poultry industry. In light of this, provincial and federal governments and bodies should communicate better and create awareness regarding these benefits for more producers to participate actively.

If scenario 5 is anything to go by, changes in feed cost (which will happen more often than not) can wreak havoc on the farm profitability. Welfare optimization in poultry is vital because the value contributed by the poultry industry to the GDP of Canada would be affected by IB and feed cost rise. The best approach to this issue is to vaccinate the birds, which would mitigate the damage done by an outbreak of the disease which amounts to a little over $207 billion annually and the rise in feed cost. It necessitates the support of policies (mentioned in the following paragraphs) that facilitates vaccine uptake. I find it worthy to note here that the policy recommendations and options I have presented here represent only a few among ample possibilities. Additionally, the paradoxes of policy options for any disease control are the need to consider the support for producers from the market vulnerabilities and meet the targeted objectives of policy decisions.

A simulation-modelling method can preclude the need for expensive surveys designed to capture the farm cost and revenue structure for the estimation of the impact of various diseases and interventions on farms.

4.5 Important policy recommendations and policy options

The continued approach of vaccinating against IB as a form of insurance looks very promising, as the models in this study showed. However, layer poultry producers and the broader poultry industry, in general, need to understand the threat posed by new strains of IBV and the benefits of a more active approach to vaccination against IB and objectives to mitigate its impact. Layer producers opting to continue vaccinating routinely against IB may realize financial benefits at the farm level.

As much as it has benefits, Canada's supply management has downsides, which encumber unhindered growth of the poultry industry and trade market dynamics. If the profit margin changes due to a free market, layer and other poultry producers would compete among themselves, and there will be more open trade (import and export) of poultry and egg products, trade partners would demand low-risk products (low risk of IB), and producers would need to level up their vaccination plans.

Scenarios 4 and 5 outline the potential hazards of new strains of IBV and how it would spell disaster if vaccination were not done. Academia and vaccine producers would work on developing new vaccines that would either incorporate or provide cross-protection to new strains. Futhermore, the communication among poultry producers and other stakeholders, vis-a-vis benefits of vaccinating to both individual farm as well as the poultry industry, is highly recommended in order to upscale awareness of IB, the threat of new IBV, and pathways to mitigate it so that the producers and the industry stay profitable and globally competitive.

4.6 Limitations

The data used were from secondary sources, and inconsistencies in data from various sources may have skewed the results. Generalization of the findings to other countries is possible, but factors specific to the location need to be considered, especially similar systems of production and market dynamics.

A limitation of this study is that BCR reduces ventures into a simple number when its success or failure may depend on multiple factors and unforeseen events that are not accounted for. Following the rule of thumb that a BCR greater than one indicates desirable and less than one indicates undesirable would be misleading and may give the wrong picture if we do not assess and analyze the input variables that influence the BCRs (Campbell & Brown, 2015). Therefore, BCRs must be used as a tool in conjunction with other analytical parameters such as NPV, PV, IRR, and cash flow statements to arrive at a well-informed decision.

Despite these limitations, this study contributes a substantially more profound understanding of the impact of IB on layer producers individually and the Canadian poultry industry in general. Moreover, it also gives insight into how new strains of IB and changes in feed cost may impact the profitability of layer farms. These findings are expected to influence producers' decisions on adopting (if not already) IB vaccines and adhering to regulatory control strategies and frameworks.

4.7 Future directions

Although this study has resolved some gaps in the literature in terms of estimating the impact of IB on the Canadian poultry industry and the value of vaccinating as an important mitigation strategy, some questions have arisen right along that need further research.

Layer producers opting to continue vaccinating routinely against IB may realize financial benefits at the farm level. However, it needs to be seen if all producers would receive a more active IB control campaign well, especially when there is no immediate need or benefit.

Having understood the risk of potential losses that individual farms would incur in the event of an outbreak and that the actual vaccine prices are minimal in comparison with other operating expenses, it would be of value to study the attitude and behaviour of Canadian layer poultry producers for uptake of IB vaccines that are currently in the market and which combination of IBV strains in vaccine they prefer.

Given the possibility that new strains of IBV may disrupt the whole poultry industry, not to mention substantial losses to individual producers, it would be of great value to study the attitude of Canadian layer poultry producers to adopt new vaccines that incorporate newer strains of IBV with higher efficacy for improved protection of birds. It would help understand whether aversion to adopting vaccines is due to a lack of willingness to adopt biotechnologies in the form of vaccines or relates to other beliefs and choices. In addition, understanding the beliefs, preferences, and choices of layer producers about IB would offer important insight into this matter.

It would be of value to perform a knowledge, attitudes, and practices study of Canadian layer producers on IB, IB vaccines, and associated control and mitigating strategies as a cross-sectional study. There are differences in prevalence rates of IB in broiler and layer poultry (Yilmaz *et al.,* 2016), suggesting that attitudes of broiler and layer poultry producers to vaccines and IB control strategies could be different. Therefore, it would be of value to study the knowledge, attitudes, and practices of Canadian broiler poultry producers compared to layer poultry producers.

A survey of Canadian poultry producers to capture revenues, expenses, and income comprehensively to get accurate data on costs of production and revenues generated would be of high value as it would make such simulation studies more robust.

Last but not least, a comprehensive survey to capture attitudes, preferences, and perceptions of consumers toward public health concerns regarding poultry and egg products in Canada would be invaluable in understanding current market demands and their impact on the behaviour of producers to control IB on their farms.

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5. References

Agriculture and Agri-Food Canada. (2020). Investment behavior of Canadian Egg Producers: Analyzing the Impacts of Risk Aversion and Variability of Prices and Costs of Production - ProQuest. https://search-proquest-com.ezproxy.lib.ucalgary.ca/docview/1698743546?accountid=9838&rfr_id=info%3Axri%2Fsid%3Aprimo

Akaike, H. (1998). Information Theory and an Extension of the Maximum Likelihood Principle. In E. Parzen, K. Tanabe, & G. Kitagawa (Eds.), Selected Papers of Hirotugu Akaike (pp. 199–213). Springer. https://doi.org/10.1007/978-1-4612-1694-0_15

Ali, A., Kilany, W. H., Zain El-Abideen, M. A., Sayed, M. E., & Elkady, M. (2018). Safety and efficacy of attenuated classic and variant 2 infectious bronchitis virus candidate vaccines. Poultry Science, 97(12), 4238–4244. https://doi.org/10.3382/ps/pey312

Allen, R. G. D., & Bowley, A. L. (1935). Family expenditure; a study of its variation,. P.S. King.

Amarasinghe, A., De Silva Senapathi, U., Abdul-Cader, M. S., Popowich, S., Marshall, F., Cork, S. C., van der Meer, F., Gomis, S., & Abdul-Careem, M. F. (2018). Comparative features of infections of two Massachusetts (Mass) infectious bronchitis virus (IBV) variants isolated from Western Canadian layer flocks. https://doi.org/10.1186/s12917-018-1720-9

Anderson, T. W., & Darling, D. A. (1952). Asymptotic Theory of Certain "Goodness of Fit" Criteria Based on Stochastic Processes. The Annals of Mathematical Statistics, 23(2), 193–212. http://www.jstor.org/stable/2236446

Andrew, R., Makindara, J., Mbaga, S. H., & Alphonce, R. (2019). Economic viability of newly introduced chicken strains at village level in Tanzania: FARMSIM model simulation approach. Agricultural Systems, 176, 102655. https://doi.org/10.1016/j.agsy.2019.102655

Anonymous, BCA history. (n.d.).

Ariaans, M. P., Matthijs, M. G. R., van Haarlem, D., van de Haar, P., van Eck, J. H. H., Hensen, E. J., & Vervelde, L. (2008). The role of phagocytic cells in enhanced susceptibility of broilers to colibacillosis after Infectious Bronchitis Virus infection. Veterinary Immunology and Immunopathology, 123(3), 240–250. https://doi.org/10.1016/j.vetimm.2008.02.003

AWAD, F., CHHABRA, R., BAYLIS, M., & GANAPATHY, K. (2014). An overview of infectious bronchitis virus in chickens. World's Poultry Science Journal, 70(2), 375–384. https://doi.org/10.1017/S0043933914000385

Bagust, T. J. (2013). Poultry health and disease control in developing countries. 1.

Bande, F., Arshad, S. S., Hair Bejo, M., Moeini, H., & Omar, A. R. (2015a). Progress and challenges toward the development of vaccines against avian infectious bronchitis. In Journal of Immunology Research. https://doi.org/10.1155/2015/424860

Bande, F., Arshad, S. S., Hair Bejo, M., Moeini, H., & Omar, A. R. (2015b). Progress and Challenges toward the Development of Vaccines against Avian Infectious Bronchitis. Journal of Immunology Research, 2015, 424860–12. https://doi.org/10.1155/2015/424860

Bande, F., Arshad, S. S., Omar, A. R., Bejo, M. H., Abubakar, M. S., & Abba, Y. (2016). Pathogenesis and Diagnostic Approaches of Avian Infectious Bronchitis. Advances in Virology, 2016, 1–11. https://doi.org/10.1155/2016/4621659

Bande, F., Arshad, S. S., Omar, A. R., Hair-Bejo, M., Mahmuda, A., & Nair, V. (2017). Global distributions and strain diversity of avian infectious bronchitis virus: A review. Animal Health Research Reviews, 18(1), 70–83. https://doi.org/10.1017/S1466252317000044

Benyeda, Z., Mató, T., Süveges, T., Szabó, É., Kardi, V., Abonyi-Tóth, Z., Rusvai, M., & Palya, V. (2009). Comparison of the pathogenicity of QX-like, M41 and 793/B infectious bronchitis strains from different pathological conditions. Avian Pathology, 38(6), 449–456. https://doi.org/10.1080/03079450903349196

Berentsen, P. B. M., Dijkhuizen, A. A., & Oskam, A. J. (1992). A dynamic model for cost-benefit analyses of foot-and-mouth disease control strategies. Preventive Veterinary Medicine, 12(3), 229–243. https://doi.org/10.1016/0167-5877(92)90052-H

Bijlenga, G., Cook, J. K. A., Gelb, Jr, J., & Wit, J. J. de. (2004). Development and use of the H strain of avian infectious bronchitis virus from the Netherlands as a vaccine: A review.

Avian Pathology, 33(6), 550–557. https://doi.org/10.1080/03079450400013154

Branch, G. of C. and A.-F. C. and I. S. (2008, December 10). Agricultural Industry Market Information System (AIMIS). https://aimis-simia.agr.gc.ca/rp/index-eng.cfm?action=pR&R=23&E=2&PDCTC=#clfinput_err

Brewer, A. (2010). The Making of the Classical Theory of Economic Growth. Taylor & Francis.

Buy Spreadsheet Software—Try Excel Free | Microsoft Excel. (n.d.). Retrieved November 8, 2021, from https://www.microsoft.com/en-ca/microsoft-365/excel

Campbell, H. F., & Brown, R. P. C. (2003). Benefit-cost analysis: Financial and economic appraisal using spreadsheets. In Benefit-Cost Analysis: Financial and Economic Appraisal Using Spreadsheets. https://doi.org/10.1017/CBO9780511791291

Campbell, H. F., & Brown, R. P. C. (2015). Cost-Benefit Analysis: Financial And Economic Appraisal Using Spreadsheets. Routledge.

Canada, F. C. C.-F. agricole. (n.d.). Market Prices | FCC. Retrieved November 17, 2021, from https://www.fcc-fac.ca/en/resources/market-prices.html

Cardwell, R., Lawley, C., & Xiang, D. (2015). Milked and Feathered: The Regressive Welfare Effects of Canada's Supply Management Regime. Canadian Public Policy, 41(1), 1–14. https://doi.org/10.3138/cpp.2013-062

Carlson, G. A., Zilberman, D., & Miranowski, J. A. (1993). Agricultural and environmental resource economics. Oxford University Press, New York : Oxford University Press.

Carlsson, P., Ygge, F., & Andersson, A. (2001). Extending equilibrium markets. IEEE Intell. Syst. IEEE Intelligent Systems, 16(4), 18–26.

Cavanagh, D. (2005). Coronaviruses in poultry and other birds. Avian Pathology: Journal of the W.V.P.A, 34(6), 439–448. https://doi.org/10.1080/03079450500367682

Cavanagh, D. (2007). Coronavirus avian infectious bronchitis virus. In Veterinary Research. https://doi.org/10.1051/vetres:2006055

Cavanagh, D., & Gelb, J. (2008). Infectious Bronchitis.

Cavanagh, D., Mawditt, K., Welchman, D. de B., Britton, P., & Gough, R. E. (2002). Coronaviruses from pheasants (Phasianus colchicus) are genetically closely related to coronaviruses of domestic fowl (infectious bronchitis virus) and turkeys. Avian Pathology, 31(1), 81–93. https://doi.org/10.1080/03079450120106651

CDC. (1975). TEM of IBV. https://phil.cdc.gov/Details.aspx?pid=15523

Ceriani, L., & Verme, P. (2012). The origins of the Gini index: Extracts from Variabilità e Mutabilità (1912) by Corrado Gini. The Journal of Economic Inequality, 10(3), 421–443. https://doi.org/10.1007/s10888-011-9188-x

Chan, H. P., & Walther, G. (2014). Detection with the scan and the average likelihood ratio. ArXiv:1107.4344 [Stat]. http://arxiv.org/abs/1107.4344

Chicken Farmers of Canada. (2013, November 14). How does it work|Chicken Farmers of Canada. https://www.chickenfarmers.ca/how-does-it-work/

Circella, E., Camarda, A., Martella, V., Bruni, G., Lavazza, A., & Buonavoglia, C. (2007). Coronavirus associated with an enteric syndrome on a quail farm. Avian Pathology, 36(3), 251–258. https://doi.org/10.1080/03079450701344738

Clemen, R. T. (2014). Making hard decisions with DecisionTools. South-Western, Cengage Learning, Mason, OH, USA : South-Western, Cengage Learning; 3rd ed/ Robert TClemen, Terence Reilly ; with contributions by Samuel EBodily and Jeffrey Guyse ; and cases by Samuel EBodily et al.

Cochran, W. G. (1952). The $\chi 2$ Test of Goodness of Fit. The Annals of Mathematical Statistics, 23(3), 315–345. http://www.jstor.org/stable/2236678

Colvero, L. P., Villarreal, L. Y. B., Torres, C. A., & Brandão, P. E. (2015). Assessing the economic burden of avian infectious bronchitis on poultry farms in Brazil. OIE Revue Scientifique et Technique, 34(3), 993–999. https://doi.org/10.20506/rst.34.3.2411

Cook, J. K. A., Chesher, J., Baxendale, W., Greenwood, N., Huggins, M. B., & Orbell, S. J. (2001). Protection of chickens against renal damage caused by a nephropathogenic infectious bronchitis virus. Avian Pathology. https://doi.org/10.1080/03079450120066421

Cook, J. K. A., Jackwood, M., & Jones, R. C. (2012). The long view: 40 years of infectious bronchitis research. Avian Pathology, 41(3), 239–250. https://doi.org/10.1080/03079457.2012.680432

Cost-benefit analysis: Concepts and practice. (n.d.). Retrieved November 26, 2021, from http://scholar.google.com/citations?view_op=view_citation&hl=en&user=FzPD2YQAAAAJ&citation_for_view=FzPD2YQAAAAJ:u5HHmVD_uO8C

Crinion, R. A. P. (1972). Pathogenicity of four serotypes of avian infectious bronchitis virus for the oviduct of chickens. 103.

Davis, H. S. (2016). Productivity Accounting. In Productivity Accounting. University of Pennsylvania Press. https://doi.org/10.9783/9781512815450

De Jong, M. C., & Kimman, T. G. (1994). Experimental quantification of vaccine-induced reduction in virus transmission. Vaccine, 12(8), 761–766. https://doi.org/10.1016/0264-410X(94)90229-1

de Wit, J. J., de Jong, M. C. M., Pijpers, A., & Verheijden, J. H. M. (1998). Transmission of infectious bronchitis virus within vaccinated and unvaccinated groups of chickens. Avian

Pathology, 27(5), 464–471. https://doi.org/10.1080/03079459808419370

de Wit, J. J., Dijkman, R., Guerrero, P., Calvo, J., Gonzalez, A., & Hidalgo, H. (2017). Variability in biological behaviour, pathogenicity, protectotype and induction of virus neutralizing antibodies by different vaccination programmes to infectious bronchitis virus genotype Q1 strains from Chile. Avian Pathology: Journal of the W.V.P.A, 46(6), 666–675. https://doi.org/10.1080/03079457.2017.1346782

de Wit, J. J. S., Cook, J. K. A., & van der Heijden, H. M. J. F. (2011). Infectious bronchitis virus variants: A review of the history, current situation and control measures. In Avian Pathology. https://doi.org/10.1080/03079457.2011.566260

de Wit, J. J. (Sjaak), & Cook, J. K. A. (2019). Spotlight on avian pathology: Infectious bronchitis virus. In Avian Pathology. https://doi.org/10.1080/03079457.2019.1617400

De Wit, J. J., Swart, W. A. J. M., & Fabri, T. H. F. (2010). Efficacy of infectious bronchitis virus vaccinations in the field: Association between the α-IBV IgM response, protection and vaccine application parameters. Avian Pathology, 39(2), 123–131. https://doi.org/10.1080/03079451003604639

Dec-2016-OAHN-special-report-on-IBV-FINAL.pdf. (n.d.). Retrieved June 28, 2021, from https://www.oahn.ca/wp-content/uploads/2016/12/Dec-2016-OAHN-special-report-on-IBV-FINAL.pdf

Derksen, T., Lampron, R., Hauck, R., Pitesky, M., & Gallardo, R. A. (2018). Biosecurity Assessment and Seroprevalence of Respiratory Diseases in Backyard Poultry Flocks Located Close to and Far from Commercial Premises. Avian Diseases, 62(1), 1–5. https://doi.org/10.1637/11672-050917-Reg.1

Dijkhuizen, A. A. (1989). Epidemiological and economic simulation of Foot-and-Mouth disease control strategies in The Netherlands. Netherlands Journal of Agricultural Science, 37, 1–12. https://www.narcis.nl/publication/RecordID/oai:library.wur.nl:wurpubs%2F8219

Dijkhuizen.pdf. (n.d.).

Dohoo, I. R., Martin, W., & Stryhn, H. E. (2003). Veterinary epidemiologic research | Island Scholar. https://www.islandscholar.ca/islandora/object/ir:ir-batch6-2657

Dorfman, R. (1979). A Formula for the Gini Coefficient. The Review of Economics and Statistics, 61(1), 146–149. https://doi.org/10.2307/1924845

Dupuit, J. (1844). Annales des ponts et chaussées: Partie technique. Mémoires et documents relatifs à l'art des constructions et au service de l'ingenieur. 1. partie. V.C. Dunod.

Evans report. (2009). Principles and Guidelines for Evaluating Federal Water Projects. 99.

Evans, S. M. (2019). Hutterite agriculture in Alberta: The contribution of an ethnic isolate. Agricultural History, 93(4), 656–681. http://www.cabdirect.org/cabdirect/abstract/20203081554

Fadly, A. M., Glisson, J. R., McDougald, L. R., Nolan, L. K., & Swayne, D. E. (2009). Diseases of Poultry. John Wiley & Sons.

Faizal, C. (2022, September 9). Personal Communication [Personal communication].

Fischer, R. A. (1974). The design of experiments. Hafner.

Frey, S. C., & Pfeifer, P. E. (2013). With contributions by Samuel E. Bodily and Jeffery Guyse and. 51.

Gallardo, R. A., Hoerr, A. F. J., & Berry, B. W. D. (n.d.). Infectious Bronchitis Virus in Testicles and Venereal Transmission. 5.

Gallardo, R. A., Santen, V. L. van, & Toro, H. (2012). Effects of chicken anaemia virus and infectious bursal disease virus-induced immunodeficiency on infectious bronchitis virus replication and genotypic drift. Avian Pathology, 41(5), 451–458. https://doi.org/10.1080/03079457.2012.702889

Ganapathy, K. (2009). Diagnosis of infectious bronchitis in chickens. In Practice, 31(9), 424–431. https://doi.org/10.1136/inpract.31.9.424

Gini, C. (1912). Variabilit?? E mutabilit??; contributo allo studio delle distribuzioni e delle relazioni statistiche. [Fasc. I. Tipogr. di P. Cuppini.

Government of Canada, C. F. I. A. (2014, May 19). Annex C - Producer Self-Quarantine Protocol—General Producer Guide—National Avian On-Farm Biosecurity Standard [Reference material]. https://inspection.canada.ca/animal-health/terrestrial-animals/biosecurity/standards-and-principles/general-producer-guide/eng/1398640321596/1398640379048?chap=10

Government of Canada, S. C. (2016, January 26). Employee wages by occupation, annual, inactive. https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=1410030701

Government of Canada, S. C. (2018a, April 26). Production of table eggs by census division (CD), 2015. https://www150.statcan.gc.ca/n1/pub/95-634-x/2017001/article/54906/catm-ctra-303-eng.htm

Government of Canada, S. C. (2018b, November 27). Number of farms classified by farm type and household income classCorrection. https://www150.statcan.gc.ca/n1/en/catalogue/32100030

Government of Canada, S. C. (2021a, March 26). Farm operating revenues and expenses, annual. https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3210013601

Government of Canada, S. C. (2021b, May 27). Production and disposition of eggs, annual. https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3210011901

Government of Canada, S. C. (2021c, May 27). Production, disposition and farm value of poultry meat. https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3210011701

Green, R. A. (1962). Why is the Modern Poultry Farmer a Sitting Duck? The Canadian Veterinary Journal, 3(8), 257–259. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1585915/

Greene, W. W. H. . (2005). Econometric analysis: Fifth Edition—Chapter 21—Discrete Choice.

Haan, C. A. M. de, Vennema, H., & Rottier, P. J. M. (2000). Assembly of the Coronavirus Envelope: Homotypic Interactions between the M Proteins. Journal of Virology, 74(11), 4967–4978. https://doi.org/10.1128/JVI.74.11.4967-4978.2000

Harrison, R. L. (2010). Introduction To Monte Carlo Simulation. AIP Conference Proceedings, 1204, 17–21. https://doi.org/10.1063/1.3295638

Hassan, M. S. H., Ali, A., Buharideen, S. M., Goldsmith, D., Coffin, C. S., Cork, S. C., van der Meer, F., Boulianne, M., & Abdul-Careem, M. F. (2021). Pathogenicity of the Canadian Delmarva (DMV/1639) Infectious Bronchitis Virus (IBV) on Female Reproductive Tract of Chickens. Viruses, 13(12), 2488. https://doi.org/10.3390/v13122488

Hassan, M. S. H., Ojkic, D., Coffn, C. S., Cork, S. C., Meer, F. V. D., & Abdul-Careem, M. F. (2019). Delmarva (dmv/1639) infectious bronchitis virus (ibv) variants isolated in eastern Canada show evidence of recombination. Viruses, 11(11). https://doi.org/10.3390/v11111054

Hausman, J. A., & Wise, D. A. (1978). A Conditional Probit Model for Qualitative Choice: Discrete Decisions Recognizing Interdependence and Heterogeneous Preferences (No. 2; Vol. 46, pp. 403–426).

Heady, E. O., Reynolds, T. M., & Mitchell, D. O. (1978). An Econometric Simulation Model of the US Farm Sector and Its Policies and Food Exports. Vandenhoeck und Ruprecht.

Hicks, J. R. (1939). The Foundations of Welfare Economics. The Economic Journal, 49(196), 696–712. https://doi.org/10.2307/2225023

Hyde, J., & Engel, P. (2002). Investing in a robotic milking system: A Monte Carlo simulation analysis. Journal of Dairy Science. https://doi.org/10.3168/JDS.S0022-0302(02)74300-2

IADB. (n.d.). Time Goes By: Recent Developments on the Theory and Practice of the Discount Rate | Publications. Retrieved November 27, 2021, from https://publications.iadb.org/publications/english/document/Time-Goes-By-Recent-Developments-on-the-Theory-and-Practice-of-the-Discount-Rate.pdf

Ignjatović, J., & Sapats, S. (2000a). Avian infectious bronchitis virus. OIE Revue Scientifique et Technique, 19(2), 493–508. https://doi.org/10.20506/rst.19.2.1228

Ignjatović, J., & Sapats, S. (2000b). Avian infectious bronchitis virus. OIE Revue Scientifique et Technique, 19(2), 493–508. https://doi.org/10.20506/rst.19.2.1228

Ignjatović, J., & Sapats, S. (2000c). Avian infectious bronchitis virus. Revue Scientifique Et Technique (International Office of Epizootics), 19(2), 493–508. https://doi.org/10.20506/rst.19.2.1228

Ike, A. C., Ononugbo, C. M., Obi, O. J., Onu, C. J., Olovo, C. V., Muo, S. O., Chukwu, O. S., Reward, E. E., & Omeke, O. P. (2021). Towards Improved Use of Vaccination in the Control of Infectious Bronchitis and Newcastle Disease in Poultry: Understanding the Immunological Mechanisms. Vaccines, 9(1), 20. https://doi.org/10.3390/vaccines9010020

Inglis (2018) Ask the Vet—Live vaccines multi-age poultry farms—Cdn Poultry Mag.pdf. (n.d.).

Jackwood, M., & Sjaak de Wit. (2013). Infectious Bronchitis.

http://onlinelibrary.wiley.com/doi/chapter-epub/10.1002/9781119421481.ch4

Jackwood, M. W. (2012a). Review of Infectious Bronchitis Virus Around the World. Avian Diseases, 56(4), 634–641. https://doi.org/10.1637/10227-043012-review.1

Jackwood, M. W. (2012b). Review of Infectious Bronchitis Virus Around the World. Avian Diseases, 56(4), 634–641. https://doi.org/10.1637/10227-043012-review.1

Jackwood, M. W. (2012c). Review of infectious bronchitis virus around the world. Avian Diseases, 56(4), 634–641. https://doi.org/10.1637/10227-043012-Review.1

Jackwood, M. W., & de Wit, S. (2017). Infectious Bronchitis. In Diseases of Poultry: Thirteenth Edition. https://doi.org/10.1002/9781119421481.ch4

Jackwood, M. W., Hall, D., & Handel, A. (2012). Molecular evolution and emergence of avian gammacoronaviruses. Infection, Genetics and Evolution, 12(6), 1305–1311. https://doi.org/10.1016/j.meegid.2012.05.003

Jackwood, M. W., Hilt, D. A., Sellers, H. S., Williams, S. M., & Lasher, H. N. (2010). Rapid heat-treatment attenuation of infectious bronchitis virus. Avian Pathology, 39(3), 227–233. https://doi.org/10.1080/03079451003801516

Jackwood, M. W., & Lee, D. H. (2017). Different evolutionary trajectories of vaccinecontrolled and non-controlled avian infectious bronchitis viruses in commercial poultry. PLoS ONE, 12(5). https://doi.org/10.1371/journal.pone.0176709

Johansson, P.-O. (1991). An Introduction to Modern Welfare Economics. Cambridge University Press.

Johnson, M. A., Pooley, C., Ignjatovic, J., & Tyack, S. G. (2003). A recombinant fowl adenovirus expressing the S1 gene of infectious bronchitis virus protects against challenge with infectious bronchitis virus. Vaccine, 21(21), 2730–2736.

https://doi.org/10.1016/S0264-410X(03)00227-5

Jonassen, C. M., Kofstad, T., Larsen, I.-L., Løvland, A., Handeland, K., Follestad, A., & Lillehaug, A. (2005). Molecular identification and characterization of novel coronaviruses infecting graylag geese (Anser anser), feral pigeons (Columbia livia) and mallards (Anas platyrhynchos). Journal of General Virology, 86(6), 1597–1607. https://doi.org/10.1099/vir.0.80927-0

Jones, R. C. (2010). Viral respiratory diseases (ILT, aMPV infections, IB): Are they ever under control? British Poultry Science, 51(1), 1–11. https://doi.org/10.1080/00071660903541378

Jong, M. de (Centraal D. I., & Diekmann, O. (1992). A method to calculate—For computer-simulated infections—The threshold value, R(0), that predicts whether or not the infection will spread. Preventive Veterinary Medicine, 12(3–4).

Jordan, B. (2017). Vaccination against infectious bronchitis virus: A continuous challenge. Veterinary Microbiology, 206, 137–143. https://doi.org/10.1016/j.vetmic.2017.01.002

Kaldor, N. (1939). Welfare Propositions of Economics and Interpersonal Comparisons of Utility. The Economic Journal, 49(195), 549–552. https://doi.org/10.2307/2224835

Karki, S., Karki, S., Lupiani, B., Lupiani, B., Budke, C. M., Budke, C. M., Karki, N. P. S., Karki, N. P. S., Rushton, J., Rushton, J., Ivanek, R., & Ivanek, R. (2015). Cost-benefit analysis of avian influenza control in Nepal. Revue Scientifique et Technique (International Office of Epizootics), 34(3), 813–827. https://doi.org/10.20506/rst.34.3.2397

Kolmogorov–Smirnov test. (2021). In Wikipedia. https://en.wikipedia.org/w/index.php?title=Kolmogorov%E2%80%93Smirnov_test&oldid=1051865496

Kolmogorov–Smirnov test. (2022). In Wikipedia. https://en.wikipedia.org/w/index.php?title=Kolmogorov%E2%80%93Smirnov_test&oldid=1092451253

Korn, R., Korn, E., & Kroisandt, G. (2010). Monte Carlo methods and models in finance and insurance. In Chapman & Hall/CRC Financial Mathematics Series. CRC Press. https://doi.org/10.1201/9781420076196

Kovacs, S., Ertsey, I., & Balogh, P. (2007). Monte Carlo simulation of technological risks in chicken production in a Bayesian approach. Scientific Papers Animal Science and Biotechnologies, 40(2), 273–278.

KUSNAMAN, D., DJUHARYANTO, T., & SUMANTO, B. (2018). Profit Volatility of Small Laying Hens Poultry Farm and Rice Farming Relation to Capital Productivity. Journal of Applied Economic Sciences, 13(3).

Lai, M. M., & Cavanagh, D. (1997). The molecular biology of coronaviruses. Advances in Virus Research, 48, 1–100.

Landman, W. J. M., & van Eck, J. H. H. (2015). The incidence and economic impact of the Escherichia coli peritonitis syndrome in Dutch poultry farming. Avian Pathology, 44(5), 370–378. https://doi.org/10.1080/03079457.2015.1060584

Lapar, L. A., Nuryartono, N., Toan, N. N., Rafani, I., Bett, B., McLaws, M., Unger, F., Schoonmann, L., Jost, C., & Mariner, J. (2011, October 13). Are smallholders willing to pay for animal disease control? Empirical evidence from a study of mass vaccination for Avian Influenza in Indonesia (No. 2232-2019–2473). AgEcon Search. https://doi.org/10.22004/ag.econ.290627

Law, A. M., Kelton, W. D., & Kelton, W. D. (2000). Simulation modeling and analysis (Vol. 3).

McGraw-Hill New York.

Learn How to Create a Monte Carlo Simulation Using Excel. (n.d.). Investopedia. Retrieved September 19, 2021, from https://www.investopedia.com/articles/investing/093015/create-monte-carlo-simulation-using-excel.asp

Leinonen, I., Williams, A. G., Wiseman, J., Guy, J., & Kyriazakis, I. (2012). Predicting the environmental impacts of chicken systems in the United Kingdom through a life cycle assessment: Egg production systems. Poultry Science, 91(1), 26–40. https://doi.org/10.3382/ps.2011-01635

Maples, J. G., Thompson, J. M., Anderson, J. D., & Anderson, D. P. (2020). Estimating COVID-19 Impacts on the Broiler Industry. Applied Economic Perspectives and Policy, n/a(n/a). https://doi.org/10.1002/aepp.13089

Marangon, S., & Busani, L. (n.d.). The use of vaccination in poultry production. 10.

Martin, E. A. K., Brash, M. L., Hoyland, S. K., Coventry, J. M., Sandrock, C., Guerin, M. T., & Ojkic, D. (2014). Genotyping of infectious bronchitis viruses identified in Canada between 2000 and 2013. Avian Pathology, 43(3), 264–268. https://doi.org/10.1080/03079457.2014.916395

Martinelli, G., Vogel, E., Decian, M., Farinha, M. J. U. S., Bernardo, L. V. M., Borges, J. A. R., Gimenes, R. M. T., Garcia, R. G., & Ruviaro, C. F. (2020). Assessing the eco-efficiency of different poultry production systems: An approach using life cycle assessment and economic value added. Sustainable Production and Consumption, 24, 181–193. https://doi.org/10.1016/j.spc.2020.07.007

Marwala, T., Boulkaibet, I., & Adhikari, S. (2016). Probabilistic Finite Element Model Updating

Using Bayesian Statistics: Applications to Aeronautical and Mechanical Engineering. John Wiley & Sons, Incorporated. http://ebookcentral.proquest.com/lib/ucalgary-ebooks/detail.action?docID=4696763

Mas-Colell, A., Whinston, M. D., & Green, J. R. (1995). Microeconomic theory.

Mbaga, M. D. (1994). Supply management in the Manitoba egg industry: Performance and implications of trade liberalization. National Library of Canada = Bibliothèque nationale du Canada.

McConnell, C. (2021). Identifying, Protecting and Managing Stopover Habitats for Wild Whooping Cranes on U.S. Army Corps of Engineers Lakes (p. 2020.12.30.424870). https://doi.org/10.1101/2020.12.30.424870

Meeusen, E. N. T., Walker, J., Peters, A., Pastoret, P.-P., & Jungersen, G. (2007). Current Status of Veterinary Vaccines. Clinical Microbiology Reviews, 20(3), 489–510. https://doi.org/10.1128/CMR.00005-07

Mooney, C. (1997). Monte Carlo Simulation. SAGE Publications, Inc. https://doi.org/10.4135/9781412985116

National Farm Animal Care Council—Poultry Code of Practice. (2021). https://www.nfacc.ca/poultry-code-of-practice#section5

Ontario. (2021). https://www.ontario.ca/page/about-ontario

O'Sullivan, A., Sheffrin, S. M., Prentice-Hall, inc, & Wall Street Journal (Firm). (2003). Economics: Principles in action. Needham, Mass. : Prentice Hall. http://archive.org/details/economicsprincip00osul

Palisade. (2018). @RISK: Risk Analysis using Monte Carlo Simulation in Excel and Project. Palisade. https://www.palisade.com/risk/default.asp

Palisade. (2021). How @RISK Correlates Inputs—Palisade Knowledge Base. https://kb.palisade.com/index.php?pg=kb.page&id=71

Pareto, V. (1896). Cours d’économie politique: Professé à l’Universi̧té de Lausanne. F. Rouge.

Partial Budgeting. (n.d.). Penn State Extension. Retrieved November 22, 2021, from https://extension.psu.edu/partial-budgeting

Penson, J. B., Jr, O. C., III, C. P. R., & Woodward, R. T. (2017). Introduction to Agricultural Economics. Pearson Education.

Pereira, C. G., Saraiva, G. L., Vidigal, P. M. P., Fietto, J. L. R., Bressan, G. C., Moreira, M. A. S., de Almeida, M. R., & Júnior, A. S. (2016). Distribution of infectious bronchitis virus strains in different organs and evidence of vertical transmission in natural infection. Archives of Virology, 161(12), 3355–3363. https://doi.org/10.1007/s00705-016-3030-5

Persky, J. (1992). Retrospectives: Pareto’s Law. Journal of Economic Perspectives, 6(2), 181–192. https://doi.org/10.1257/jep.6.2.181

Persky, J. (2001). Retrospectives: Cost-Benefit Analysis and the Classical Creed. Journal of Economic Perspectives, 15(4), 199–208. https://doi.org/10.1257/jep.15.4.199

Petty, W. (1662). A Treatise of Taxes & Contributions. 61.

Pindyck, R. S., & Rubinfeld, D. L. (2013). Microeconomics. Pearson.

Poultry Health Management for Commercial Poultry. (n.d.). Canadian Poultry Consultants Ltd. Retrieved July 22, 2020, from https://canadianpoultry.ca/lifestyle/poultry-health-management-for-commercial-poultry/

Poultry Health Management for Commercial Poultry—Canadian Poultry Consultants Ltd_.pdf. (n.d.).

Purswell, J. L., Branton, S. L., & Evans, J. D. (2019). Performance of an automated whole-house spray vaccination system. Journal of Applied Poultry Research, 28(1), 215–220. https://doi.org/10.3382/japr/pfy060

Purwaningsih, R., Arief, M., Handayani, N. U., Rahmawati, D., & Mustikasari, A. (2018). Market risk assessment on poultry industry using Monte Carlo simulation. IOP Conference Series: Materials Science and Engineering, 403, 012044. https://doi.org/10.1088/1757-899X/403/1/012044

Rashid, M., Akbar, H., Bakhsh, A., Rashid, M. I., Hassan, M. A., Ullah, R., Hussain, T., Manzoor, S., & Yin, H. (2019). Assessing the prevalence and economic significance of coccidiosis individually and in combination with concurrent infections in Pakistani commercial poultry farms. Poultry Science, 98(3), 1167–1175. https://doi.org/10.3382/ps/pey522

Rasmussen, P., Barkema, H. W., Mason, S., Beaulieu, E., & Hall, D. C. (2021). Economic losses due to Johne’s disease (paratuberculosis) in dairy cattle. Journal of Dairy Science, 104(3), 3123–3143. https://doi.org/10.3168/jds.2020-19381

Richard M. Fulton. (2017). Causes of Normal Mortality in Commercial Egg-Laying Chickens. Avian Diseases, 61(3), 289–295. https://doi.org/10.1637/11556-120816-RegR

Richardson, J. W., Klose, S. L., & Gray, A. W. (2000). An Applied Procedure for Estimating and Simulating Multivariate Empirical (MVE) Probability Distributions In Farm-Level Risk Assessment and Policy Analysis. Journal of Agricultural and Applied Economics, 32(2), 299–315. https://doi.org/10.1017/S107407080002037X

Rivera, C., & Walther, G. (2013). Optimal detection of a jump in the intensity of a Poisson process or in a density with likelihood ratio statistics. Scandinavian Journal of Statistics, 40(4), 752–769. https://doi.org/10.1111/sjos.12027

Roskam, J. L., Lansink, A. G. J. M. O., & Saatkamp, H. W. (2019). The technical and economic impact of veterinary interventions aimed at reducing antimicrobial use on broiler farms. Poultry Science, 98(12), 6644–6658. https://doi.org/10.3382/ps/pez517

Saatkamp, H. W., Berentsen, P. B. M., & Horst, H. S. (2000). Economic aspects of the control of classical swine fever outbreaks in the European Union. Veterinary Microbiology, 73(2–3), 221–237. https://doi.org/10.1016/S0378-1135(00)00147-4

Sakomura, N. K., Reis, M. D. P., Ferreira, N. T., & Gous, R. M. (2019). Modeling egg production as a means of optimizing dietary nutrient contents for laying hens. Animal Frontiers, 9(2), 45–51. https://doi.org/10.1093/af/vfz010

Sanei (2018) Utilizing vaccines to reduce antimicrobial use—Cdn Poultry Mag.pdf. (n.d.).

Shahwan, K., Hesse, M., Mork, A.-K., Herrler, G., & Winter, C. (2013). Sialic Acid Binding Properties of Soluble Coronavirus Spike (S1) Proteins: Differences between Infectious Bronchitis Virus and Transmissible Gastroenteritis Virus. Viruses, 5(8), 1924–1933. https://doi.org/10.3390/v5081924

Smith, J., Sadeyen, J. R., Cavanagh, D., Kaiser, P., & Burt, D. W. (2015a). The early immune response to infection of chickens with Infectious Bronchitis Virus (IBV) in susceptible and resistant birds. BMC Veterinary Research. https://doi.org/10.1186/s12917-015-0575-6

Smith, J., Sadeyen, J.-R., Cavanagh, D., Kaiser, P., & Burt, D. W. (2015b). The early immune response to infection of chickens with Infectious Bronchitis Virus (IBV) in susceptible and resistant birds. BMC Veterinary Research, 11(1), 256. https://doi.org/10.1186/s12917-015-0575-6

Snyder, D. B., Marquardt, W. W., & Kadavil, S. K. (1983). Ciliary Activity: A Criterion for

Associating Resistance to Infectious Bronchitis Virus Infection with ELISA Antibody Titer. Avian Diseases, 27(2), 485–490. JSTOR. https://doi.org/10.2307/1590174

Stachowiak, B., Key, D. W., Hunton, P., Gillingham, S., & Nagy, É. (2005). Infectious Bronchitis Virus Surveillance in Ontario Commercial Layer Flocks. Journal of Applied Poultry Research, 14(1), 141–146. https://doi.org/10.1093/japr/14.1.141

Stadig, L. M., Tuyttens, F. A. M., Rodenburg, T. B., Verdonckt, P., Wauters, E., Borremans, L., & Reubens, B. (2020). Opportunities for short rotation coppice production on free-range chicken farms in Flanders: Farmers' perceptions and cost-benefit analysis. Renewable Agriculture and Food Systems, 35(3), 286–295. https://doi.org/10.1017/S1742170518000546

Steel, R. G. D., & Torrie, J. H. (1980). Principles and procedures of statistics: A biometrical approach. McGraw-Hill. https://catalog.hathitrust.org/Record/000018269

Sumner, D. A., Gow, H., Hayes, D., Matthews, W., Norwood, B., Rosen-Molina, J. T., & Thurman, W. (2011). Economic and market issues on the sustainability of egg production in the United States: Analysis of alternative production systems. Poultry Science, 90(1), 241–250. https://doi.org/10.3382/ps.2010-00822

Tazari, M. (2006). Strategy for improving genetic aspects of fertility and hatchability in breeding lines of White Leghorns, and choosing hens for second cycle of production [M.Sc., University of Guelph (Canada)]. https://www.proquest.com/docview/305339159/abstract/1B38B7334B2A48A2PQ/1

Thompson, JadaM., & Seitzinger, A. H. (2019). Economic evaluation of low pathogenic avian influenza in northeastern US live bird markets. Journal of Applied Poultry Research, 28(1), 78–84. https://doi.org/10.3382/japr/pfy020

Tomo, A., Crawford, E., Donovan, C., Lloyd, J., Udo, H., & Viets, T. (2012). Does Village Chickens Vaccination Raise Farmers' Income? Evidence from Rural Mozambique. IDEAS Working Paper Series from RePEc. http://search.proquest.com/docview/1697477703/?pq-origsite=primo

Torres, J. L. L. (2021, June 1). Infectious Bronchitis: Key points about vaccination. https://www.thepoultrysite.com/articles/infectious-bronchitis-key-points-about-vaccination

Tran, C., Yanagida, J., Saksena, S., & Fox, J. (2016). An Alternative Vaccination Approach for The Prevention of Highly Pathogenic Avian Influenza Subtype H5N1 in The Red River Delta, Vietnam—A Geospatial-Based Cost-Effectiveness Analysis. Veterinary Sciences, 3(1), 6. https://doi.org/10.3390/vetsci3010006

University of California, Berkeley. (2008, October 16). California Department of Transportation—Division of Transportation Planning. https://web.archive.org/web/20081016040649/http://www.dot.ca.gov/hq/tpp/offices/ote/benefit_cost/index.html

US EPA guidelines for preparing BCA. (n.d.). Retrieved November 27, 2021, from https://www.epa.gov/sites/default/files/2017-08/documents/ee-0568-50.pdf

Varian, H. R. (2014). Microeconomic analysis.

Villarreal, L. Y. B., Brandão, P. E., Chacón, J. L., Saidenberg, A. B. S., Assayag, M. S., Jones, R. C., & Ferreira, A. J. P. (2007). Molecular Characterization of Infectious Bronchitis Virus Strains Isolated from the Enteric Contents of Brazilian Laying Hens and Broilers. Avian Diseases, 51(4), 974–978. https://doi.org/10.1637/7983-041307.1

Wilcox, R. (2011). Modern Statistics for the Social and Behavioral Sciences: A Practical

Introduction. CRC Press LLC. http://ebookcentral.proquest.com/lib/ucalgary-ebooks/detail.action?docID=1648203

Wille, M., & Holmes, E. C. (2020). Wild birds as reservoirs for diverse and abundant gamma- and deltacoronaviruses. FEMS Microbiology Reviews, 44(5), 631–644. https://doi.org/10.1093/femsre/fuaa026

Winston, W. (2016). Microsoft Excel Data Analysis and Business Modeling. Pearson Education.

Winston, W. L. (1999). Financial models using simulation and optimization: A step-by-step guide with Excel and Palisade’s DecisionTools software. Palisade Corporation,.

Winter, C., Schwegmann-Wessels, C., Cavanagh, D., Neumann, U., & Herrler, G. (2006). Sialic acid is a receptor determinant for infection of cells by avian Infectious bronchitis virus. Journal of General Virology, 87(5), 1209–1216. https://doi.org/10.1099/vir.0.81651-0

Wood, M. K., Ladman, B. S., Preskenis, L. A., Pope, C. R., Bautista, D. A., & Gelb, J. (2009). Massachusetts Live Vaccination Protects Against a Novel Infectious Bronchitis Virus S1 Genotype DMV/5642/06. Avian Diseases Digest, 4(1), e17–e17. https://doi.org/10.1637/8598.1

World Bank and The TAFS Forum, L. D. A. (2011). The World Bank and The TAFS Forum. World Livestock Disease Atlas: A Quantitative Analysis of Global Animal Health Data (2006–2009). November.

Yates, C., Dorward, P., Hemery, G., & Cook, P. (2007). The economic viability and potential of a novel poultry agroforestry system. Agroforestry Systems, 69(1), 13–28. https://doi.org/10.1007/s10457-006-9015-8

Yilmaz, H., Altan, E., Cizmecigil, U. Y., Gurel, A., Ozturk, G. Y., Bamac, O. E., Aydin, O., Britton, P., Monne, I., Cetinkaya, B., Morgan, K. L., Faburay, B., Richt, J. A., & Turan,

N. (2016). Phylogeny and S1 Gene Variation of Infectious Bronchitis Virus Detected in Broilers and Layers in Turkey. Avian Diseases, 60(3), 596–602. https://doi.org/10.1637/11346-120915-Reg.1

Yin, L., Zeng, Y., Wang, W., Wei, Y., Xue, C., & Cao, Y. (2016). Immunogenicity and protective efficacy of recombinant fusion proteins containing spike protein of infectious bronchitis virus and hemagglutinin of H3N2 influenza virus in chickens. Virus Research, 223, 206–212. https://doi.org/10.1016/j.virusres.2016.07.010

Zachar, T., Popowich, S., Goodhope, B., Knezacek, T., Ojkic, D., Willson, P., Ahmed, K. A., & Gomis, S. (2016). A 5-year study of the incidence and economic impact of variant infectious bursal disease viruses on broiler production in Saskatchewan, Canada. Canadian Journal of Veterinary Research, 80(4), 255–261.

Zerbe, R. O., & Bellas, A. S. (2006). A Primer for Benefit-cost Analysis. Edward Elgar Publishing.

Zoetis Animal Health. (2020). Newcastle-Bronchitis Vaccine for Poultry. https://www.valleyvet.com/ct_detail.html?pgguid=2958B310-96EC-4201-A635-BB5F4219C6D0

6. Appendices

6.1 Questionnaire

Professor David Hall, DVM, PhD (AgrEcon) Email: dchall@ucalgary.ca Tel: (403)210-7589
University of Calgary, Faculty of Veterinary Medicine, Dept. Ecosystem and Public Health

Study: Economic impact of a vaccine to prevent infectious bronchitis in layer chickens in Canada.
Investigator: Prof. David Hall
Purpose: The purpose of our study is to examine the economic impact of a potential vaccine to prevent infectious bronchitis in layer chickens.
UC ethics certificate (approved): REB21-0442
Funding: Canadian Poultry Research Council, Agriculture and Agri-Food Canada, Egg Farmers of Canada (2018-2023 Poultry Science Cluster, supported by Agriculture and Agri-Food Canada as part of the Canadian Agricultural Partnership).
Larger project title: Assessment of impact of Canadian infectious bronchitis virus (IBV) variants on egg production and fertility of chickens (ENV119).
Investigators (larger project): Profs. Faizal Careem and David Hall, University of Calgary
The questionnaire was managed online via SurveyMonkey. A link to the questionnaire was shared by email or social media. A two-page informed consent preceded the questionnaire, explaining the purpose of the research, that all questions were optional, and that results would be anonymized before any publication.

Section 1: Project purpose, ethics statement and acceptance by respondent.

Section 2: Farm characteristics

1. Do you now or have you in the last 12 months owned or managed an egg layer farm?
(“No” will end the questionnaire)
2. How many years have you been a poultry farmer?
3. In an average year, how many layer birds in total are on your farm(s)?
4. What is the average number of eggs laid per bird per year on your farm(s)?
5. At what age do layer birds enter the farm?
6. At what age of birds do you end the production cycle?

Section 3: Knowledge of infectious bronchitis

1. Had you heard of avian infectious bronchitis prior to this questionnaire? (Yes/No)
2. Has your farm ever had a case of infectious bronchitis (confirmed by a veterinarian)? a. If yes, when was the last case?
3. How do you think infectious bronchitis is transmitted? (Multiple choice)
(Infected eggs, litter, feed and water, contact with infected birds, aerosols, wild birds)
4. Which of the following are signs of infectious bronchitis? (Multiple choice)
(Curled toes, death, diarrhea, feather loss, gasping, nasal discharge, production drop, sneezing/coughing, soft shelled eggs, twisted neck)
5. Are vaccines available for the following avian diseases? If yes, do you use this vaccine?
(Avian influenza, infectious bronchitis, infectious bursal disease, infectious laryngotracheitis, Marek’s disease, navel ill, Newcastle disease)
6. If you do not use any vaccines, why not?
(Not necessary, Too expensive, Low efficacy, Cannot obtain, Other)

Section 4: Attitude regarding infectious bronchitis

1. What do you think will be:

(Responses use a Likert scale: None; Low; Intermediate; High; Extremely high)
Risk of your flock contracting IB if not vaccinated?
Risk of your flock contracting IB if vaccinated?
Likelihood that other farms in your community vaccinate against IB?
Risk of other farms in your community contracting IB?
Risk of your birds contracting IB from other farms?

2. Rate the benefits of the following activities on your farm.
(Responses use a Likert scale: None; Low; Intermediate; High; Extremely high)
Vaccinating your flock against IB
Wearing protective clothing while working in barns.
Additional farm biosecurity measures (e.g., rodent control, no visitors)
Reporting outbreaks to authorities
Sending samples/poultry to diagnostic labs
Regular visits from a veterinarian

3. Rate the severity of economic impact of IB on egg production of layer birds.
(Responses use a Likert scale: None; Low; Intermediate; High; Extremely high)

4. Considering the potential negative impact of IB on poultry, to what extent do you agree to the following statements?
(Responses use a Likert scale: None; Low; Intermediate; High; Extremely high)
IB effect on culling
IB effect on growth
IB effect on profitability
IB impact on human public health

5. For the scenarios below, rate the likelihood you would vaccinate against IB on your farm. (Prevalence refers to the number of cases of IB in the poultry population; efficacy refers to how well a vaccine prevents disease).
(Responses use a Likert scale: None; Low; Intermediate; High; Extremely high)
Low prevalence of IB, moderate efficacy vaccine
Low prevalence of IB, high efficacy vaccine
Moderate prevalence of IB, low efficacy vaccine
Moderate prevalence of IB, high efficacy vaccine
High prevalence of IB, low efficacy vaccine
High prevalence of IB, high efficacy vaccine

Section 5: Risk attitudes

(Responses use a Likert scale: Strongly disagree; Disagree; Neutral; Agree; Strongly agree)
1. Futures markets reduce price risk
2. Good farm management includes checking market prices often
3. Making seatbelts mandatory reduces harm from accidents
4. Regular smoking cigarettes is harmful to one’s health
5. High rates of vaccination for COVID-19 is good for the health of society

6. How often does a veterinarian visit your farm for any reason?
(Responses Likert scale: Never; Rarely; A few times a year; Monthly; Weekly or more)
7. How would you rate your poultry farm management abilities?
(Responses use a Likert scale: None; Low; Intermediate; High; Extremely high)
8. How confident are you about your ability to raise healthy birds on your farm?
(Responses use a Likert scale: None; Low; Intermediate; High; Extremely high)
9. What are your three most valued source of information for animal health? (Score 1 for most valued)
(Egg Farmers of Canada; Provincial non-government poultry organizations; Provincial government; Federal government (e.g., CFIA); My veterinarian; Online information sources; Social media; News media; Other (please specify))

Section 6: Revenue and costs

1. What is the % of your total farm revenue from all types of poultry?
2. What is the % of your total farm revenue from table eggs (if not the same as above)?
3. Do you know your costs of production per egg/dozen eggs?
4. What % of your annual income comes from your farm?

Section 7: Demographics

1. What is your age bracket? (Check one of 5 age ranges)
2. What is your gender? (Female/Male/Other)
3. In what province are you located:
4. What is the nearest major city:
5. What is your highest level of completed education:
a. No formal education

b. Primary school
c. High school
d. College or University
e. Post-graduate

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

6.2 Stakeholders

The table below shows the stakeholder positions with respect to IB vaccination and expected impact with relevant policy instruments applicable in each case. These details are indicative only, not definitive, and will be revised during the fuller development of my thesis.

Category of stakeholder	**Stakeholder**	**Expected impact**	**Policy instrument**	**Impact indicator (**Objectively Verifiable Indicator**)**
Producers	1. Poultry producers	Revenue loss due to IB outbreaks.	Mandatory vaccination in all flocks.	Benefit-Cost Analysis (BCA)
	2. Processing units	Reduced supply of chicken carcasses for processing.	Vaccination	BCA
	3. Vaccine Producers	Fluctuating demand for vaccines.	Mandatory vaccination in all flocks.	Income Statement
	4. Medicine and Drug Industries	Increased sale of medicines.	NA	NA
	5. Feed industry	Reduced demand for feed.	Mandatory vaccination in all flocks.	BCA
	6. Academia	More fund needed for research.	Mandatory vaccination in all flocks.	Publications in this field
	7. US producers	Increased revenue as they can export the products to Canada.	Mandatory vaccination in all flocks.	Import figures
	8. Input suppliers	Revenue loss due to IB outbreaks (chick mortality and malformed ovaries).	Mandatory vaccination in all flocks.	BCA

Consumers	1. Restaurants	Chicken supply fluctuation (price mostly constant due to supply management).	Store and stockpile in freezers (supply management).	Compare number of customers over the years.
	2. General public (vegans)	Substitution effect on other commodities/ complementary effect.	Store and stockpile in freezers (supply management).	Sales record of the poultry and egg products.
	3. Retail Stores	Chicken supply fluctuation.	Store and stockpile in freezers (supply management).	Sales record of the poultry and egg products.
	4. Chicken consumers	Substitution effect on other commodities/ complementary effect	Store and stockpile in freezers (supply management).	Sales record of the poultry and egg products.
	5. Egg consumers	Substitution effect on other commodities/ complementary effect	Store and stockpile in freezers (supply management).	Sales record of the poultry and egg products.
Governance	1. Agriculture and Agri-Food Canada	Unsteady supply of the poultry and egg products.	Mandatory vaccination in all flocks.	Measure supplied amounts and vaccination coverage.
	2. Granting Institutions	Inject more fund to research and studies.	Yearly fund for research and study of economic impact of infectious diseases.	Publications
	3. Provincial authorities and poultry associations	Unsteady supply of poultry and egg products to the market.	Mandatory vaccination in all flocks.	Measure amounts of the products supplied and vaccination coverage.
	4. Federal government	Invest in stabilizing the supply of poultry.	Fund for research and regulations to vaccinate the flocks.	Measure amounts of the products supplied and vaccination coverage.

6.3 Variables, values, and references

	All revenue categories					Medium farms: $250,000 - $499,000					Large farms: $1,000,000-$1,999,000					
	CAN	BC	AB	ON	QC	CAN $250K-$499K	BC $250K-$499K	AB $250K-$499K	ON $250K-$499K	QC $250K-$499K	CAN $1000K -$1,999K	BC $1000K - $1,999K	AB $1000K - $1,999K	ON $1000K - $1,999K	QC $1000K - $1,999K	References
Number of farms	4,900	1,220	373	1,816	875	480	75	30	215	95	905	170	65	360	205	DOI: https://doi.org/10.25318/3210040301-eng
Total operating revenue per farm reporting ($)	1,310,731.00	1,128,643.00	1,348,182.00	1,143,126.00	1,745,391.00	378,514.00	380,687.00	392,036.00	388,687.00	359,822.00	1,414,134.00	1,423,932.00	1,404,063.00	1,387,486.00	1,436,645.00	STATCAN Table 32-10-0136-01 - "Farm operating revenues and expenses, annual" - Poultry and egg production - All revenue classes - Average per farm reporting
Poultry and egg revenue per farm reporting ($)	1,178,686.00	1,082,857.00	1,172,760.00	989,623.00	1,581,760.00	336,940.00	355,071.00	426,031.00	326,745.00	286,886.00	1,256,555.00	1,368,470.00	1,187,237.00	1,167,226.00	1,281,483.00	STATCAN Table 32-10-0136-01 - "Farm operating revenues and expenses, annual" - Poultry and egg production - All revenue classes - Average per farm reporting
Percent of revenue from poultry and eggs (%)	0.90	0.96	0.87	0.87	0.91	0.89	0.93	1.09	0.84	0.80	0.89	0.96	0.85	0.84	0.89	
Total operating expenses ($)	1,107,343.00	966,069.00	1,138,045.00	954,261.00	1,495,868.00	328,548.00	364,364.00	289,614.00	327,483.00	305,115.00	1,175,648.00	1,185,693.00	1,179,375.00	1,131,091.00	1,196,578.00	STATCAN Table 32-10-0136-01 - "Farm operating revenues and expenses, annual" - Poultry and egg production - All revenue classes - Average per farm reporting
Operating expenses due to poultry and eggs ($)	995,787.61	926,878.19	989,965.49	826,119.46	1,355,629.87	292,462.00	339,846.36	314,727.58	275,294.60	243,268.12	1,044,643.84	1,139,510.38	997,247.02	951,533.08	1,067,343.96	
Total profit ($)	203,388.00	162,574.00	210,137.00	188,865.00	249,523.00	49,966.00	16,323.00	102,422.00	61,204.00	54,707.00	238,486.00	238,239.00	224,688.00	256,395.00	240,067.00	
Poultry and egg profit ($)	182,898.39	155,978.81	182,794.51	163,503.54	226,130.13	44,478.00	15,224.64	111,303.42	51,450.40	43,617.88	211,911.16	228,959.62	189,989.98	215,692.92	214,139.04	
Live price per kg ($)	1.65	1.69	1.64	1.60	1.59	1.65	1.69	1.64	1.60	1.59	1.65	1.69	1.64	1.60	1.59	https://aimis-simia.agr.gc.ca/rp/index-eng.cfm?action=gR&r=23&signature=3EFFDD47E132BDFBA998FEAAC5895245&pdctc=&pTpl=1#wb-cont
Average weight of bird (kg)	1.89	1.73	1.84	2.03	1.88	1.73	1.84	2.03	1.88	1.73	1.84	2.03	1.88	1.73	1.84	How to cite: Statistics Canada. Table 32-10-0118-01 Fowl and chicken meat production, weight and farm value (x 1,000) DOI: https://doi.org/10.25318/3210011801-eng
Revenue from one bird ($)	3.11	2.93	3.02	3.25	2.99	2.86	3.11	3.33	3.01	2.75	3.04	3.43	3.09	2.77	2.93	
Percent from chicken meat (%)	0.67	0.69	0.65	0.67	0.72	0.67	0.69	0.65	0.67	0.72	0.67	0.69	0.65	0.67	0.72	
Percent of revenue from eggs (of total poultry and eggs revenue) (%)	0.33	0.31	0.35	0.33	0.28	0.33	0.31	0.35	0.33	0.28	0.33	0.31	0.35	0.33	0.28	Statistics Canada. Table 32-10-0117-01 Production, disposition and farm value of poultry meat (x 1,000) DOI: https://doi.org/10.25318/3210011701-eng
Revenue from eggs ($)	386,448.35	338,107.12	408,030.24	323,425.42	445,049.96	110,470.39	110,866.01	148,226.01	106,785.76	80,719.33	411,978.77	427,285.83	413,067.12	381,469.07	360,562.89	
Expense due to eggs ($)	107,031.09	289,375.96	344,397.37	269,962.72	381,386.99	95,878.09	106,101.71	109,490.03	89,961.90	68,439.99	342,466.54	355,760.78	346,930.53	310,945.90	300,281.89	
Chicks ($)	43,813.97	38,838.14	46,222.75	36,232.62	51,187.25	12,868.13	14,240.27	14,695.03	12,074.09	9,185.57	45,963.61	47,747.87	46,562.73	41,733.11	40,301.86	
Feed ($)	159,943.83	141,779.46	168,737.15	132,267.96	186,860.17	46,975.37	51,984.43	53,644.53	44,076.74	33,532.11	167,791.14	174,304.64	169,978.27	152,347.63	147,122.81	
Housing ($)	41,626.53	36,899.12	43,915.06	34,423.69	48,631.70	12,225.68	13,529.32	13,961.38	11,471.29	8,726.97	43,668.85	45,364.04	44,238.07	39,649.57	38,289.77	
Labor ($)	15,344.68	13,602.03	16,188.30	12,689.52	17,926.98	4,506.72	4,987.28	5,146.55	4,228.63	3,217.00	16,097.54	16,722.43	16,307.37	14,615.92	14,114.66	
Additional costs ($)	65,720.95	58,257.21	69,334.12	54,348.93	76,780.88	19,302.19	21,360.41	22,042.55	18,111.14	13,778.35	68,945.41	71,621.81	69,844.10	62,599.67	60,452.79	
Income from eggs ($)	279,417.26	48,731.17	63,632.87	53,462.70	63,662.97	14,592.31	4,764.30	38,735.98	16,823.85	12,279.34	69,512.23	71,525.05	66,136.59	70,523.17	60,281.00	
Total number of birds sold (Nos)	254,375.08	254,507.66	253,257.36	204,908.17	379,953.22	79,268.95	78,481.22	83,362.82	73,063.39	74,885.63	278,005.15	274,071.65	250,882.27	283,625.56	314,573.96	
Revenue from dozen eggs ($)	1.91	2.19	2.06	1.77	1.92	1.91	2.19	2.06	1.77	1.92	1.91	2.19	2.06	1.77	1.92	https://www150.statcan.gc.ca/n1/daily-quotidien/210527/dq210527e-eng.htm
Total number of dozens sold (Nos)	202,507.16	154,411.80	198,179.23	182,594.51	231,569.94	57,888.84	50,631.94	71,992.99	60,287.45	42,000.16	215,885.64	195,139.27	200,625.64	215,363.89	187,609.34	
Total number of layers Nos)	8,265.32	6,578.18	8,362.88	7,237.44	9,833.47	2,362.73	2,157.00	3,038.00	2,389.59	1,783.51	8,811.36	8,313.23	8,466.11	8,536.31	7,966.71	
Wage rate per hour ($)	24.91	26.32	32.32	21.16	21.13	24.91	26.32	32.32	21.16	21.13	24.91	26.32	32.32	21.16	21.13	STATCAN Table 14-10-0307-01 - "Natural resources, agriculture and related production occupations" - https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=1410030701&pickMembers%5B0%5D=1.11&pickMembers%5B1%5D=2.2&pickMembers%5B2%5D=3.1&pickMembers%5B3%5D=5.1&pickMembers%5B4%5D=6.1
Vax labour (seconds)	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	
Vax labour ($)	0.07	0.07	0.09	0.06	0.06	0.07	0.07	0.09	0.06	0.06	0.07	0.07	0.09	0.06	0.06	
Vax direct cost ($)	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	https://www.valleyvet.com/ct_detail.html?pgguid=2958B310-96EC-4201-A635-BB5F4219C6D0
Vax total cost ($)	0.12	0.12	0.14	0.11	0.11	0.12	0.12	0.14	0.11	0.11	0.12	0.12	0.14	0.11	0.11	
Farm-level incidence (%)	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	Derksen, T., Lampron, R., Hauck, R., Pitesky, M., & Gallardo, R. A. (2018). Biosecurity Assessment and Seroprevalence of Respiratory Diseases in Backyard Poultry Flocks Located Close to and Far from Commercial Premises. Avian Diseases, 62(1), 1–5. https://doi.org/10.1637/11672-050917-Reg.1
Bird-level incidence rate in infected farms (%)	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	Ignjatović J, Sapats S. Avian infectious bronchitis virus. Rev Sci Tech. 2000

																Aug;19(2):493-508. doi: 10.20506/rst.19.2.1228. PMID: 10935276.
Mortality rate due to infection (%)	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	Moderate mortality estimate from Cavanagh and Gelb, 2008, Jackwood, 2012, Smith *et al.,* 2015
Egg output reduction due to infection (%)	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	Jackwood, M.W. and de Wit, S. (2013). Infectious Bronchitis. In Diseases of Poultry, D.E. Swayne (Ed.). https://doi-org.ezproxy.lib.ucalgary.ca/10.1002/9781119421481.ch4
Vaccine efficacy (%)	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	J. J. De Wit, W. A. J. M. Swart & T. H. F. Fabri (2010) Efficacy of infectious bronchitis virus vaccinations in the field: association between the α-IBV IgM response, protection and vaccine application parameters, Avian Pathology, 39:2, 123-131, DOI: 10.1080/03079451003604639
Vaccine adoption (%)	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	
Recovery time for layers (days)	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	Chapter 4 Free Access Infectious Bronchitis Mark W. Jackwood, de Wit, Book Editor(s):David E. Swayne, First published: 04 October 2013 https://doi.org/10.1002/9781119421481.ch4
Eggs per bird per day (Nos)	0.81	0.77	0.78	0.83	0.77	0.81	0.77	0.78	0.83	0.77	0.81	0.77	0.78	0.83	0.77	Statistics Canada. Table 32-10-0119-01 Production and disposition of eggs, annual DOI: https://doi.org/10.25318/3210011901-eng
Dozens sold per week (Nos)	3,883.70	2,961.32	3,800.69	3,501.81	4,441.06	1,110.20	971.02	1,380.69	1,156.20	805.48	4,140.27	3,742.39	3,847.61	4,130.26	3,597.98	
Profit per bird ($)	0.61	0.69	0.60	0.60	0.70	0.52	0.21	1.01	0.57	0.75	0.66	0.81	0.62	0.67	0.82	
Profit per dozen ($)	0.30	0.32	0.32	0.29	0.27	0.25	0.09	0.54	0.28	0.29	0.32	0.37	0.33	0.33	0.32	
Chick cost (%) of total exp	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	Sumner, D.A., Gow, H., Hayes, D., Matthews, W., Norwood, B., Rosen-Molina, J.T. and Thurman, W. (2011), "Economic and market issues on the sustainability of egg production in the United States: analysis of alternative production systems 1", Poultry Science, Vol. 90 No. 1, pp. 241-250.
Feed (%) of total exp	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	Sumner, D.A., Gow, H., Hayes, D., Matthews, W., Norwood, B., Rosen-Molina, J.T. and Thurman, W. (2011), "Economic and market issues on the sustainability of egg production in the United States: analysis of alternative production systems 1", Poultry Science, Vol. 90 No. 1, pp. 241-250.
Housing (%) of total exp	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	Sumner, D.A., Gow, H., Hayes, D., Matthews, W., Norwood, B., Rosen-Molina, J.T. and Thurman, W. (2011), "Economic and market issues on the sustainability of egg production in the United States: analysis of alternative production systems 1", Poultry Science, Vol. 90 No. 1, pp. 241-250.
Labor (%).of total exp	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	Sumner, D.A., Gow, H., Hayes, D., Matthews, W., Norwood, B., Rosen-Molina, J.T. and Thurman, W. (2011), "Economic and market issues on the sustainability of egg production in the United States: analysis of alternative production systems 1", Poultry Science, Vol. 90 No. 1, pp. 241-250.
Additional costs (%) of total exp	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	Sumner, D.A., Gow, H., Hayes, D., Matthews, W., Norwood, B., Rosen-Molina, J.T. and Thurman, W. (2011), "Economic and market issues on the sustainability of egg production in the United States: analysis of alternative production systems 1", Poultry Science, Vol. 90 No. 1, pp. 241-250.
Production per bird (eggs per year)	294.01	281.68	284.37	302.75	282.59	294.01	281.68	284.37	302.75	282.59	294.01	281.68	284.37	302.75	282.59	
Normal mortality rate for a layer population	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	Ref: weekly mortality rate is 0.09% according to the refereece but we are assuming the yearly rate to be 1% approximately at best
Normal production per bird (eggs per year)	300.01	287.43	290.17	308.93	288.36	300.01	287.43	290.17	308.93	288.36	300.01	287.43	290.17	308.93	288.36	
Ratio of Abnormal prod (Ap) & abnormal mortality (Am) to Normal prodn (Nm) and normal mortality (Nm) in unvax exposed cohort	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	Ref: Attenuation, Safety, and Efficacy of an Infectious Bronchitis Virus GA98 Serotype Vaccine Authors: Jackwood, Mark W., Hilt, Deborah A., and Brown, Thomas P. Source: Avian Diseases, 47(3) : 627-632 Published By: American Association of Avian Pathologists URL: https://doi.org/10.1637/6094
Ratio of Np and Nm to Ap and Am in vax, exposed, vax ineffective cohort	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	Ref: Attenuation, Safety, and Efficacy of an Infectious Bronchitis Virus GA98 Serotype Vaccine Authors: Jackwood, Mark W., Hilt, Deborah A., and Brown, Thomas P. Source: Avian Diseases, 47(3) : 627-632 Published By: American Association of Avian Pathologists URL: https://doi.org/10.1637/6094
Price of stewing chicken (spent hen) ($/bird)	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	Pers comm. Dr. David Hall
Reference needed																
Assumption																
Calculated																
Calculated from available sources																

Contact at karma.phuntsho@ucalgary.ca for more detailed information.