Estimates of Human Exposure to Antimicrobial-Resistant Foodborne Pathogens and the Resulting Burden of Illness

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Abstract

Foodborne illnesses caused by nontyphoidal *Salmonella* (NTS) and *Campylobacter* pose significant challenges to Canada's public health and the economy. This study aims to estimate the economic costs and health burden of these infections, differentiating between antimicrobial-resistant (AMR) and susceptible strains from 2015 to 2019. The study also assessed the impact of voluntary reductions in antimicrobial use in the chicken industry on these infections' incidence and economic burden. The study quantified the microeconomic and macroeconomic impacts on industrial output, GDP, and employment using Markov models combined with input-output analysis.

The Markov model analyses indicated a downward trend in *Salmonella* cases, physician visits, hospitalizations, and deaths, alongside reductions in economic costs and Quality Adjusted Life Years (QALYs) losses. The predicted number of *Salmonella* cases decreased from 119,432 in 2015 to 93,199 in 2019, with costs dropping from $155 million to $131 million. For chicken-associated *Salmonella* cases, numbers decreased from 96,424 in 2015 to 67,097 in 2019, translating to a cost reduction from $122 million to $ 93 million. The total estimated annual costs of *Campylobacter* infections remained stable at approximately $137 million, with AMR strains consistently incurring higher costs and health impacts than susceptible strains.

Macroeconomic analyses showed that in total industrial output decreased due to lost income from *Salmonella* infections declined from $36 million in 2015 to $32 million in 2019. *Campylobacter* infections resulted in higher output reductions ranging from $43 million to $46 million between 2017 and 2019. GDP losses in 2019 were estimated at $19 million for *Salmonella* and $27 million for *Campylobacter* infections. Employment losses were also greater for *Campylobacter* infections, with 214 jobs lost in 2019 compared to 149 jobs for Salmonella. The study highlights the importance of continued investment in public health interventions, improved surveillance systems, actions taken by producers, and public awareness campaigns to combat antimicrobial resistance and enhance food safety.

Résumé

Les maladies d'origine alimentaire causées par *Salmonella* non typhique et *Campylobacter* posent des défis importants pour la santé publique et l'économie au Canada. Cette étude visait à estimer les coûts économiques et le fardeau sanitaire de ces infections, en différenciant les souches résistantes aux antimicrobiens (RAM) et les souches sensibles de 2015 à 2019. De plus, l'étude a évalué l'impact des réductions volontaires de l'utilisation des antimicrobiens dans l'industrie avicole sur l'incidence et le fardeau économique de ces infections. En utilisant des modèles de Markov combinés à une analyse input-output, l'étude a quantifié les impacts microéconomiques et macroéconomiques sur la production industrielle, le PIB et l'emploi.

Les analyses réalisées à partir du modèle de Markov ont révélé une tendance à la baisse du nombre de cas de Salmonella, des consultations médicales, des hospitalisations et des décès, s'accompagnant d'une diminution des coûts économiques et des pertes en années de vie ajustées sur la qualité (AVAQ). Le nombre total de cas de *Salmonella* est passé de 119 432 en 2015 à 93 199 en 2019, tandis que les coûts associés ont chuté de 155 millions de dollars à 131 millions de dollars. Concernant les infections à *Salmonella* liées au poulet, le nombre de cas est passé de 96 424 en 2015 à 67 097 en 2019, ce qui correspond à une réduction des coûts de 122 millions à 93 millions de dollars. En revanche, les coûts annuels totaux estimés pour les infections à *Campylobacter* sont demeurés stables, autour de 137 millions de dollars, les souches RAM entraînant systématiquement des coûts et des répercussions sanitaires plus élevés que les souches sensibles.

Les analyses macroéconomiques ont montré que la baisse de la production industrielle liée aux pertes de revenus dues aux infections à *Salmonella* a diminué de 36 millions de dollars en 2015 à 32 millions en 2019. Les infections à *Campylobacter* ont entraîné des réductions plus importantes, allant de 43 à 46 millions de dollars entre 2017 et 2019. Les pertes de PIB en 2019 ont été estimées à 19 millions de dollars pour Salmonella et 27 millions de dollars pour *Campylobacter*. Les pertes d'emplois liées à *Campylobacter* ont également été plus élevées, avec 214 emplois perdus en 2019, contre 149 emplois pour *Salmonella*. L'étude souligne l'importance de continuer à investir dans des interventions de santé publique, à améliorer les systèmes de surveillance et à mener des campagnes de sensibilisation du public pour lutter contre la résistance aux antimicrobiens et améliorer la sécurité alimentaire.

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List of Abbreviations

AMR	Antimicrobial Resistance
AMU	Antimicrobial Use
BOI	Burden of Illness
CBA	Cost-Benefit Analysis
CEA	Cost-Effectiveness Analysis
CGE	Computable General Equilibrium
CIPARS	Canadian Integrated Program for Antimicrobial Resistance
COI	Cost of Illness
DALYs	Disability-Adjusted Life Years
ED	Emergency Department
EQ-5D	The EuroQol Group EQ-5D
FAO	Food and Agriculture Organization
GBS	Guillain-Barré Syndrome
GDP	Gross Domestic Product
HALY	Health-Adjusted Life Years
HCA	Human Capital Approach
HRQL	Health-Related Quality Loss
HUS	Hemolytic Uremic Syndrome
iAM.AMR	Integrated Assessment Model for AMR
IBD	Inflammatory Bowel Disease
IBS	Irritable Bowel Syndrome
IO	Input-Output
MFS	Miller Fisher Syndrome
MIC	Minimum Inhibitory Concentrations
MTM	Markov Transition Models
PHAC	Public Health Agency of Canada
PSA	Probabilistic Sensitivity Analysis
QALYs	Quality-Adjusted Life Years
RA	Reactive Arthritis
RR	Relative Risk
SUT	Supply-Use Table
UC	Ulcerative Colitis
WGS	Whole Genome Sequencing
WHO	World Health Organization
WOAH	World Organization for Animal Health
WTP	Willingness to Pay
YLD	Years Lived with Disability
YLL	Years of Life Lost

Chapter 1. Introduction

1.1. Background and Significance

The discovery of antibiotics revolutionized modern medicine and provided a powerful defence against previously untreatable bacterial infections (Lobanovska and Pilla 2017). Alexander Fleming discovered penicillin in 1928, setting the stage for an era in which minor scratches no longer posed the risk of a potentially life-threatening infection (Roope et al. 2019). These advances are often regarded as the miracles of the 20th century due to the effective role of antibiotics in infection management and control (Uddin et al. 2021). However, the substantial benefits also come with considerable challenges. Antibiotics that once helped save lives are becoming increasingly ineffective, primarily due to antimicrobial resistance (AMR) (Lobanovska and Pilla 2017, Uddin et al. 2021). This resistance in bacteria reduces the therapeutic effectiveness of antibiotics, thereby reducing their ability to treat and prevent bacterial infections effectively.

Antimicrobial resistance is a natural phenomenon in which microorganisms undergo genetic mutations or acquired resistance genes form other bacteria, viruses or the environment in which provide mechanisms that stop the antimicrobial from killing or inhibiting the target microorganisms (Uddin et al. 2021). Resistance requires using more effective, expensive, and toxic antibacterial drugs to treat the disease. Although this evolutionary process occurs naturally, human activity has greatly accelerated its pace (Aminov 2010). Inappropriate use of antibiotics, including using them to treat viral infections or as livestock growth promoters, unnecessarily adds to the development of resistance (Lobanovska and Pilla 2017).

The misuse and overuse of antibiotics inadvertently creates excess selective pressure that promotes the survival and proliferation of resistant bacteria relative to susceptible bacteria (Uddin et al. 2021). From a broader perspective, the impacts of uncontrolled AMR extend beyond individual health. It disrupts public health systems, jeopardizes food security, and poses significant risks to global health security (Naylor 2019). AMR represents a classic example of a negative externality. While the immediate use of antibiotics may benefit individuals by treating infections, it imposes long-term costs on society by reducing the effectiveness of these drugs for future treatments. This societal cost arises because the overuse or misuse of antibiotics accelerates the development and spread of resistant pathogens. Therefore, maintaining the efficacy of antibiotics is critical in sustaining modern medicine and promoting the health and wellbeing of humans and animals.

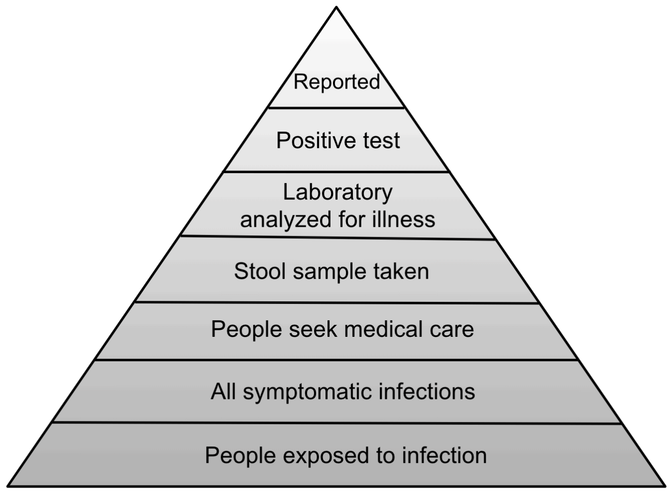
1.2. The Threat of Antimicrobial Resistance

Antimicrobial resistance is an important emerging threat with substantial negative impacts on global health and economies. The World Health Organization (WHO) and the United Nations have listed AMR as one of the humanity's top ten global health threats (UNEP 2020). In Canada, AMR bacterial infections are responsible for more than 14,000 deaths annually and resulted in medical costs of $1.4 billion in 2018 (Council of Canadian Academies, 2019). The Council of Canadian Academies (2019) predicts that without appropriate intervention, bacterial resistance to drugs could increase from 26% to 40% by 2050, potentially resulting in 256,000 deaths and a $268 billion reduction in Canadian gross domestic product (GDP). The impact of AMR is much more severe in low-income countries than in high-income countries. Projections indicate that AMR may exacerbate the challenge of eradicating extreme poverty, potentially pushing an additional 24.1 million people into extreme poverty, with 18.7 million of whom live in low-income countries (Ahmed et al. 2018). Therefore, AMR requires global attention and has the potential to impact everyone.

In 2019, the WHO reported that approximately 1.5 million people died worldwide from diarrheal diseases (World Health Organization 2020), with 70% of these illnesses being foodborne (World Health Organization 2015). In Canada, the Public Health Agency of Canada (PHAC) estimates that 30 pathogens are responsible for 4 million cases of foodborne illnesses each year, which leads to 11,600 hospitalizations and 238 deaths (Government of Canada, 2016). While antimicrobial drugs have played an essential role in saving countless human and animal lives, the escalating problem of antimicrobial resistance may reduce the future effectiveness of these drugs and limit the availability of infection treatment options (Huber et al. 2021, McCubbin et al. 2021). The COVID-19 pandemic further complicated this issue. The widespread use of antimicrobials for COVID-19 patients, either to treat bacterial co-infections or as prophylaxis, coupled with the fact that antimicrobial stewardship programs were likely disregarded or overlooked during the pandemic, has contributed to the exacerbation of AMR (McCubbin et al. 2021).

The burden of AMR infections is often underestimated. Figure 1.1 illustrates the reporting process for foodborne illnesses, highlighting the multiple steps required for a case to be confirmed within a public health system. This process begins at the base with an individual being exposed to a hazard (e.g. a pathogen in food) and progresses as the individual becomes ill, seeks medical care, undergoes diagnostic testing, and receives a confirmed positive result from a laboratory. Only these confirmed cases are reported to public health authorities, representing a fraction of the actual number of cases due to underreporting (Thomas et al. 2013). Surveillance systems often miss milder cases that do not result in medical care, hospitalization, or death, further contributing to underestimation.

Figure 1.1 Morbidity surveillance pyramid

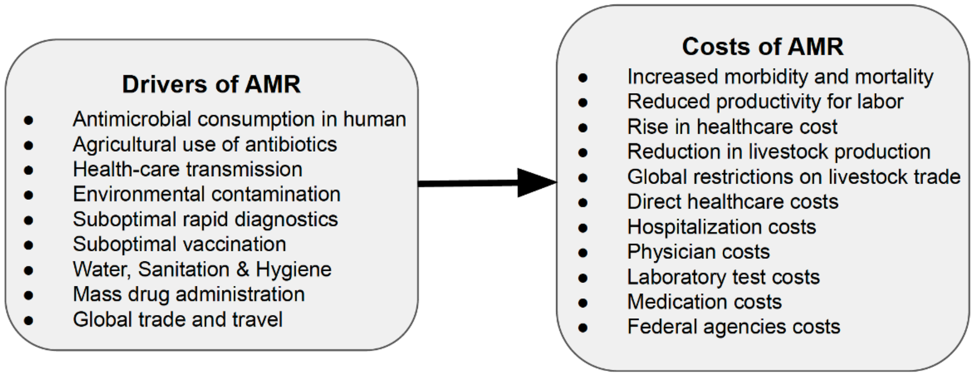


Source: Adapted from Drudge et al. 2019 and Sundström 2018

Various methods have been used to estimate the actual number of cases to address this challenge. Community cohort studies can help gather more accurate data by following up with participants for symptoms and collecting stool samples. Serological surveys offer another approach that identifies new infections through antibody testing and accounts for both symptomatic and asymptomatic cases. Despite their utility, these approaches are subject to biases and logistical difficulties that can affect the accuracy of the estimates.

This study addresses the underestimation issue by using stochastic modelling to simulate probabilities, offering a more robust estimate of the actual number of cases. AMR-related infections impose a substantial burden of illness (BOI), resulting in both direct health costs (e.g., medication, hospitalization) and indirect costs, such as lost income due to reduced productivity (see Figure 1.2). Foodborne diseases are largely preventable since they are caused by pathogens whose spread can be effectively controlled through targeted interventions.

Figure 1.2 Drivers and costs associated with AMR



Source: Adapted from Shrestha et al. 2018 and McGowan Jr. 2001

1.3. The Trend of Antimicrobial Use

Antimicrobial use (AMU) has been widespread in healthcare and animal production since its introduction. Antimicrobial drugs are frequently prescribed in human medicine, but up to 50% of these prescriptions may be unnecessary (Schwartz et al. 2020). While hospitals and other inpatient facilities are often considered the primary sites of antibiotic use, most antimicrobial use is in agricultural practices. Approximately 82% of total AMU comes from agriculture, with healthcare accounting for 18% and less than 1% related to pets and crops (Ebrahim et al. 2016). In agriculture, the misuse or overuse of antimicrobials is a major concern. Antimicrobial drugs in agriculture are mainly administered to livestock through feed, water, or injection. Antimicrobials are used not only to prevent or treat common diseases but also to promote the growth of animals, for example, poultry, pigs, and cattle (Huber et al. 2021). In Canada, as of December 1, 2018, the use of medically important antimicrobials as growth promoters was phased out (Public Health Agency of Canada 2023). Globally, the widespread use of antimicrobials in agriculture poses a potential food safety risk, including outbreaks caused by drug-resistant strains.

The natural environment, including water, soil, and air, contains many antibiotic resistance genes, collectively known as the "resistome" (Nair, Venkitanarayanan, and Johny 2018). These genes can be transferred into pathogenic bacteria directly (transformation) or by viruses (transduction). The transfer of these resistance genes from the environment to pathogenic bacteria is a critical pathway in which AMR can impact public health.

The relationship between antimicrobial use and resistance is complex and influenced by many factors (Lobanovska and Pilla 2017). Microorganisms can acquire resistance through genetic mutations or inheritance of genetic material from other entities, and plasmid transmission is central to this process (Holmes et al. 2016). The spread of drug-resistant strains from human to human is influenced by multiple factors, including sanitation, hospital environments, and even intimate interactions. Technological advances such as whole-genome sequencing (WGS) have improved our ability to track these transmission pathways (Jain, Mukhopadhyay, and Thomassin 2019).

The problem of AMR is not limited to human medicine but extends to veterinary medicine, livestock and crop production. Since the 1960s, it has been recognized that using antimicrobial growth promoters in animals is associated with increased drug-resistant bacteria in these populations (Holmes et al. 2016). The transfer of these drug-resistant microorganisms from animals to humans is a pressing issue, especially given the resistance mechanisms shared among various microorganisms. Humans can be exposed to drug-resistant bacteria originating from the agri-food system through multiple pathways. For example, foodborne pathogens such as Salmonella spp. enter farms from people, incoming animals from earlier production stages (e.g. broiler chicks, weaner pigs), water, animal waste, equipment, vehicles, rodents, insects, and pets. In addition, these pathogens can be transported to farms or slaughterhouses by the movement of vehicles and portable equipment and may end up in animal carcasses during the slaughtering process (Nair, Venkitanarayanan, and Johny 2018). Water contamination, often caused by poor waste management and using manure as fertilizer, further contributes to pesticide resistance in aquaculture and crops. Sapkota et al. (2014) showed that switching from conventional to organic farming practices can reduce AMR Salmonella. This suggests that reducing the prevalence of antibiotic-resistant bacteria on farms could play an important role in reducing the spread of resistant strains to consumers through contaminated poultry products. Once resistant bacteria are on a farm, selection pressure from AMU enables the competitive survival of the resistant strains over susceptible strains. Therefore, limiting AMU is an important strategy to control the spread of AMR pathogens.

1.4. Antimicrobial Resistance Surveillance and the One Health Approach

Antimicrobial resistance is a global One Health problem because it can be transmitted between humans, animals, and environmental reservoirs without borders. The One Health concept emphasizes the interconnectedness between human, animal and environmental health, and is increasingly recognized worldwide, particularly concerning foodborne diseases. In response, international organizations such as the United Nations, including the WHO, the Food and Agriculture Organization (FAO), as well as the World Organization for Animal Health (WOAH) advocate collaborative and multisectoral strategies. These strategies aim to prevent and manage infectious diseases and health threats that emerge from human-animal-environment interactions (Velazquez-Meza et al., 2022). However, accurately quantifying the impact of antimicrobial use in agriculture and the dissemination of AMR from livestock and crops on antimicrobial resistance in humans remains a challenge.

Surveillance is critical in identifying trends in emerging AMR pathogens and informing necessary actions against AMR. Surveillance data are important for identifying strategic intervention points, understanding the extent of the impact of antimicrobial resistance, and assessing the effectiveness of antimicrobial stewardship interventions (Public Health Agency of Canada 2023). Researchers involved with CIPARS, along with multiple partners have developed an integrated assessment (Integrated Assessment Model for AMR; iAM.AMR) to understand the relative contributions of different pathways for the spread of AMR, particularly along the food chain; and inform decision-making processes (Murphy et al. 2018, Phillips et al. 2022). However, the model extends only to human exposure, not illness and does not currently incorporate the economic costs associated with AMR.

Antimicrobial-resistant *Salmonella* spp. and *Campylobacter* spp. are significant concerns in poultry production. In 2012, the poultry industry initiated a stewardship program called the Antimicrobial Use Reduction Strategy to mitigate AMR and reduce overall AMU (Huber et al. 2021). The plan begins with the elimination of the preventive use of Category I antimicrobials (as classified by Health Canada's Veterinary Medicines Agency) in 2014, followed by the elimination of Category II antimicrobials in 2018, with plans to phase out Category III antimicrobials at a later date (Chicken Farmers of Canada, 2020). Health Canada ranks antibiotics (Categories I-IV) based on their importance to human medicine (See Table 1.1). The evaluation by Huber et al. (2021) showed that AMR in broiler chickens was reduced by 6% – 38% after reduced prophylactic antimicrobial use. They also noted that the withdrawal of specific compounds could lead to resistance to other drug classes. Stopping the use of antibiotics earlier in the life of chickens may further reduce AMR (Huber et al., 2021). In addition, a report from FoodNet Canada in 2019 showed that there was less *Salmonella* spp. on frozen breaded chicken in 2019 compared to 2018 (Public Health Agency of Canada 2020). This decline is associated with the April 2019 regulations requiring manufacturers of frozen raw breaded chicken products to have no detectable *Salmonella*, primarily achieved by switching to pre-cooked products (Canadian Food Inspection Agency 2019).

Although these findings are encouraging, a comprehensive assessment of the economic benefits of reducing AMR in chicken products remains an important area for future research.

Table 1.1 Classification of antimicrobials

Category	Category Criteria	Drug Family
Category I Very High Importance	Essential for serious human infections with limited or no alternatives available	Excenel (extra-label) Enrofloxacin
Category II High Importance	Essential for treating serious human infections and few alternatives available	Virginiamycin Penicillins Tvlosin Gentamcyin Lincosamides Trimethoprim-Sulfadiazole
Category III Medium Importance	Important for treating human infections and alternatives are generally available	Bacitracin Sulphonamides Apramycin Spectinomycin Tetracyclines Neomycin (Sulfate, Oxytetracycline, Tetracycline)
Category IV Low Importance	Not used in human medicine	Bambermycin lonophores Uncategorized
Uncategorized		Avilamycin

Source: Health Canada, 2009. Available at: https://www.canada.ca/en/health-canada/services/drugs-health-products/veterinary-drugs/antimicrobial-resistance/categorization-antimicrobial-drugs-based-importance-human-medicine.html.

1.5. Thesis Aims and Structure

Assessing the health and economic burden of disease caused by AMR can help understand the scope of the problem. Many evaluations of AMR infections have a narrow focus, primarily examining healthcare costs while overlooking broader economic consequences. However, AMR's impacts extend beyond healthcare, potentially disrupting labour markets, reducing workforce productivity, and constraining national income and economic growth. Existing research has primarily used the human capital or friction cost methods to assess productivity effects, which do not capture broader macroeconomic implications like changes to GDP or inflation (Shrestha et al. 2018, Sundström 2018). While these strategies have been implemented in other sectors, especially environmental conservation, there was no comprehensive macroeconomic framework to assess their potential economic impact on AMR.

This study aims to add an economic evaluation to the iAM.AMR, enabling quantification of the economic costs of drug-resistant *Salmonella* spp. and *Campylobacter* spp. by translating the likelihood of human exposure to AMR into estimates of the BOI. It provides additional information for policy decision-making and the assessment of alternative policy choices. A case study on the chicken industry will be used to test the model and to evaluate the economic costs of AMR Salmonella infections attributed to chicken. In addition, lower labour productivity results in lower incomes, which has a multiplier effect on the entire economy. Therefore, the study also estimates the macroeconomic impact on Canadian industrial output, GDP, and employment. The following research questions will be investigated:

1. What is the annual and lifetime added burden of illness for humans due to exposure to resistant foodborne bacteria (*Salmonella* spp. and *Campylobacter* spp.)?
2. How might reducing human exposure to foodborne bacteria and AMR bacteria impact Canadian industrial output, GDP, and employment at the macroeconomic level?
3. What are the impacts of reducing AMU on the poultry industry between 2015 and 2019?

The thesis is organized into six chapters, starting with an introductory chapter that presents the research questions and objectives. Chapter 2 provides a literature review on the incidence, prevalence, and economic impact of AMR foodborne diseases and introduces the economic models associated with the analysis. Chapter 3 explains the methods, including Markov model with Monte

Carlo simulations and Input-Output models, with case studies to test the theoretical approach. Chapter 4 presents the results and Chapter 5 discusses the insights drawn from the results, explores policy implications, and discusses the study's limitations and suggestions for future research. Chapter 6 concludes the thesis by summarizing the key findings of the research.

Chapter 2. Literature Review

2.1. Introduction

Antimicrobials are essential in treating infectious diseases across humans, animals, and plants, significantly aiding livestock production by enhancing feed efficiency, growth, and managing infections (McCubbin et al. 2021). However, their overuse and lack of regulation in animal food production have contributed to the emergence of AMR zoonotic pathogens (Prestinaci, Pezzotti, and Pantosti 2015). These pathogens can be transmitted to humans via environmental exposure and the food chain, leading to foodborne illnesses and every illness has an economic cost. While most cases of foodborne illness are mild and self-limiting, characterized by gastrointestinal symptoms, a fraction can escalate to severe conditions requiring hospitalization or even resulting in death (McLinden 2013). Though less common, chronic complications from these illnesses pose greater threats to human health and the economy due to their extended duration and severity (Lindsay 1997, Sundström 2018). The BOI and economic costs associated with AMR in foodborne pathogens are emerging as critical challenges for global public health systems (Porooshat Dadgostar 2019). The rise of AMR threatens the effective treatment of infections and imposes a substantial economic burden on society due to increased healthcare costs, lost productivity, and the need for alternative treatments (Prestinaci, Pezzotti, and Pantosti 2015).

While many studies have concentrated on either the BOI or the cost implications of foodborne illnesses or on estimating the burden of AMR separately, there needs to be more exploration of the economic impacts associated explicitly with AMR foodborne diseases. This literature review examines various studies on the methods used for estimating the BOI and economic costs associated with AMR foodborne pathogens. It explores the purposes and examples of using these methods in cost-effectiveness analyses. It also discusses the mechanisms and underlying factors contributing to the emergence and spread of AMR. Additionally, it identifies existing research gaps and the current state of AMR. A significant emphasis is placed on using Markov models in medical decision-making. These models are crucial for accurately representing the long-term costs and health outcomes related to AMR foodborne pathogens, particularly given the chronic nature of the health issues they cause.

2.2. Antimicrobial Resistance

The rise of antibiotic resistance in pathogens has emerged as a significant global health challenge in the last few decades. Norovirus, *Campylobacter* spp., and nontyphoidal *Salmonella* spp. stand out as the top three causes of foodborne illness, representing 90% of the total pathogen-specific illnesses in Canada (Thomas et al. 2013). The primary transmission method is through the consumption of raw or undercooked foods, especially meats and dairy products, as well as contaminated water (Naushad, Ogunremi, and Huang 2023). The symptoms include diarrhea, fever and abdominal cramps, and individuals may require hospitalization and even risk death in severe cases. Many of these outbreaks have been caused by antibiotic-resistant strains of the bacteria, leading to treatment complications and increased hospitalizations.

Determining whether bacteria are resistant or susceptible to antimicrobial agents requires assessment of their reaction to specific antibiotic concentrations, known as minimum inhibitory concentrations (MIC) (Naylor 2019, Reygaert 2018). The MIC is the lowest concentration of an antibiotic that prevents bacterial growth. Bacterial susceptibility is not uniform across species (José Luis Martínez 2014). It varies and is influenced by both intrinsic properties and acquired resistance genes. The susceptibility of a bacterial species to an antibiotic is gauged by comparing its average

MIC to established ranges. If the average MIC falls within the resistant range for that drug, the species is considered intrinsically resistant. Conversely, bacteria are considered susceptible if they exhibit inhibited growth at an antibiotic concentration commonly associated with effective treatment outcomes (Reygaert 2018). These classifications are based on MIC thresholds or breakpoints set by authoritative organizations such as the European Committee on Antimicrobial Susceptibility Testing (Naylor 2019).

2.2.1. The Case of *Salmonella* spp. and *Campylobacter* spp.

Salmonellosis is the term for an infection caused by the bacteria *Salmonella*. There are two broad types: typhoid and nontyphoid. Nontyphoid salmonellosis is more common in developed countries and is caused by various *Salmonella* serotypes. It also causes food poisoning symptoms such as diarrhea, cramps, and fever. In extreme cases, individuals may develop enlargement of the spleen and lymph nodes, fluid accumulation in organs such as the lungs, liver damage, and even chronic arthritis known as Reiter's syndrome (Eng et al. 2015, Naushad, Ogunremi, and Huang 2023). It is worth noting that *Salmonella* spp. can survive in dry environments for weeks and even longer in water. Their survival is not affected by freezing temperatures but is destroyed at temperatures above 75°C (Naushad, Ogunremi, and Huang 2023). This resiliency emphasizes the importance of proper food cooking and handling procedures to prevent transmission.

Campylobacter enteritis is a notable bacterial foodborne illness in Canada, with an estimated 447 cases per 100,000 people yearly (Thomas et al. 2013). Although many people recover from Campylobacteriosis without medical intervention, some cases require antimicrobial treatment (Dramé et al. 2020). *Campylobacter jejuni* is considered a leading cause of gastroenteritis worldwide and may lead to autoimmune diseases such as Guillain-Barré syndrome

(GBS) and Miller Fisher syndrome (Kaakoush et al., 2015). Sundström (2018) showed that the incidence and economic impact of *Campylobacter* infection exceeds that of *Salmonella* spp., and long-term health consequences or sequelae after infection double the estimated costs.

2.2.2. The Case of Chicken

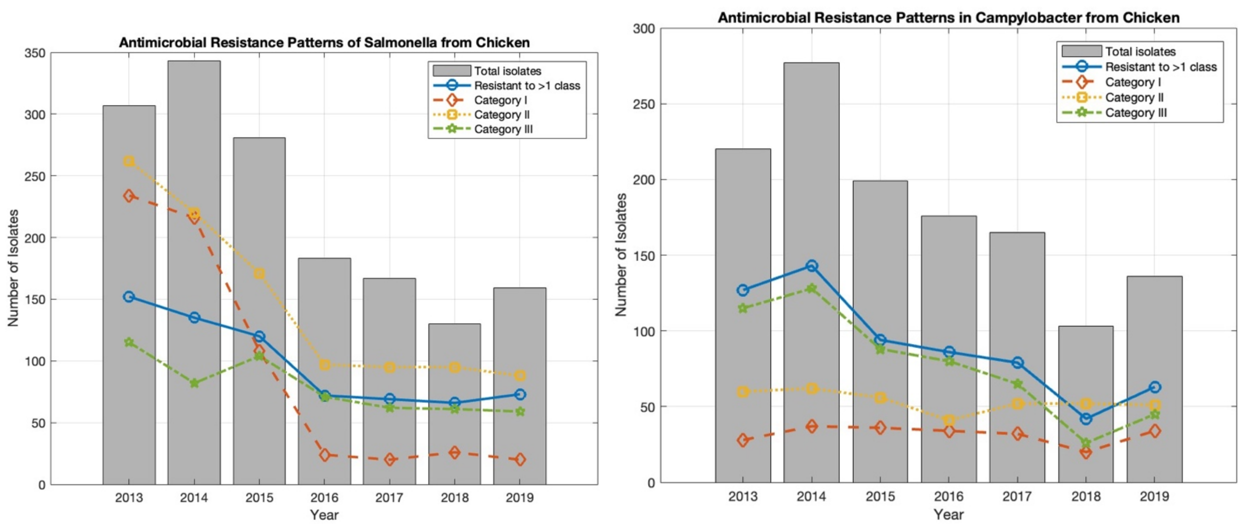
Antimicrobial-resistant *Salmonella* spp. is a prominent problem in poultry production. After introducing fluoroquinolones in 1995 to promote poultry farming, widespread use of these antibiotics led to a surge in antibiotic-resistant *Salmonella* spp. (Nair, Venkitanarayanan, and Johny 2018). Despite the later withdrawal of certain antibiotics like fluoroquinolones, resistant strains remain prevalent in poultry and pose a health risk. The farm environment is often a hotspot for these resistant pathogens. *Salmonella* variants such as *S. Enteritidis*, *S. Infantis*, *S. Typhimurium*, and *S. Heidelberg* have been frequently found in broiler chicken carcasses, with many showing resistance to multiple drugs (Augusto et al. 2011). Studies also report a high prevalence of antibiotic-resistant *Salmonella* spp. in retail poultry meat. In Canada, investigations from different provinces show that a substantial portion of retail meat samples contains *Salmonella* spp. resistant to several antibiotics (CARSS 2022).

Campylobacter spp. is ubiquitous in various environments and commonly found in the food-producing animals intestines, especially poultry. Almost all broiler chickens in a flock may harbour *Campylobacter jejuni* (Dramé et al. 2020). Human infections usually result from poultry consumption, but raw milk and untreated water are also potential sources (Sahin, Morishita, and Zhang 2002). International travel and subsequent consumption of contaminated food and water exacerbate this spread (Kaakoush et al., 2015). The role of water is twofold: it acts as a medium for spreading *Campylobacter* spp. to birds and animals and is a vector for further contamination when animal manure is introduced into water sources. The use of antimicrobial agents in food-producing animals, whether for prevention, treatment, or growth promotion, is a cause for concern.

In Canada, CIPARS has been actively tracking AMR in enteric bacteria across the "farm to fork" continuum, including livestock, abattoirs, retail meats, and human clinical cases (Public Health Agency of Canada 2022). This program highlights the evidence of AMR in bacteria from retail meats such as poultry, beef, and pork, noting substantial regional and temporal variations. The surveillance at the retail level, mainly through the Retail Meat Surveillance component of CIPARS, focuses on assessing human exposure to resistant bacteria via the consumption of raw meat (Avery et al. 2014). CIPARS publishes annual reports that detail the prevalence and trends in AMR across various sectors.

Between 2016 and 2020, substantial progress was observed in reducing antimicrobial use and resistance in poultry and pigs across sentinel farms (Public Health Agency of Canada 2023). A general declining trend in the total number of isolates and multi-class resistance from retail chicken is shown in Figure 2.1. For *Salmonella* spp., Category I appears to decrease over the years, while Category II shows an initial drop until 2015 and then stabilizes. Category I and II for *Campylobacter* spp. also show a decreasing trend, particularly after 2016. Results from Dramé et al. (2018) were consistent with CIPARS, showing that of 1,460 tested isolates, 53% demonstrated resistance to at least one antimicrobial. Regional disparities were noted, with British Columbia showing higher resistance to quinolones while Ontario and Quebec exhibited higher resistance to several other antimicrobials. There was no notable difference in resistance between samples from slaughterhouses and retail establishments, suggesting that AMR originates at the earlier stages, possibly on farms (Dramé et al. 2020). These changes coincide with regulatory changes and policy interventions by Health Canada in 2017 and 2018 aimed at controlling the use of medically important antimicrobials. These include prescription-only access to such antimicrobials, removal of growth-promoting claims, sector-specific initiatives targeting the prophylactic use of certain antimicrobials, and federal efforts to improve labelling and access to antimicrobial alternatives (Public Health Agency of Canada 2023).

Figure 2.1 AMR patterns of *Salmonella* spp. and *Campylobacter* spp. from chicken (2013-2019)



Source: CIPARS 2013 - 2019

2.3. Incidence and Prevalence of AMR in Foodborne Pathogens

Many studies have been done to model the incidence (number of new patients) and prevalence (the total number of patients) of foodborne disease. Estimating the number of human cases due to foodborne pathogens is the starting point for estimating the BOI. The general method of counting the number of patients is to extract the annual incidence number from the surveillance report directly, multiply it by the underreporting multiplier and the percentage of specific food categories (Adhikari, Angulo, and Meltzer 2004, Jain, Mukhopadhyay, and Thomassin 2019, Sundström 2018, Thomas et al. 2013). In contrast, the stochastic model proposed by Otto et al.

(2014) accommodated the uncertainties inherent in the data, such as population variability, measurement error, and uncertainty in model parameters, resulting in a more realistic estimate of the number of cases.

Stochastic models generate a range of possible outcomes, making it possible to assess the probabilities of different scenarios and identify high-risk areas or populations. They allow for sensitivity analysis, which can provide insights into how different assumptions or model parameters affect the final estimate. Using a stochastic model, Otto et al. (2014) provided a comprehensive estimate of human cases of ceftiofur-resistant *Salmonella* enterica in Quebec and Heidelberg in Ontario from 2003 to 2011. The model has four parts and incorporates uncertainty in the input variables through stochastic simulation. The result of this study provides a basis for future estimates of the increased severity, mortality, and medical costs associated with these pathogens.

Statistical modelling is another method used to determine the prevalence of foodborne illness. A study by Van Cauteren et al. (2017) estimated the number of illnesses, hospitalizations, and deaths caused by 15 foodborne pathogens in France between 2008 and 2013. This approach integrates data from surveillance systems, laboratory networks and hospital records, using statistical models to estimate the burden of foodborne illness. The study identified *Campylobacter* spp., nontyphoidal *Salmonella* spp., and Norovirus as the leading causes of foodborne pathogen-related illness and hospitalization, accounting for more than 70% of these events. Nontyphoidal *Salmonella* spp. and Listeria monocytogenes were primarily responsible for deaths. However, reliance on existing surveillance and hospital data may lead to underreporting and underdiagnosis, potentially leading to an underestimation of the actual burden of foodborne illness. The accuracy of a statistical model and its assumptions depends heavily on the quality and completeness of the input data. Developing more sophisticated models that account for varying degrees of underreporting and underdiagnosis across pathogens and population groups will be critical to improving the accuracy of these estimates.

2.4. Symptoms and Chronic Sequelae of Foodborne Diseases

Recent studies have expanded our understanding of the long-term health effects of acute foodborne infections. Batz, Henke, and Kowalcyk (2013) indicate that these infections may lead to chronic sequelae affecting multiple organ systems that appear weeks to years after infection. These complications are challenging to quantify due to factors such as epidemiological constraints, latency of sequelae, and diverse disease mechanisms, making it difficult to establish direct causation (Hoffmann and Walter 2020). Furthermore, the interaction of host genetics, environmental factors, and the nature of the microbial insult adds complexity to these conditions. The limited detection of certain pathogens and scarcity of systematic long-term data further hinder the comprehension of these effects. Comprehensive, long-term, prospective studies are critical to gain a better understanding of the long-term consequences of these infections and to account for the complex interactions between host, environment, and pathogens (Batz, Henke, and Kowalcyk 2013).

Traditionally, the impact of foodborne disease is estimated through acute incidence rates (Batz, Henke, and Kowalcyk 2013). This method may overlook the chronic and potential sequelae of these infections. Integrated approaches including disability-adjusted life years (DALYs) and quality-adjusted life years (QALYs), provide a more comprehensive view by covering the full range of disease outcomes. The costs associated with conditions such as GBS during

Campylobacter infection demonstrate the need for broader economic assessments of foodborne illness that consider long-term health consequences and their public health implications.

The relationship between nontyphoidal *Salmonella* and chronic sequelae such as reactive arthritis (RA) and irritable bowel syndrome (IBS) is complex. Keithlin et al. (2014) found significant variability in the proportion of cases developing these conditions, suggesting that a unified approach is insufficient to understand these sequelae. Factors contributing to this variability include study size, follow-up duration, and diagnostic methods, emphasizing the need for standardized diagnostic criteria and consistent reporting in future research. Similarly, Esan et al. (2017) observed a high heterogeneity among studies examining the effects of proton pump inhibitors and antibiotics on developing sequelae. This variability was partly attributed to differences in healthcare access and practices and follow-up duration. Table 2.1 shows the complexity and diversity of the symptoms, sequelae, and complications of *Salmonella* spp. and *Campylobacter* spp. infections. Further research should emphasize the broader economic impact of foodborne illnesses beyond direct medical costs, including long-term health consequences and their implications for public health policy and regulation.

Table 2.1 The common symptoms, sequelae, and complications of *Salmonella* spp. and *Campylobacter* spp. Infections

	Symptoms	Sequelae	Complications
***Salmonella* spp.**	Vomiting and nausea	Reactive Arthritis (RA)	Cardiovascular complications
	Chills	Hemolytic Uremic Syndrome (HUS)	Central Nervous System complications
	Diarrhea	Irritable Bowel Syndrome (IBS)	Pulmonary complications
	Stomach cramps	Ulcerative Colitis (UC)	Reactive arthritis
	Fever	Crohn’s disease	Osteomyelitis
	Headache	Guillain-Barré Syndrome (GBS)	Hepatobiliary complications

		Miller Fisher Syndrome (MFS)	
		Inflammatory Bowel Disease (IBD)	
***Campylobacter* spp.**	Headache	Reactive Arthritis	*Campylobacter* infection relapse
	Fatigue	Guillain-Barré Syndrome	Reactive arthritis
	Fever	Irritable Bowel Syndrome	Hemolytic uremic syndrome
	Abdominal cramps	Inflammatory Bowel Disease	Meningitis
	Nausea or vomiting		Recurrent colitis
	Bloody diarrhea		Cholecystitis
			Urinary tract infections
			Guillain-Barre syndrome

Source: Batz, Henke, and Kowalcyk (2013), Kaakoush et al. (2015), Keithlin et al. (2014), Rigby et al. (2017), and Schorling et al. (2023)

2.5. Burden of Illness

The concept of the BOI described in public health and epidemiology combines the assessment of mortality and morbidity. This approach focuses on non-fatal outcomes, with a particular emphasis on healthy quality of life (Hessel 2008). The term 'burden' in this context refers to the adverse effects of a health condition (McGuire et al. 2002). It covers the impact on an individual's well-being and the wider impact on their family and social network. Historically, disease burden has been quantified using indicators such as “years of life lost” (YLL), which primarily measure premature mortality (Hessel 2008). However, recent developments have led to the adoption of more comprehensive indicators such as DALYs and QALYs.

Disability-adjusted life years was developed through a collaboration between Harvard University researchers and the WHO’s Global Burden of Disease Project. It combines YLL due to premature death with "years lived with disability" (YLD) (Hessel 2008, McLinden 2013). In contrast, QALYs measure both the quality and quantity of life gained, focusing on improvements in health status rather than solely tracking deterioration (McGuire et al. 2002). QALYs are widely used in cost-effectiveness analysis to evaluate healthcare interventions that enhance quality of life or extend life expectancy, making them useful for assessing clinical outcomes. In addition, Health Canada uses health-adjusted life years (HALYs), another composite measure that combines aspects of premature death and functional decline due to disease (Bushnik, Tjepkema, and Martel 2018). These measures, whether DALYs, QALYs, or HALYs, are critical for policymakers in prioritizing resources and addressing disease-related problems. In this study, QALYs are well-suited for evaluating interventions that improve health outcomes, such as new treatments or preventive measures.

In the context of foodborne pathogens in the United States, Hoffmann, Batz, and Morris (2012) studied the cost of illness and QALYs lost due to 14 foodborne pathogens. This study utilizes disease outcome trees to describe the probabilities of symptoms, severity, duration, outcomes, and health states associated with each pathogen. The EQ-5D scale was used to calculate QALY loss for each health state. They also estimated the cost of illness, including medical expenses, lost productivity and the value of premature death for each pathogen. Their findings indicate that these pathogens collectively account for approximately $14 billion in disease costs and 61,000 QALYs lost annually. Notably, pathogens such as nontyphoidal *Salmonella enterica*, *Campylobacter* spp., *Listeria monocytogenes*, *Toxoplasma gondii*, and Norovirus account for approximately 90% of these losses.

2.6. Economic Burden of Illness

The economic burden of disease represents a critical dimension of healthcare analysis beyond traditional health metrics such as DALYs and QALYs. This dimension involves the monetary quantification of disease outcomes, providing a comprehensive perspective on the financial impact of health conditions (McLinden 2013). Cost of illness (COI) analysis is a key component of the field, which assesses costs at individual and societal levels (Jo 2014). This contrasts with other forms of economic evaluations such as cost-effectiveness analysis (CEA) and cost-benefit analysis (CBA). While COI studies form the basis for broader economic evaluations, CEA compares costs with health outcomes, using natural health units such as QALYs to assess benefits (Brent 2023). Conversely, CBA assesses costs and benefits in monetary terms. Over time, these studies have evolved from broad disease category assessments to more detailed analyses of specific diseases. They play an important role in highlighting health issues, informing healthcare service planning, and evaluating policy options.

There are two primary epidemiological approaches in COI studies: prevalence-based and incidence-based (Jo 2014). Prevalence-based studies focus on the total number of existing cases within a given time frame, thereby reflecting the total cost of a disease at a specific point in time (McLinden 2013). Alternatively, incidence-based studies assess the lifetime costs of newly diagnosed cases in a defined base year, including economic discounting (Jo 2014). This approach is suitable for diseases where costs vary with the duration of the condition and is critical for planning targeted medical interventions. Both strategies require precise and clinically relevant case definitions to estimate disease burden accurately.

2.6.1. Direct Cost and Indirect Cost Estimation Methods

COI studies divide costs into direct, indirect, and societal costs (McGuire et al. 2002). Direct costs are those directly related to the treatment and management of a disease. These can include healthcare services, medications, and hospitalizations. Indirect costs cover the economic impact beyond direct medical expenses, such as lost productivity due to absence from work or reduced ability to work, as well as intangible costs, such as pain and suffering (Jo 2014). While direct costs are generally easier to measure, indirect costs pose considerable challenges because they require econometric estimates to assess the impact of disease on employment and earnings (McGuire et al. 2002). Societal costs cover a wider range of expenditures across sectors such as industry and government and extend to public health and legal activities (Jo 2014). Aggregating these costs provides a comprehensive understanding of the economic impact of disease, which is critical for strategic healthcare planning and policy development.

A variety of methods are used to estimate direct costs in COI studies. Top-down approaches, also known as aggregation approaches, involve allocating a portion of total healthcare expenditures to specific disease categories. In contrast, bottom-up or individual approaches calculate costs by multiplying unit costs by service utilization rates (Jain, Mukhopadhyay, and Thomassin 2018). Another approach is the econometric approach, which involves comparing healthcare costs for people with and without a disease. The choice of method depends on factors such as the nature of the disease, the purpose of the study, and data availability. In the United States, direct cost data typically come from national datasets and surveys such as the National Hospital Discharge Survey, while in Canada, sources such as the Canadian Institute for Health Information's National Health Expenditure Trends are utilized.

Indirect costs are mainly measured using the human capital approach (HCA) or the willingness to pay (WTP) approach. HCA focuses on quantifying productivity losses due to morbidity and mortality, whereas WTP methods assess an individual's monetary value of a reduced likelihood of illness (Jain, Mukhopadhyay, and Thomassin 2018, Shrestha et al. 2018). While HCA tends to underestimate costs for demographics such as the elderly or children, the WTP approach can more effectively cover intangible costs but is more complex to implement. Other approaches include the integrated WTP-HCA approach and the frictional cost approach, which only considers productivity losses over the period required to replace workers. Data sources for HCA typically include government statistics on disability and the workforce, whereas WTP methods often rely on surveys and other primary data collection techniques. Each method has unique advantages and limitations that can contribute to a comprehensive understanding of disease-related indirect costs.

In the context of *Salmonella* infections in the United States, Adhikari, Angulo, and Meltzer (2004) used laboratory-confirmed case data and FoodNet multipliers to estimate the economic burden. They categorized treatment costs according to the type of *Salmonella* infection, distinguishing between invasive and gastrointestinal forms due to different cost implications. Their findings showed the substantial costs associated with *Salmonella* infections, including average medical expenditures and lost productivity of $210 per outpatient and up to $16,441 in lost productivity per inpatient due to invasive infections. The total burden was estimated to be $2.8 billion. Jain, Mukhopadhyay, and Thomassin (2018) conducted a comprehensive benefit-cost analysis of foodborne illness caused by nontyphoidal *Salmonella* species. The annual costs associated with *Salmonella* from various food sources and the economic benefits of introducing WGS in outbreak detection in Canada are described. They estimated the total net benefits from the introduction of WGS to be $90.25 million (in 2013 CAD), which translates into an increase in industrial output of $15.88 million, an increase in GDP of $13.38 million and labour of 116.

2.6.2. Cost of Foodborne Illness

Cost-of-illness estimates for foodborne illness are critical in deciding food safety interventions. These estimates provide a valuable tool for assessing and quantifying the impact of foodborne illness, which can vary widely in severity and incidence (Hoffmann and Walter 2020). However, these estimates are often challenged by methodological inconsistencies and difficulty in accurately determining the number of diseases and severity of outcomes. An important problem with foodborne disease data is underreporting, which can lead to underestimation of the actual burden of these diseases.

The study by Sundström (2018) in Sweden addressed the discrepancy between reported and actual foodborne illness cases. He applied the COI method to analyze four post-infectious sequelae for major foodborne diseases such as campylobacteriosis and salmonellosis. The study used a variety of methods, including friction costing and human capital methods, to estimate direct and indirect costs. The findings showed that the actual number of cases, especially those of the *Campylobacter* genus, was far higher than reported, meaning that sequelae accounted for a substantial portion (approximately 50%) of the total costs. This emphasizes the importance of considering information loss and post-infectious sequelae in cost estimates.

In Canada, Thomas et al. (2013) and Thomas et al. (2015) estimated the burden of foodborne diseases from 2000 to 2010. Their first study examined underreporting and underdiagnosis, estimating the proportion of domestically acquired diseases and those transmitted through foodborne routes. They identified Norovirus, C. perfringens, *Campylobacter* spp., and nontyphoidal *Salmonella* spp. as the leading causes of foodborne illnesses. Their subsequent study focused on hospitalizations and deaths, estimating that approximately 4,000 hospitalizations and 105 deaths per year are associated with these conditions. These studies highlight the need for further research to inform DALYs, provide cost estimates, and facilitate international comparisons.

Drudge et al. (2019) also made a contribution to the field by estimating annual deaths, hospitalizations, and emergency room and physician office visits for 15 diseases in Ontario. Their approach involves calculating burden estimates using attributable fractions, which describe the proportion of disease attributable to all food sources. Studies have shown that nonspecific gastroenteritis was the predominant disease, causing increases in healthcare utilization and mortality. Their results indicate that nonspecific gastroenteritis was the dominant disease, resulting in about 137,000 physician office visits, 40,000 emergency department (ED) visits, 6,200 hospitalizations, and 59 deaths annually in Ontario. Their findings suggest that pathogen-specific approaches to foodborne illness surveillance may underestimate the overall burden caused by foodborne pathogens and other sources of foodborne illness. These studies collectively highlight the complexity of estimating the economic impact of foodborne illness. They emphasize the need for a comprehensive approach to address underreporting and a wide range of health outcomes to more accurately characterize the economic burden associated with foodborne illness.

2.7. Economic Analysis of AMR Pathogens

Economic analyses of AMR pathogens often focus on the healthcare sector and may overlook broader societal costs and benefits. To address this problem, more comprehensive models are used, such as computable general equilibrium (CGE) models. CGE models view the economy as a network of interrelated markets while establishing equilibrium values for all variables. Taylor et al. (2014) used a CGE model to estimate AMR's current global economic burden and project its future impact to 2050 under various scenarios. The study divides the economy into different regions and analyzes the impact of regions on the global economy. It links changes in effective labour supply to changes in production and consumption, thereby linking the spread of antimicrobial resistance to economic dynamics. The study hypothesized that antimicrobial resistance would reduce labour efficiency, leading to lower production, consumption, and overall welfare. The model also covers the direct and indirect economic impacts of antimicrobial resistance, including impacts on trade and investment. The findings suggest that AMR could reduce the global working-age population and GDP, with Eurasia facing the greatest losses. In the worst-case scenario, based on current mortality rates, cumulative losses could reach $49.4 trillion, equivalent to three-quarters of global GDP (Taylor et al. 2014).

Ahmed et al. (2018) broadened this perspective by examining AMR's impact on global poverty using a macro-micro framework. Using a multi-country, multi-sector CGE model, they predict that AMR could increase the number of people living in extreme poverty by 24.1 million, most of whom live in low-income countries. The study estimates GDP losses at $85 trillion and global export losses at $23 trillion between 2015 and 2050, with the global GDP baseline likely to deviate by 3.8% by 2050. Smith et al. (2006) also applied a CGE model to assess the economic effects of AMR and containment policies, including regulation, permits, and taxes/charges. The model evaluated the impact of these policies on various economic indicators such as labour productivity, GDP, and household income. The findings highlighted that AMR affects healthcare and disrupts overall economic productivity, increasing wages, prices, and production costs, and reducing output, profits, and welfare. Among the proposed solutions, the permit system was identified as the most effective to optimize antimicrobial consumption and reduce resistance.

CGE models have the advantage of capturing endogenous interlinkages between markets, which is crucial for comprehensive analysis. However, these models are complex and rely on numerous assumptions, which may not always reflect real-world conditions. Aggregating public and private sector consumption and production, including healthcare services, may oversimplify the analysis. Additionally, these models may not fully capture the complexity of economic interactions and are sensitive to underlying assumptions. In contrast, the Input-Output (IO) Model discussed by Jain, Mukhopadhyay, and Thomassin (2018) provides a more direct representation of inter-industry relationships. The model helps analyze the economic linkages between different industries and provides an alternative approach to understanding the macroeconomic impact of foodborne disease.

2.8. Markov Model

Markov models are a fundamental tool for decision-making in situations where there are continuous risks over time, the timing of events is critical, and significant events can occur multiple times (Sonnenberg and Beck 1993). These models classify patients into different health states and simulate transitions between these states to represent different events. Techniques such as matrix algebra, cohort simulation, and Monte Carlo simulation are used to evaluate these models. A key assumption of Markov models is that an individual is in only one state during each cycle, with the simplest models including only the "alive" or "dead" states. However, for more complex or non-fatal diseases, intermediate states such as complications or recovery are included.

Markov models have broad applications, including assessing the cost-effectiveness of public health interventions, such as introducing the typhoid conjugate vaccine in India (Chauhan et al. 2021), and identifying cost-effective options in medical treatments (Virk, Sandhu, and Khan

2012), and estimating the economic burden of mental illness and chronic illness (Lin et al., 2014; Song et al., 2013). Herrick et al. (2011) used Markov models to estimate the severity, duration, and cost of *Salmonella* spp. Outbreaks include self-treatment, physician/emergency room visits, hospitalizations, recovery, and death. The model demonstrates the utility of Monte Carlo simulation in predicting a range of outcomes for large numbers of patients, including disease severity and associated costs.

A study conducted in the UK by Rigby et al. (2017) estimated pain and suffering caused by major foodborne pathogens using QALYs and WTP metrics, calculated by Markov transition models (MTM) and stated preference surveys, respectively. The results showed that *Campylobacter* spp. and Norovirus dominated the overall QALY burden, accounting for 52% and 36% of the ten pathogens considered. The WTP increased with respondents' income level, and the study estimated the monetary value of a QALY to range between £6,100 and £61,500. However, they also identified limitations of Markov models, such as their inability to account for individual's past experiences with disease, suggesting that subgroup-specific models are needed to reflect the different experiences and outcomes of different demographic groups.

In a related context, Naylor (2019) focused on estimating the burden of *E. coli* infections in the UK using a cohort simulation model. The study categorized the population by age and sex and estimated the burden from patient, healthcare, and economic perspectives. Similarly, Regula et al. (2005) used Markov chain Monte Carlo simulations to evaluate sampling strategies for estimating fluoroquinolone resistance in *Campylobacter* spp. from poultry. They show the model's ability to predict AMR prevalence while accounting for uncertainties in prevalence, sampling, and diagnostic testing. Overall, these studies demonstrate that Markov models can capture the progression of diseases and interventions over the long term, making them applicable to chronic and recurrent diseases such as AMR infections.

2.9. Literature Review Summary

The emergence and spread of AMR pose a considerable health and economic burden and have a significant impact on public health systems worldwide. Overuse and inappropriate regulation of antimicrobials in animal food production have been identified as critical factors in the increase in antimicrobial-resistant zoonotic pathogens. This results in the spread of these pathogens to humans through environmental exposure and the food chain, resulting in varying degrees of foodborne illness and associated economic costs. Furthermore, surveillance data from CIPARS Canada have provided valuable insights into AMR patterns in enteric bacteria, showing an overall downward trend in antimicrobial use and resistance in poultry and pigs (Public Health Agency of Canada 2023). Regional differences in resistance patterns highlight the complexity of the problem and the need for targeted interventions. Therefore, given the chronic nature of AMR foodborne pathogens, a comprehensive framework is needed to assess their associated long-term costs and health outcomes.

Chapter 3. Methodology and Data

This chapter outlines the methodological framework and data sources used to analyze the cost of AMR foodborne illness and its macroeconomic impact on the Canadian economy. It presents the use of Markov models to estimate the individual costs of AMR foodborne pathogens and antibiotic-susceptible foodborne pathogens. Additionally, it explains the methods used to quantify the transition probabilities, duration, and utility values associated with these health states. Input-output analysis is used to assess the broader economic impact, enabling an evaluation of changes in industrial output, GDP, and employment. This chapter is divided into two parts: the first focuses on developing and applying the Markov model, and the second on constructing the input-output model to determine the macroeconomic impacts. This structured approach allows for a comprehensive exploration of both the direct health impacts and the indirect economic impacts of AMR foodborne illness in the Canadian context. Using the Markov model, a case study is included to illustrate the impacts of the voluntary reduction of Category I and Category II antimicrobials by Canadian poultry farmers between 2015 and 2019.

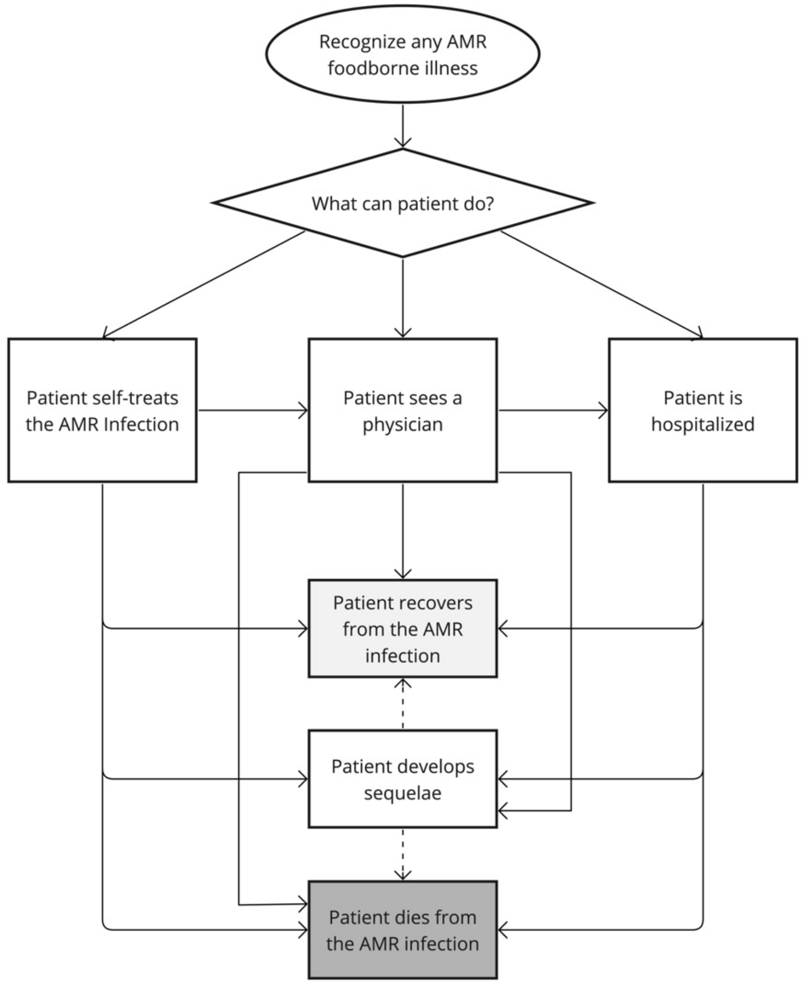
3.1. Markov Model Monte Carlo Simulation

Markov models provide a robust framework for estimating AMR foodborne illness's health and economic burden, capturing the complexity of disease transmission, recurrence, and the long-term impact of AMU interventions. In a Markov model, an individual moves through a sequence of health states over time, each with a specific probability of transitioning to another state or remaining in the current state, reflecting the duration of symptoms (Sonnenberg and Beck 1993). Each health state is assigned a health utility value or a cost that reflects the severity of being in that state. The model aggregates values based on the distribution of cases across different health states to calculate a population's cumulative health utility or cost over time. Disease burden is then assessed by comparing cumulative QALYs or costs to a baseline scenario in which the population was not affected by the AMR foodborne pathogen.

The basic elements of a Markov model include different health states. These health states must have mutually exclusive and exhaustive properties (Drabo and Padula 2023). Mutually exclusive states prevent an individual from appearing in multiple states simultaneously at any point in time. A set of states is considered exhaustive if it contains all possible states are relevant to the disease process (Drabo and Padula 2023). Within this framework, health states are divided into two categories: absorbing states and transient states. Absorbed states, such as death or permanent recovery, represent the final stage of transformation without subsequent transformation. For example, once people are in a dead state, they cannot move from that state to another state, so the dead state is an absorbing state (Herrick et al., 2011).

The flowchart in Figure 3.1 illustrates the decision-making process and subsequent pathways for individuals moving from recognizing AMR foodborne illness symptoms to one of three therapeutic interventions: self-treatment, consultation with a physician, or hospitalization. This study assumes that each event in the flowchart is discrete, meaning that individual progression does not occur repeatedly. Post-treatment trajectories were divided into three potential outcomes: recovery, chronic sequelae, or in the most severe cases, death from AMR infection. The flow chart below supports the construction of the Markov model in Figures 3.2 and 3.3.

Figure 3.1 The actions of a patient determine the potential outcomes of AMR infection.



The selection of sequelae in this analysis is based on their contribution to the long-term health impact on individuals. The persistence of IBS symptoms was demonstrated in a study by Agréus et al. (2001), in which 86.4% reported symptoms ten years after diagnosis, emphasizing the chronic nature of this sequelae. RA is modeled to acknowledge its potential for chronicity and relapse. The model predicts that relapsed RA cases will resolve within a year, rejoining the pool of potential relapses. GBS was included due to its acute severity and variable prognosis. In severe cases, GBS can lead to respiratory failure and possibly death. The duration of GBS symptoms varies from person to person; therefore, the model uses point estimates derived from multiple studies for baseline calculations. The time frame of the Markov cycle is critical and was chosen to reflect clinically relevant intervals. This study uses an annual cycle, which reduces the complexity of a monthly cycle length model and helps estimate the annual disease burden associated with the health conditions considered (Sonnenberg and Beck 1993). A lifetime horizon is modelled over 100 years to account for the chronic sequelae of AMR infections and long-term productivity costs associated with mortality.

Figure 3.2 Markov Model of *Salmonella* Infection

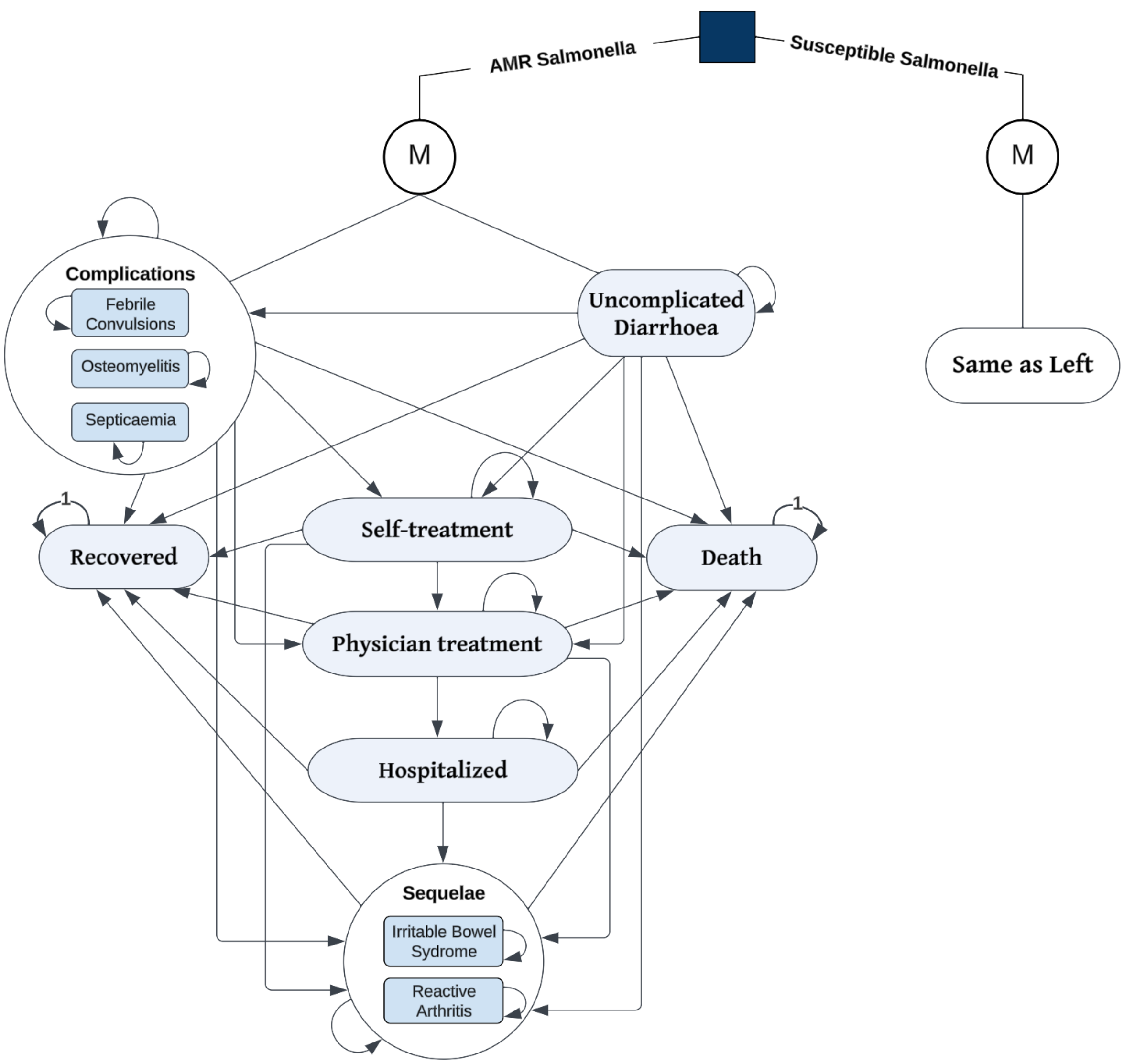
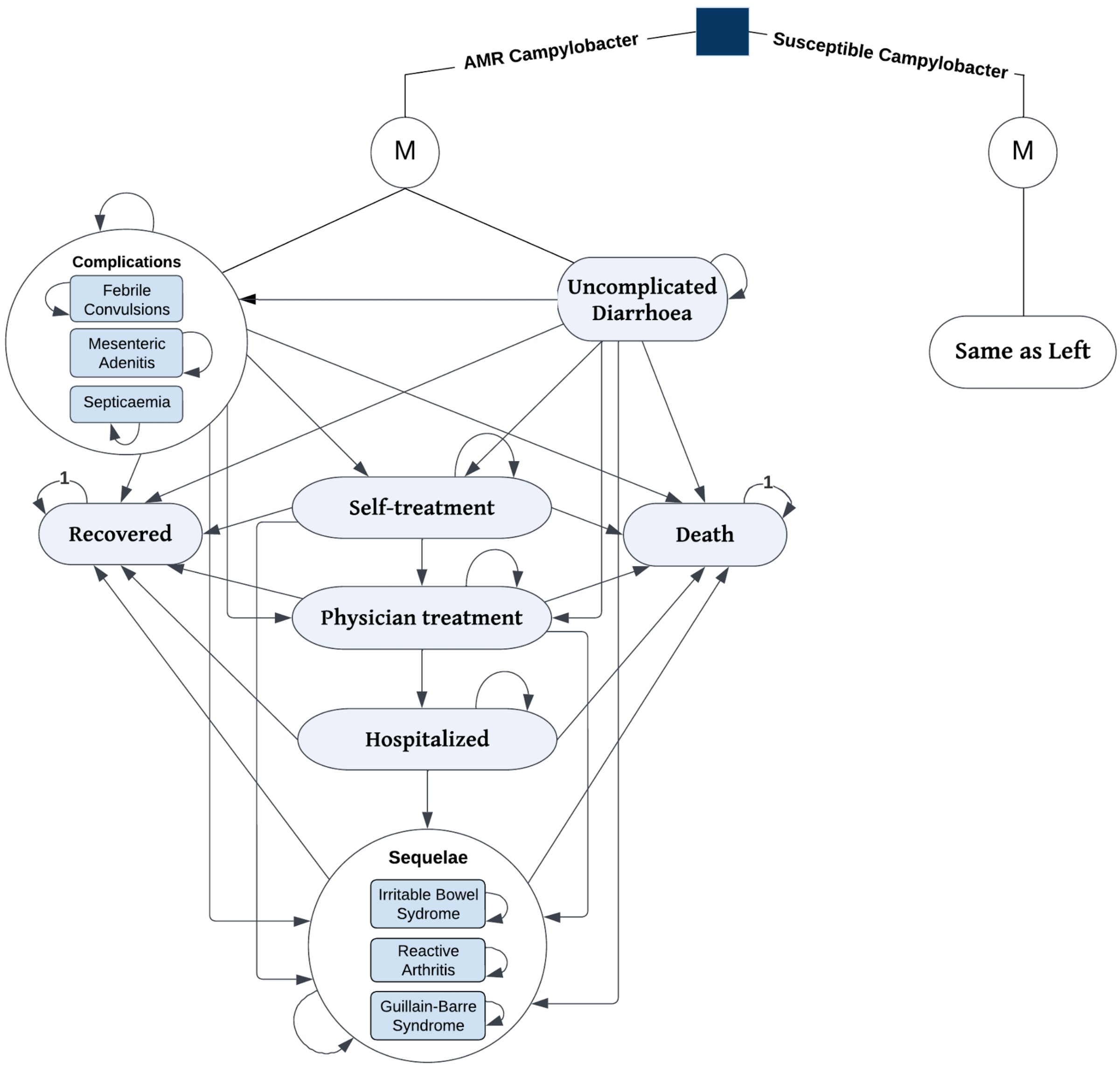


Figure 3.3 Markov Model of *Campylobacter* Infection



The model was built and analyzed using TreeAge Pro Healthcare 2024 software (TreeAge Software, Williamstown, MA, USA). Figure 3.2 shows the Markov model outlining the progression of *Salmonella* infections by dividing it into AMR and susceptible strains. The model contains eight health states representing the clinical cycle of AMR infections. Patients are initially classified based on the severity of diarrhea, which may be uncomplicated or accompanied by severe illness such as febrile convulsions, osteomyelitis, and septicemia. Treatment pathways are divided into self-treatment or physician treatment, which can potentially result in hospitalization. It is assumed that patients have to visit physicians before hospitalization. The model simulates the progression from initial treatment to subsequent health outcomes, including full recovery, the development of long-term sequelae such as IBS and RA, or death in severe cases. The model stops cycling once the patient recovers or dies. An arrow leading from one state to itself indicates that the patient may remain in that state in successive cycles. This structure allows the analysis of different pathways and outcomes affected by resistance in *Salmonella* pathogens. Figure 3.3 illustrates a similar Markov model for *Campylobacter* infections. While the structure of the model remains unchanged for AMR strains and susceptible strains of *Salmonella* and *Campylobacter*, the inputs (i.e., transition probabilities, utilities, and associated costs) are modified to be consistent with the actual situation of each strain.

Figure 3.4 illustrates the generalized transition probability matrix P of the Markov model. The matrix's rows signify the present health state, while the columns indicate the subsequent state. Each probability P_{ij} represents the probability of transitioning from state i to state j, given the current state i. In addition, the sum of probabilities in each row must equal 1 to represent the exhaustive set of potential transitions from a given state. Markov models assume that the future state depends only on the current state, regardless of the order of previous events. This concept is called the memoryless property or Markov assumption, which assumes that state S(t) is determined only by S(t-1) and, in turn, only affects S(t+1). The Markov hypothesis simplifies stochastic processes by requiring only expressions for joint or conditional probabilities of continuous states (Herrick et al., 2011).

Figure 3.4 Generalized transition probability matrix of Markov model

	From/To	1 Febrile Convulsions	2 Osteomyelitis	3 Septicaemia	. . .	9 RA	a Recovered	b Dead
1	Febrile Convulsions	P11	P12	P13	. . .	P19	P1a	P1b
2	Osteomyelitis	0	P22	P23	. . .	P29	P2a	P2b
3	Septicaemia	0	0	P33	. . .	P39	P3a	P3b
.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.
9	RA	0	0	0	. . .	P99	P9a	P9b
a	Recovered	0	0	0	. . .	0	1	0
b	Dead	0	0	0	. . .	0	0	1

Markov models use two main evaluation methods: cohort simulations and Monte Carlo simulations (Sonnenberg and Beck 1993). In cohort simulation models, a group of hypothetical patients are assumed to be homogeneous and experience the same risks and transitions at any given point in time. This approach aggregates patients into a single cohort, and the model tracks the cohort's progress through the various health states over a fixed time horizon (Drabo and Padula 2023). Due to the aggregated nature of this simulation, it is less computationally intensive and, therefore, faster and less resource-demanding. Cohort simulation is often sufficient for modelling chronic diseases with well-established disease progression patterns, especially when individual variability is not the primary focus of the analysis.

In contrast, Monte Carlo simulation simulates the pathways of individuals through the Markov models one individual at a time (Sanyal et al. 2014). This method incorporates stochastic elements, allowing for the modelling of individual variability by assigning different transition probabilities and time horizons to each simulated individual. Monte Carlo simulations can be adapted to patients with different characteristics and study durations, capturing a wide range of possible outcomes. Due to the level of detail and the individualized approach, this method is computationally more intensive and time-consuming compared to cohort simulations. This study uses the Monte Carlo simulation approach to capture the stochastic nature of patient pathways and uncertainty in outcomes.

3.1.1. Estimating Transition Probabilities in a Markov Model

Estimating transition probabilities between states is critical when building Markov models for health outcomes. These probabilities must reflect the realistic likelihood that such transitions will occur within a specified timeframe. To determine these transition probabilities for our model, a comprehensive review of the published literature was conducted and focused on data relevant to the Canadian context. The review aimed to identify epidemiological studies describing the experiences of patients with each type of foodborne pathogen and the number of cases experiencing different symptoms. Where Canadian data were unavailable, data from high-income countries with comparable settings and populations were used.

There are challenges in deriving transition probabilities for use in Markov models. For example, the literature does not present data in a probabilistic format, and the reported time frame may not be consistent with the model's cycle length (Gidwani and Russell 2020). Therefore, conversion rates of events were needed to convert the range of periods to annual probabilities to match the model’s cycle length (Gebretekle et al. 2021). It is important to note that converting to annual probabilities is not a direct division by the number of years. They require an exponential transformation to account for persistent risk over time. This process can be described as follows:

1. **Rate estimate:** Rate (r) is an estimate of the instantaneous likelihood of a transition occurring at any given point in time. This calculation assumes a constant rate of change over time, a common assumption in continuous-time Markov models. The ratio reflects the intensity of the

transition and is typically expressed as events per unit of time (e.g., per year). The rate is estimated from study data using the formula:

$$Rate = \frac{-ln(1-p)}{t}$$

where p represents the event probability as reported in the study, and t is the duration over which this probability is observed. The negative natural logarithm (ln) of one minus the probability (1−p) ensures that the rate accurately reflects the constant hazard over the period.

2. **Probability estimation:** Once the rate (r) has been determined, the probability of a transition occurring within a specific time interval (t) can be calculated as:

$$P(t) = 1 - e^{-rt}$$

This formula is based on the exponential distribution, which assumes that events occur independently and at a constant rate. For instance, to adjust an annual probability to a monthly rate, the formula used is:

$$p = 1 - exp(-r \times \frac{1}{12})$$

3. **Utilizing relative risk (RR):** When meta-analysis provides relative risk (RR) data, this can adjust the transition likelihood due to interventions. RR is defined as the probability of an event occurring in the exposed group divided by that in the unexposed group (Gidwani and Russell 2020):

$$RR = \frac{P_1}{P_0}$$

Here P_1 and P_0 represent the probabilities of the event in exposed and unexposed individuals, respectively. Given P_0, RR allows for the calculation of P_1, the event probability in the exposed group as:

$$P_1 = \mathrm{RR} \times P_0$$

In addition to transition probabilities derived from the peer-reviewed literature, FoodNet Canada provides a robust source of surveillance data focused on the Canadian situation. As the nation's comprehensive enteric pathogen surveillance program, FoodNet Canada monitors trends in enteric pathogen disease rates and their prevalence in both human cases and various non-human sources. These sources include retail meat such as chicken, beef, and pork, and manure from poultry, cattle, and swine operations, alongside environmental samples from recreational and irrigation water across sentinel sites in Canada. The surveillance network of FoodNet Canada includes four sentinel sites: Ontario, British Columbia, Alberta, and Quebec (Public Health Agency of Canada 2020).

Our study utilized human case data from FoodNet Canada from 2017 to 2019 to estimate transition probabilities and illness durations, primarily due to the availability of AMR data during this period. There was no systematic collection or integration of AMR data for *Salmonella* and *Campylobacter* before 2017, making earlier datasets insufficient for our analysis. Table 3.1 and Table 3.2 provide an overview of relevant variables for *Salmonella* and *Campylobacter* infections in the Canadian FoodNet dataset, classifying cases into AMR and susceptible categories. Although the dataset does not explicitly classify AMR *Salmonella* cases, differentiation is feasible by analyzing genotype and predicted phenotypes data. Over the three-year period, there were 1,045 reported cases of *Salmonella* infections, with AMR cases accounting for approximately 31.4% (328/1045) and susceptible cases constituting 68.6% (717/1045) of the total. It showed a balanced gender distribution, with males representing 50.7% (526/1038) of all cases over the three years. The mean age of individuals with AMR *Salmonella* infections over the three years was lower

(32.48 years) than those with susceptible infections (36.58 years). This suggests that AMR infections might be affecting a younger demographic more.

Table 3.1 Demographic information of *Salmonella* infections used to calculate transition probabilities (2017–2019)

Year	AMR Status	Cases	Female	Male	Bloody Diarrhea	Mean Age	Mean Ill Days
2017	AMR	88	49	39	30	31.5	9.7
2017	Susceptible	254	133	121	61	39.5	10.4
2017	Total	342	182	160	91	37.5	10.1
2018	AMR	126	57	69	31	29.2	12.4
2018	Susceptible	252	120	132	85	32.9	12.5
2018	Total	378	177	201	116	31.7	12.5
2019	AMR	114	58	56	27	36.7	10.4
2019	Susceptible	211	102	109	60	37.3	11.9
2019	Total	325	160	165	87	37.1	11.6

Source: FoodNet Canada

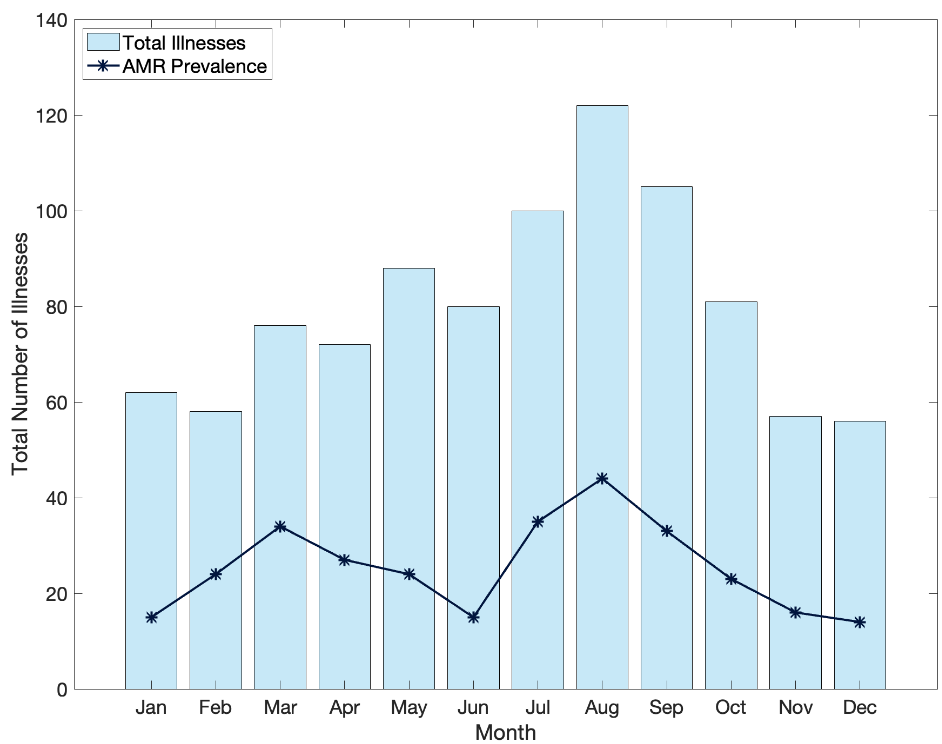
Table 3.2 Demographic information of *Campylobacter* infections used to calculate transition probabilities (2017–2019)

Year	AMR Status	Cases	Female	Male	Bloody Diarrhea	Mean Age	Mean Ill Days
2017	AMR	199	77	122	59	34.4	9.8
2017	Susceptible	145	65	80	52	39.7	9.2
2017	Total	344	142	202	111	36.7	9.5
2018	AMR	210	92	118	64	38.0	11.0
2018	Susceptible	167	83	84	68	37.9	11.5
2018	Total	377	175	202	132	37.9	11.2
2019	AMR	296	115	181	95	40.2	11.3
2019	Susceptible	165	80	85	51	41.8	9.0
2019	Total	461	195	266	146	40.8	10.4

Source: FoodNet Canada

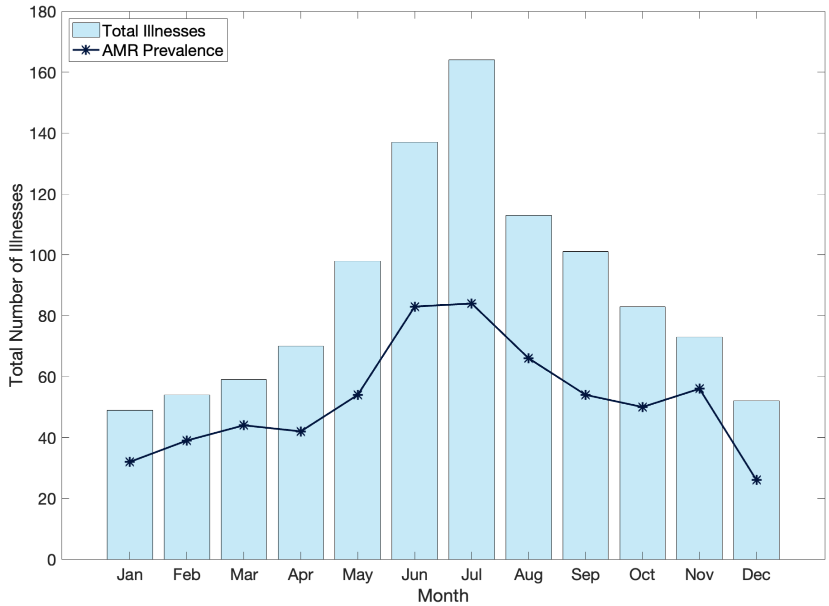
Regarding clinical characteristics, the mean duration of illness is consistent across the years for both AMR and susceptible cases, averaging approximately 11.33 days. Disease duration was estimated by subtracting the reported recovery dates from the symptom onset dates. Figures 3.5 and 3.6 show the monthly distribution of *Salmonella* and *Campylobacter* cases and the percentage of AMR infections. A clear seasonal pattern was observed, with infection rates rising over the summer, with *Salmonella* peaking in August and *Campylobacter* peaking in July. This seasonal change is consistent with a previous study by Akil, Ahmad, and Reddy (2014), which found a similar trend in *Salmonella* spp. It may be associated with factors such as temperature which can affect the proliferation of bacteria in food products and food handling practices.

Figure 3.5 Monthly distribution of *Salmonella* illness counts and AMR percentages in Canada (2017-2019)



Source: FoodNet Canada

Figure 3.6 Monthly distribution of *Campylobacter* illness counts and AMR percentages in Canada (2017-2019)



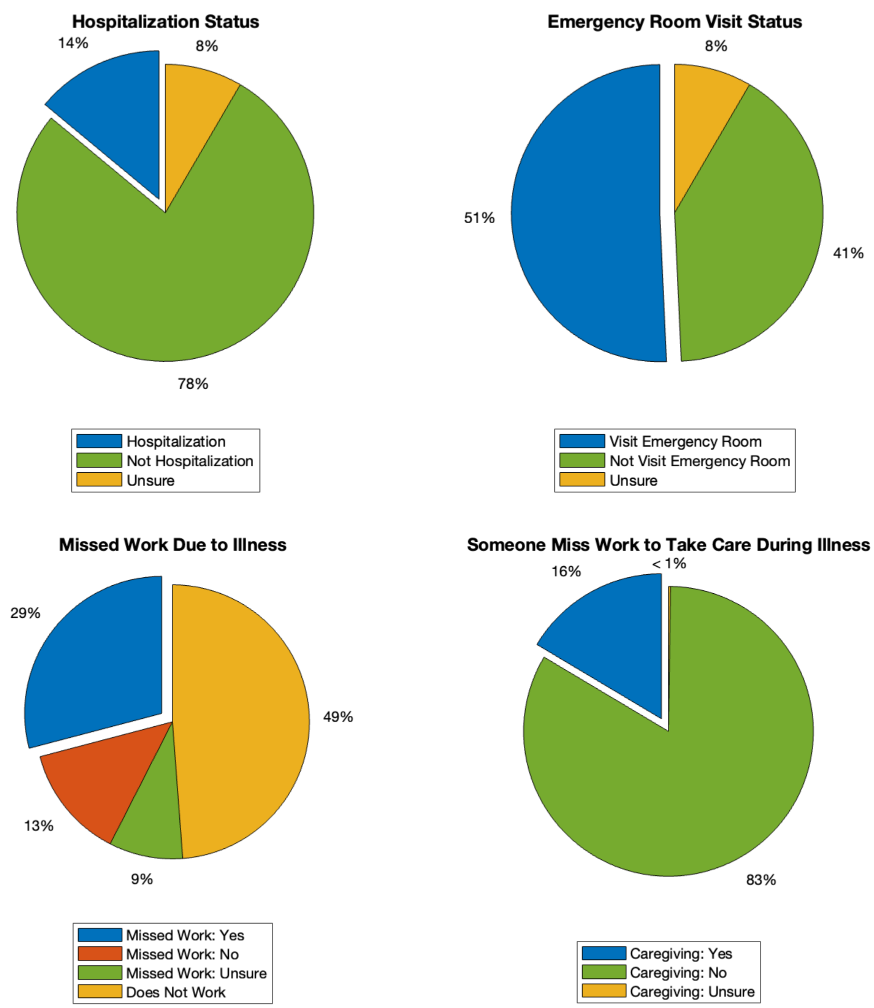
Source: FoodNet Canada

3.1.2. Health States Costs

The Markov model incorporates two categories of costs: nonrecurring and recurring. Nonrecurring costs are fixed expenses that remain unaffected during the cycle length, such as those for one-time laboratory tests. In contrast, recurring costs are usually applied per state per cycle, similar to the cost of remaining in a health state over a defined duration (Chhatwal, Jayasuriya, & Elbasha 2016). The model takes a social perspective in calculating costs and, therefore, includes direct healthcare expenditures (hospitalizations, physician visits, medications) and indirect costs associated with lost productivity due to illness. All costs are expressed in 2019 Canadian dollars, and costs and QALYs are discounted at the WHO recommended annual rate of 3% (World Health Organization et al. 2003).

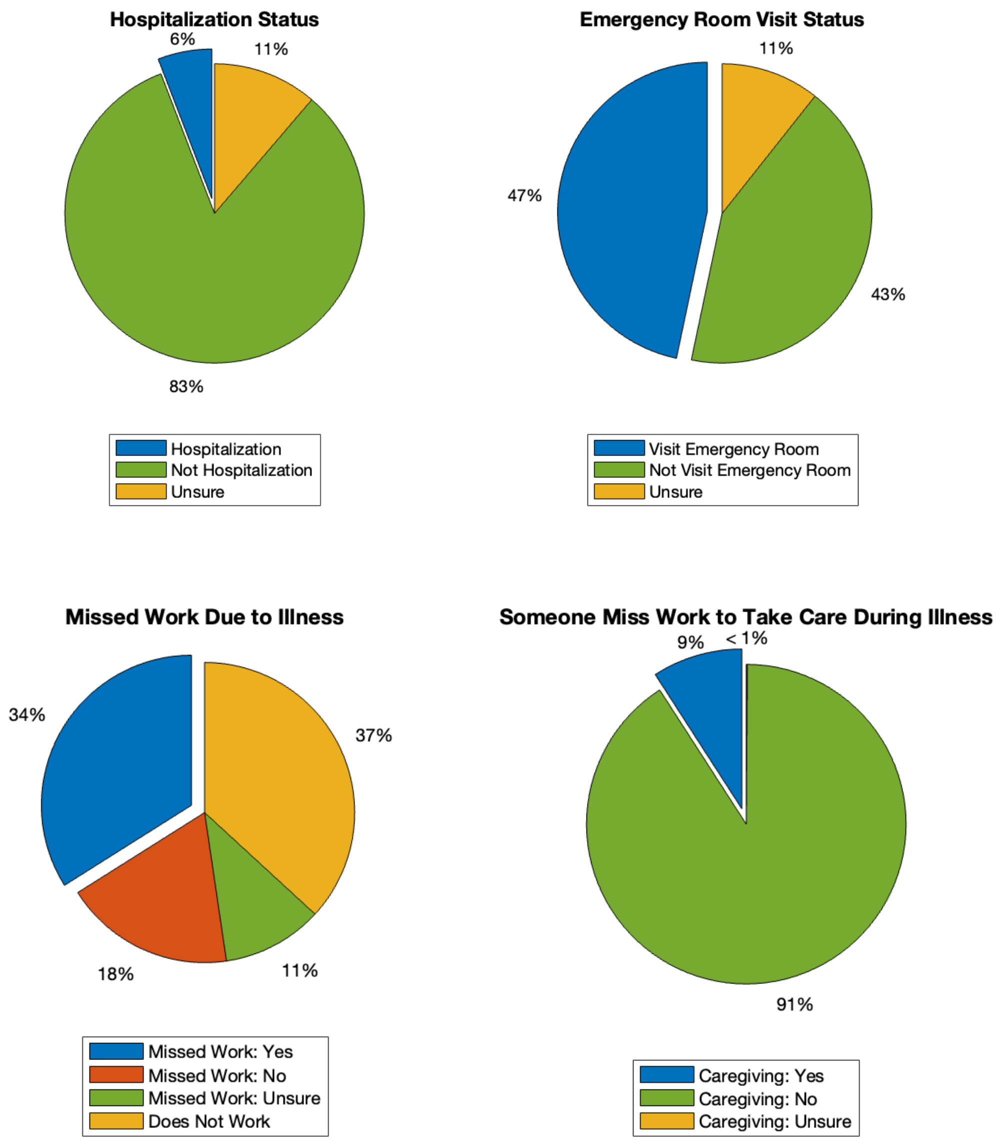
Figures 3.7 and 3.8 show the healthcare utilization and work-related impacts of *Salmonella* and *Campylobacter* infections through a series of pie charts. The figure indicates that 14% of reported *Salmonella* cases required hospitalization, with the hospitalization rate for AMR cases (14.33%) being slightly higher than for susceptible cases (13.81%). This suggests a slight increase in the severity or treatment complexity associated with AMR infections. Cases that visited their personal physician, a walk-in clinic, and/or the emergency room could not be differentiated. Thus, the model used emergency room visit data in the FoodNet Canada questionnaire were used to estimate the physician visit rate. Approximately half of the *Salmonella* cases visited emergency rooms, and 51.52% of AMR cases visited the emergency room.

Figure 3.7 Rates of *Salmonella* infection requiring hospitalization, emergency room visits, work absence, and caregiving



Source: FoodNet Canada

Figure 3.8 Rates of *Campylobacter* infection requiring hospitalization, emergency room visits, work absence, and caregiving



Source: FoodNet Canada

The economic costs of these health outcomes are illustrated in Table 3.3, which details the direct and indirect costs associated with AMR and susceptibility to *Salmonella* infections. Laboratory test costs, such as stool and blood tests, are non-occurring to determine the antimicrobial resistance of the *Salmonella* pathogen. It is assumed that a single set of laboratory tests is conducted for outpatient cases, avoiding double counting for patients who are hospitalized.

The estimated standard hospitalization cost for AMR cases was $9,611.89, exceeding the susceptible case cost of $8,529.01, reflecting the higher resource use or more extended hospital stay required to manage resistant infections. The total hospitalization cost for a *Salmonella* infection case is based on the length of stay and daily cost of hospitalization. In addition, the impact on the workforce cannot be ignored, with 29% of all *Salmonella* cases resulting in missed work. The proportion is higher for those with AMR infections at 31.4%, and 16.7% of AMR cases required someone to miss work to provide care. This suggests that AMR *Salmonella* infections may result in a greater overall social and economic burden, not only through direct medical costs but also through indirect costs through lost productivity and the need for care.

The labour productivity costs assess the economic impact of lost labour due to morbidity and mortality from AMR infection in the population. This involves multiplying the total number of working days lost by the economic value of each missed working day (see Appendix A). Average employment earnings in 2021, adjusted for the 2024 discount rate, were $45,020. This number is then divided by 49 weeks (the number of standard work weeks per year) and further divided by 5 to determine the value of lost labour per day. The calculation is adjusted for labour force participation rates to reflect actual productivity losses. In addition, the calculation of productivity losses incorporates a valuation of unpaid work, recognizing its economic contribution. According to Statistics Canada (2022), the average annual value of unpaid household labour per person is $20,650, based on the market replacement cost of these activities. Women are reported to perform 1,262 hours of unpaid work per year, compared to 874 hours for men (Statistics Canada, 2022). A replacement cost approach was used to quantify the economic impact of changes in housework and voluntary work due to illness by using the average hourly rate of unpaid work. This was $32.24 per hour.

Using the human capital approach, the productivity loss due to mortality is quantified as the present value of the labour that would have been performed by an individual at a median age during their remaining working life, taking into account a specified discount rate and labour productivity growth rate. The productivity loss associated with morbidity is the labour foregone during hospitalization, and different durations may explain resistant and susceptible infections. Traditionally, people with sequelae were believed to have the same life expectancy and labour productivity as those without sequelae. According to Canada's latest cost-benefit analysis guidance, the average value of a statistical life for adults aged 65 and older is set at $6.5 million in 2007 Canadian dollar (Government of Canada 2009).

Table 3.3 Data input of direct and indirect costs for AMR and susceptible infection

Element	AMR	Susceptible	Sources
Medication cost/day	6.10	6.10	(Herrick et al. 2011)
Physician office visit fee per visit	80.86	80.86	(CIHI 2022)
Repeat visit	47.32	47.32	(Thomas et al. 2015)
Average Visits per case	1.40	1.00	(Economic Research Service 2017)
Treatment costs	1,419.72	805.79	(Thomas et al. 2015)
Days hospitalized	3.6596	2.8081	FoodNet Canada
Cost of a Standard Hospital Stay	9,611.89	8,529.01	(Glass-Kaastra et al. 2022)
Laboratory test	476.10	476.10	(Thomas et al. 2015)
Unpaid work costs per hour	32.24	32.24	(Statistics Canada 2022)
Value of a statistical life/value of reduced mortality risk	9,166,323.30	9,166,323.30	(Government of Canada 2009)

3.1.3. QALYs

Utility values are derived from the literature (see Table 3.4). Using QALY, utility values are then combined with the duration of symptoms to generate a burden of illness. QALY is a nonmonetary measure that quantifies disease burden in terms of quality of life and length of life, ranging from 0 (death) to 1 (perfect health). The calculation of QALYs incorporates the probability of various health states, the duration of each state, and health-related quality loss (HRQL) weights (Hoffmann 2012). QALY loss represents the deviation from baseline HRQL weights due to disease (Batz, Hoffmann, & Morris 2014). In contrast, DALYs summarize the number of years lost due to mortality and morbidity, with one DALY representing one year of healthy life lost (World Health Organization 2015). Given its inclusive consideration of age and population health utility, this study uses QALYs to evaluate interventions for foodborne illness. Therefore, inputs to the Markov model include utility values, associated costs for each health state, and transition probabilities.

Table 3.4 Utility value of *Salmonella* infection symptoms

Health State	Base Value	Range	Reference
Perfect Health	1	-	-
Febrile convulsions	0.55	(0.45 - 0.64)	(Rigby et al. 2017) (Tengs and Wallace 2000)
Osteomyelitis	0.41	(0.37 - 0.44)	(Rigby et al. 2017) (Tengs and Wallace 2000)
Septicaemia	0.25	(0.22 - 0.28)	(Rigby et al. 2017) (Gebretekle et al. 2021)
Uncomplicated diarrhoea	0.77	(0.69 - 0.85)	(Rigby et al. 2017) (Tengs and Wallace 2000)
Self-treatment	0.83	(0.8 - 0.85)	(Batz, Hoffmann, and Morris 2014)
Physician treatment	0.78	(0.75 - 0.8)	(Batz, Hoffmann, and Morris 2014)
Hospitalization	0.64	(0.54 - 0.73)	(Batz, Hoffmann, and Morris 2014)
IBS	0.68	(0.58 - 0.77)	(Rigby et al. 2017) (Tengs and Wallace 2000)
RA	0.47	(0.38 - 0.57)	(Rigby et al. 2017) (Tengs and Wallace 2000)
Recovered	0.86	(0.79 - 0.93)	(Batz, Hoffmann, and Morris 2014)
Dead	0	-	-

3.1.4. Sensitivity Analysis

A probabilistic sensitivity analysis (PSA) was undertaken to evaluate the influence of key model parameters under uncertainty. These parameters included the costs of diagnosis and treatment, transition probabilities, utilities, and the length of stay. Health state utilities were varied in a range and the ranges for other parameters were selected based on the uncertainty in base-case values. Sensitivity analyses were performed using TreeAge software, which allows parameters to be adjusted individually to determine their impact on model results. Beta and gamma distributions were used to model different parameters. The Beta distribution is suitable for parameters between 0 and 1 and is used to calculate transition probabilities between health states and utility values. These probabilities were determined by aggregating case estimates for each symptom, ensuring a coherent representation of transition dynamics. A gamma distribution was chosen to model the duration of symptoms and costs, since it is suitable for parameters typically without upper bounds. A half-cycle correction was applied, to enhance the accuracy of both models. This adjustment assumes that events occur halfway through each cycle rather than at the beginning or end. The half-cycle correction improves the precision of the model by accounting for the fact that transitions between health states can occur at any point within a cycle (Briggs and Sculpher 1998).

3.2. Input-Output Model

The labour productivity costs and associated income lost due to *Salmonella* and *Campylobacter* infections can be predicted using the Markov Model, including those with and without AMR. Following Miller and Blair (2009), the IO model measures the macroeconomic impacts on the economy of the lost income from AMR foodborne diseases in terms of industrial output, GDP, and employment. The 2015 - 2019 Canadian Supply-Use Table (SUT) provided by Statistics Canada includes 492 commodities and 240 industries. To adapt the employment by industry published by Statistics Canada, the number of industries is aggregated to 20 when estimating employment impacts (see Appendix B).

The Use table includes intermediate demand by industrial sector and final demand. The final demand includes 98 categories of consumer final demand, eight categories of government final demand, 162 categories of gross capital formation, changes in inventories of finished goods and work-in-progress, changes in raw material inventories, and purchased goods for resale, international exports, and international re-exports. Supply tables show the production of goods by domestic industry, while the Use table provides insight into their allocation between intermediate inputs in the production of other goods or as components of final demand for consumption, investment, and exports.

3.2.1. Mathematical Framework

The basic IO framework can be summarized by the following equation:

$$\boldsymbol{x} = \boldsymbol{Z}\boldsymbol{i} + \boldsymbol{f} \tag{1}$$

where:

- $\boldsymbol{x}$ is the vector of industrial output,
- $\boldsymbol{Z}$ is the intermediate transaction matrix,
- $\boldsymbol{i}$ is a summation vector,
- $\boldsymbol{f}$ is the vector of final demand.

IO analysis assumes that inputs are used in fixed proportion to produce a unit of output. This ratio, known as the technical coefficient (α_{ij}), is calculated as follows:

$$\alpha_{ij} = \frac{z_{ij}}{x_j} \tag{2}$$

The technical coefficients matrix ($\boldsymbol{A}$) can be used to rewrite Equation (1):

$$\boldsymbol{x} = \boldsymbol{A}\boldsymbol{x} + \boldsymbol{f} \tag{3}$$

or, alternatively,

$$(\boldsymbol{I} - \boldsymbol{A})\boldsymbol{x} = \boldsymbol{f} \tag{4}$$

Standard matrix algebra yields the unique solution to Equation (4):

$$\boldsymbol{x} = (\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{f} \tag{5}$$

In Equation (5), $(\boldsymbol{I} - \boldsymbol{A})^{-1}$ is known as the Leontief inverse, or the total requirements matrix, which clarifies the relationship between gross output ($\boldsymbol{x}$) and final demand ($\boldsymbol{f}$) (Miller and Blair, 2009).

3.2.2. Rectangular Framework Adaptation

The rectangular input-output model of Canada is used for the study, where the number of commodities exceeds the number of industries. The mathematical derivation of the model is based on the paper by Ghanem (2010). To modify the basic model to align with the specifications of the rectangular framework, the intermediate transaction matrix ($\boldsymbol{Z}$) is replaced by the use matrix ($\boldsymbol{U}$) and the make matrix ($\boldsymbol{V}$). The rectangular framework uses $\boldsymbol{g}_j$ to denote the vector of total output by industry j, and $\boldsymbol{q}_\mathrm{i}$ to denote the vector of total output for commodity i:

$$\boldsymbol{U} = [\boldsymbol{u}_{ij}] \tag{6}$$

$$\boldsymbol{V} = [\boldsymbol{v}_{ji}] \tag{7}$$

where:

$$\boldsymbol{q_i} = \textstyle\sum_{\boldsymbol{i}} \boldsymbol{v_{ji}} \tag{8}$$

$$\boldsymbol{g_j} = \textstyle\sum_{\boldsymbol{j}} \boldsymbol{v_{ji}} \tag{9}$$

In the use matrix ($\boldsymbol{U}$), each element $\boldsymbol{u}_{ij}$ represents the value of commodity i purchased by industry j. The matrix $\boldsymbol{U}$ is a commodity-by-industry matrix, divided by total industry output ($\boldsymbol{g_j}$) to obtain the input coefficients matrix (**B**), which is defined as the ratio of intermediate inputs to total output by industry:

$$\boldsymbol{B} = \boldsymbol{U}\widehat{\boldsymbol{g}}^{-\boldsymbol{1}} \tag{10}$$

Similarly, in the make matrix ($\boldsymbol{V}$), each element $\boldsymbol{v_{ji}}$ represents the value of commodity i produced by industry j. The matrix $\boldsymbol{V}$ is an industry-by-commodity matrix, divided by total commodity output ($\boldsymbol{q_i}$) to obtain the market share matrix ($\boldsymbol{D}$), which relates the output levels of industries to the sum of its share of each commodity:

$$\boldsymbol{D} = \boldsymbol{V}\widehat{\boldsymbol{q}}^{-\boldsymbol{1}} \tag{11}$$

The expression for the total requirements matrix depends on the form of the final demand vector and the technological assumption. This research uses final demand expressed in terms of commodities, with the industry-based technological assumption:

$$(\boldsymbol{I} - \boldsymbol{DB})^{-1}\boldsymbol{D} \tag{12}$$

3.2.3. Imports and Domestic Demand

A portion of total imports is not related to domestic demand but to personal expenditures on international travel and re-exports. Imports for domestic demand ($\boldsymbol{m_i^D}$) exclude these categories:

$$\boldsymbol{m_i^D} = \boldsymbol{m_i} + \boldsymbol{c_i^M} + \boldsymbol{r_i} \tag{13}$$

where $\boldsymbol{c_i^M}$ is personal expenditure on international travel, and $\boldsymbol{r_i}$ is re-exports.

Personal expenditures on travel are split into:

- Non-travel-related personal expenditures ($\boldsymbol{c_i^O}$),
- Travel-related personal expenditures ($\boldsymbol{c_i^T}$)

$$\boldsymbol{c_i^O} = \boldsymbol{c_i} - \boldsymbol{c_i^T} \tag{14}$$

Production for the domestic market is split into:

- Production for personal expenditures on non-travel-related services ($\boldsymbol{q_i^{D,T}}$),
- Production for all other domestic demand ($\boldsymbol{q_i^{D,O}}$):

Total domestic demand, excluding personal travel expenditures, relates to production, imports, inventory withdrawals, and scrap:

$$\boldsymbol{q_i^{D,O}} - \boldsymbol{m_i^D} - \boldsymbol{n_i^{w,D}} - \boldsymbol{s_i^D} = \boldsymbol{u_i} + \boldsymbol{e_i} \tag{15}$$

$$\boldsymbol{e_i} = \boldsymbol{c_i^O} + \boldsymbol{c_i^X} + \boldsymbol{c_i^G} + \boldsymbol{k_i} + \boldsymbol{n_i^A} \tag{16}$$

where $\boldsymbol{e_i}$ is domestic final demand excluding travel-related services, $\boldsymbol{n_i^{w,D}}$ is inventory withdrawals for the domestic market, $\boldsymbol{n_i^A}$ is inventory additions, $\boldsymbol{c_i^O}$ is non-travel related personal expenditure, $\boldsymbol{c_i^X}$ is personal expenditure by non-residents, $\boldsymbol{c_i^G}$ is expenditures by government and $\boldsymbol{k_i}$ is capital expenditure by industry.

3.2.4. Accounting for Leakages

Leakages are commodities used to satisfy intermediate or final demand but not supplied by the Canadian economy. Leakages are included in the model to better estimate of the impact of a change in final demand. It is assumed that leakages are in fixed proportion to domestic commodity demand. To account for economic leakages such as imports, scraps, and inventory withdrawals, we define:

- $\boldsymbol{\mu_i}$ as the share of imports,
- $\boldsymbol{\beta_i}$ as the share of inventory withdrawals,
- $\boldsymbol{\alpha_i}$ as the share of scraps.

These are incorporated into the model as follows:

$$\boldsymbol{\mu_i} = \frac{-\boldsymbol{m_i^D}}{\sum_j \boldsymbol{u_{ij}} + \boldsymbol{e_i}} \tag{17}$$

$$\boldsymbol{\beta_i} = \frac{-\boldsymbol{n_i^w}}{\boldsymbol{u_i} + \boldsymbol{e_i} + \boldsymbol{c_i^T} + \boldsymbol{x_i}} \tag{18}$$

$$\boldsymbol{\alpha_i} = \frac{-\boldsymbol{s_i}}{\boldsymbol{u_i} + \boldsymbol{e_i} + \boldsymbol{c_i^T} + \boldsymbol{x_i}} \tag{19}$$

where $\boldsymbol{m_i^D}$ represents imports for domestic demand, $\boldsymbol{e_i}$ is the final expenditure, $\boldsymbol{c_i^T}$ are travel-related personal expenditures, and $\boldsymbol{x_i}$ are exports of commodity i.

The final equation integrates these factors and accounts for the economic impact of re-exports ($\boldsymbol{r^D}$) on industrial output:

$$\boldsymbol{g} = [\boldsymbol{I} - \boldsymbol{D}(\boldsymbol{I} - \widehat{\boldsymbol{\mu}} - \widehat{\boldsymbol{\beta}} - \widehat{\boldsymbol{\alpha}})\boldsymbol{B}]^{-1}\boldsymbol{D}[(\boldsymbol{I} - \widehat{\boldsymbol{\mu}} - \widehat{\boldsymbol{\beta}} - \widehat{\boldsymbol{\alpha}})\boldsymbol{e} + (\boldsymbol{I} - \widehat{\boldsymbol{\beta}} - \widehat{\boldsymbol{\alpha}})\boldsymbol{x} + \boldsymbol{r^D}] \tag{20}$$

where $\boldsymbol{I}$ is the identity matrix. The matrix $[\boldsymbol{I} - \boldsymbol{D}(\boldsymbol{I} - \widehat{\boldsymbol{\mu}} - \widehat{\boldsymbol{\beta}} - \widehat{\boldsymbol{\alpha}})\boldsymbol{B}]^{-1}\boldsymbol{D}$ is referred to as the impact matrix, which captures all the inter-industry relationships. The impact matrix estimates the direct plus indirect impacts on industrial sectors output that are required to meet a change in the final demand.

3.3. Case Study: *Salmonella* Illness Attribute to Chicken

The impacts of Canadian poultry farmers voluntary reduction of Category I and Category II antimicrobials during 2015 and 2019 are estimated using a previously developed Markov model. Glass-Kaastra et al. (2022) reported a 33% reduction in the incidence of *Salmonella* Enteritidis and a 16% reduction in nontyphoidal *Salmonella* in 2019. They also illustrated the reduction in foodborne pathogen incidences through a substantial reduction in illness and healthcare visits, hospitalizations, missed workdays, and deaths. It highlights the economic benefits of reducing foodborne pathogen incidence. In addition, Huber et al. (2021) observed a decline in AMR in broiler chickens by 6%-38% following the reduction in prophylactic antimicrobial use after implementing the Antimicrobial Use Reduction Strategy in Canada's poultry industry in 2014.

Chicken products are the primary source of *Salmonella* infections, accounting for a substantial proportion of the total cases in Canada. A study by Hurst et al. (2023) highlights that a 64.7% of the salmonellosis cases were attributed to chicken breast meat. This is followed by frozen raw breaded chicken products at 12.9% and ground chicken at 9.1%. The study found that the incidence of salmonellosis in chicken breast meat has been declining for many years, especially between 2015 and 2019. The year-by-year distribution of salmonellosis cases attributed to chicken showed a downward trend: 81.0% in 2015, 83.7% in 2016, 84.2% in 2017, 79.7% in 2018 and 72.8% in 2019.

This trend is related to introducing a broiler breeder vaccination program and regulatory interventions by the Canadian Food Inspection Agency, which require that *Salmonella* levels in frozen raw breaded chicken products be below detectable levels starting in 2019. These interventions have had a positive impact. These regulatory changes will significantly impact *Salmonella* more than *Campylobacter* due to the nature of these pathogens. *Campylobacter* is more sensitive to freezing and will be present in reduced quantities in frozen products. In contrast, *Salmonella* is more resilient and will not be reduced in numbers after freezing. Therefore, regulating frozen raw breaded chicken products is more effective in reducing the incidence of foodborne illnesses associated with *Salmonella*. This study examines how the decrease in salmonellosis cases attributed to chicken during this period translated to changes in Canada's economic costs and health burden.

Chapter 4. Results

4.1. Markov Model Results

This section presents the results of the Markov models used to predict the number of cases, costs, and QALYs lost due to foodborne nontyphoidal *Salmonella* and *Campylobacter* infections in Canada. Two separate timeframe Markov models were developed and run for each pathogen: an annual model and a lifetime model which extended over 100 years. The annual model, with a monthly cycle length, estimated the number of illnesses at different stages including the number of patients visiting physicians, being hospitalized, developing sequalae, and recovering or dying each year. *Salmonella* infections were assessed over the period 2015 to 2019, and due to data limitations, from 2017 to 2019 for *Campylobacter* infections. In addition, these cases are differentiated by AMR and susceptible pathogens to compare the varying impacts on costs and QALYs. The labour productivity costs are calculated based on the estimated number of workdays missed by patients and caregivers across different health stages. The lifetime model examines the long-term impacts of infections with sequelae and their associated costs and QALY losses. All results are adjusted for a discount rate and presented in 2019 Canadian dollar values.

4.1.1. Predicated Number of Cases

Tables 4.1 and 4.2 present the input data for the Markov model, illustrating the various parameters required to estimate the burden of *Salmonella* and *Campylobacter* illnesses in Canada. The Canadian population has grown steadily from 35.7 million in 2015 to 37.6 million in 2019. Reported cases of salmonellosis decreased from 7,748 cases in 2015 to 6,008 cases in 2019 and reported cases of *Campylobacter* decreased from 10,401 cases in 2017 to 10,298 cases in 2019. According to Thomas et al. (2013), 26% of *Salmonella* cases in Canada are travel-related, and 20%

are from non-food sources. Thus, a domestic infection rate of 0.74 and a foodborne infection rate of 0.80 were used, indicating that most salmonellosis cases are acquired domestically and primarily through food transmission. Similar rates were obtained for *Campylobacter* infections, with a domestic infection rate of 0.76 and a foodborne infection rate of 0.68 (Thomas et al. 2013). The underreporting and underdiagnosis multipliers were set at 26.10 for *Salmonella* and 27.20 for *Campylobacter* infections (Thomas et al. 2013) and used to estimate the total number of salmonellosis cases. It accounts for the underreporting in the surveillance system. In addition, the prevalence of AMR resistance to more than one antimicrobial agent increased from 0.2950 in 2015 to 0.4587 in 2019 for *Salmonella* illness. This indicates that treating *Salmonella* infections is becoming increasingly challenging due to rising antimicrobial resistance. Similarly, AMR resistance to more than one antimicrobial agent increased from 0.5785 in 2017 to 0.6421 in 2019 for *Campylobacter* illness.

Table 4.1 Input information for Markov model of *Salmonella* illnesses

Year	Canadian Population	Number of reported Salmonella illnesses	Domestically acquired ratio	Foodborne acquired ratio	Multiplier for under-reporting and under-diagnosis	Total number of illness	Incidence rate	Resistance rate to more than one antimicrobial class
2015	35,700,000	7,717	0.74	0.80	26.10	119,237	0.0033534	0.2950
2016	36,110,000	7,816	0.74	0.80	26.10	120,767	0.0033038	0.3619
2017	36,550,000	7,317	0.74	0.80	26.10	113,056	0.0030184	0.4333
2018	37,070,000	7,300	0.74	0.80	26.10	112,794	0.0029777	0.3876
2019	37,600,000	6,350	0.74	0.80	26.10	98,115	0.0024689	0.4587

Source: (Public Health Agency of Canada 2022) (Thomas et al. 2013)

Table 4.2 Input information for Markov model of *Campylobacter* illnesses

Year	Canadian Population	Number of reported Campylobacter illnesses	Domestically acquired ratio	Foodborne acquired ratio	Multiplier for under-reporting and under-diagnosis	Total number of illness	Incidence rate	Antimicrobial resistance rate
2017	36,550,000	10,401	0.76	0.68	27.20	146,206	0.00400020	0.5785
2018	37,070,000	10,238	0.76	0.68	27.20	143,915	0.00388230	0.5570
2019	37,600,000	10,298	0.76	0.68	27.20	144,759	0.00385000	0.6421

Source: (Public Health Agency of Canada 2022) (Thomas et al. 2013)

Table 4.3 presents the predicted number of *Salmonella* cases using the Markov model, distinguishing between AMR and susceptible cases. The predicted AMR *Salmonella* cases increased from 34,807 in 2015 to 42,645 in 2019. Hospitalizations for AMR cases also increased, from 1,673 in 2015 to 2,042 in 2019. Physician visits, IBS, RA, and deaths associated with AMR *Salmonella* cases exhibited similar upward trends. This increase highlights the escalating burden of AMR *Salmonella* infections on the healthcare systems and the need for targeted interventions to address AMR. In contrast, the number of predicted susceptible *Salmonella* cases varied over the years, with a peak of 84,625 cases in 2015 and a notable decline to 50,554 cases in 2019. Hospitalizations for susceptible cases decreased from 2,947 in 2015 to 1,762 in 2019. Reducing susceptible *Salmonella* cases and related healthcare visits reflects the overall improvements in managing non-resistant *Salmonella* infections. Combining AMR and susceptible cases, the total predicted number of *Salmonella* cases decreased from 119,432 in 2015 to 93,199 in 2019. Hospitalizations, physician visits, IBS, RA, and deaths followed a similar declining trend. However, the rising proportion of AMR cases within the total highlights the ongoing challenge of antimicrobial resistance.

Table 4.3 Predicted number of cases of *Salmonella* infection from 2015 to 2019

			AMR Salmonella Cases Mean (95% CI)			
Year	**Case Number**	**Hospitalization**	**Physician Visit**	**IBS**	**RA**	**Death**
2015	34,807 (34,450 to 35,145)	1,673 (1,593 to 1,752)	9,780 (9,442 to 10,117)	940 (879 to 1000)	235 (204 to 265)	10 (3 to 16)
2016	43,415 (43,027 to 43,794)	2,057 (1,968, to 2,145)	12,242 (11,861 to 12,622)	1,239 (1,170 to 1,307)	301 (267 to 334)	8 (2 to 13)
2017	48,077 (47,676 to 48,477)	2,268 (2,174 to 2,361)	13,346 (12,949 to 13,742)	1,374 (1,301 to 1,446)	282 (249 to 314)	9 (3 to 14)
2018	42,768 (42,385 to 43,148)	2,111 (2,021 to 2,200)	12,015 (11,639 to 12,390)	1,220 (1,151 to 1,288)	285 (251 to 318)	9 (3 to 14)
2019	42,645 (42,263 to 43,026)	2,042 (1,953 to 2,130)	12,173 (11,795 to 12,550)	1,253 (1,183 to 1,322)	275 (242 to 307)	10 (3 to 16)

			Susceptible Salmonella Cases Mean (95% CI)			
Year	**Case Number**	**Hospitalization**	**Physician Visit**	**IBS**	**RA**	**Death**
2015	84,625 (84,126 to 85,123)	2,947 (2,841 to 3,052)	16,931 (16,475 to 17,386)	1,118 (1,052 to 1,183)	246 (215 to 276)	9 (3 to 14)
2016	76,260 (75,779 to 76,740)	2,704 (2,602 to 2,805)	15,140 (14,711 to 15,568)	1,019 (956 to 1,081)	225 (195 to 254)	15 (7 to 22)
2017	62,590 (62,143 to 63,036)	2,121 (2,030 to 2,211)	12,443 (12,052 to 12,833)	771 (716 to 825)	184 (157 to 210)	11 (4 to 17)
2018	67,268 (66,808 to 67,727)	2,403 (2,307 to 2,498)	13,558 (13,150 to 13,965)	882 (823 to 940)	216 (187 to 244)	5 (1 to 9)
2019	50,554 (50,144 to 50,963)	1,762 (1,679 to 1,844)	12,173 (9,830 to 10,539)	662 (611 to 712)	160 (135 to 184)	7 (2 to 12)

			Total Salmonella Cases Mean (95% CI)			
Year	**Case Number**	**Hospitalization**	**Physician Visit**	**IBS**	**RA**	**Death**
2015	119,432 (118,576 to 120,268)	4,620 (4,434 to 4,804)	26,711 (25,917 to 27,503)	2,058 (1,931 to 2,183)	481 (419 to 541)	19 (6 to 30)
2016	119,675 (118,806 to 120,534)	4,761 (4,570 to 4,950)	27,382 (26,572 to 28,190)	2,258 (2,126 to 2,388)	526 (462 to 588)	23 (9 to 35)
2017	110,667 (109,819 to 111,513)	4,389 (4,204 to 4,572)	25,789 (25,001 to 26,575)	2,145 (2,017 to 2,271)	466 (406 to 524)	20 (7 to 31)
2018	110,036 (109,193 to 110,875)	4,514 (4,328 to 4,698)	25,573 (24,789 to 26,355)	2,102 (1,974 to 2,228)	501 (438 to 562)	14 (4 to 23)
2019	93,199 (92,407 to 93,989)	3,804 (3,632 to 3,974)	24,346 (21,625 to 23,089)	1,915 (1,794 to 2,034)	435 (377 to 491)	17 (5 to 28)

Table 4.4 shows the number of *Campylobacter* cases predicted using the Markov model. The predicted number of AMR *Campylobacter* cases increased from 84,233 in 2017 to 93,535 in 2019. Hospitalizations due to AMR cases increased from 1,627 in 2017 to 1,803 in 2019. Similar

upward trends were observed for physician visits, IBS, GBS, RA, and deaths associated with AMR *Campylobacter* cases. In contrast, the predicted number of susceptible *Campylobacter* cases varied, increasing slightly from 61,775 in 2017 to 63,904 in 2018, before decreasing to 51,451 in 2019. Hospitalizations for susceptible cases decreased from 1,137 in 2017 to 948 in 2019. Combining AMR and susceptible cases, the predicted *Campylobacter* cases remained relatively stable at 146,008 in 2017, 144,367 in 2018, and 144,986 in 2019. Both pathogens showed an increasing trend in AMR cases, but *Salmonella* showed a clear decline in total and susceptible cases, *while Campylobacter* remained stable overall.

Table 4.4 Predicted number of cases of *Campylobacter* infection from 2017 to 2019

AMR Campylobacter Cases Mean (95% CI)							
Year	**Case Number**	**Hospitalization**	**Physician Visit**	**IBS**	**GBS**	**RA**	**Death**
2017	84,233 (83,733 to 84,732)	1,627 (1,548 to 1,705)	(15,413 to 15,892)	(3,912 to 4,159)	72 (55 to 89)	625 (576 to 673)	6 (1 to 11)
2018	80,463 (79,971 to 80,954)	1,526 (1,449 to 1,602)	(14,742 to 15,211)	(3,649 to 3,888)	88 (69 to 106)	625 (576 to 673)	5 (1 to 9)
2019	93,535 (93,015 to 94,054)	1,803 (1,719 to 1,886)	(17,174 to 17,679)	(4,287 to 4,546)	89 (71 to 107)	656 (605 to 706)	7 (2 to 12)

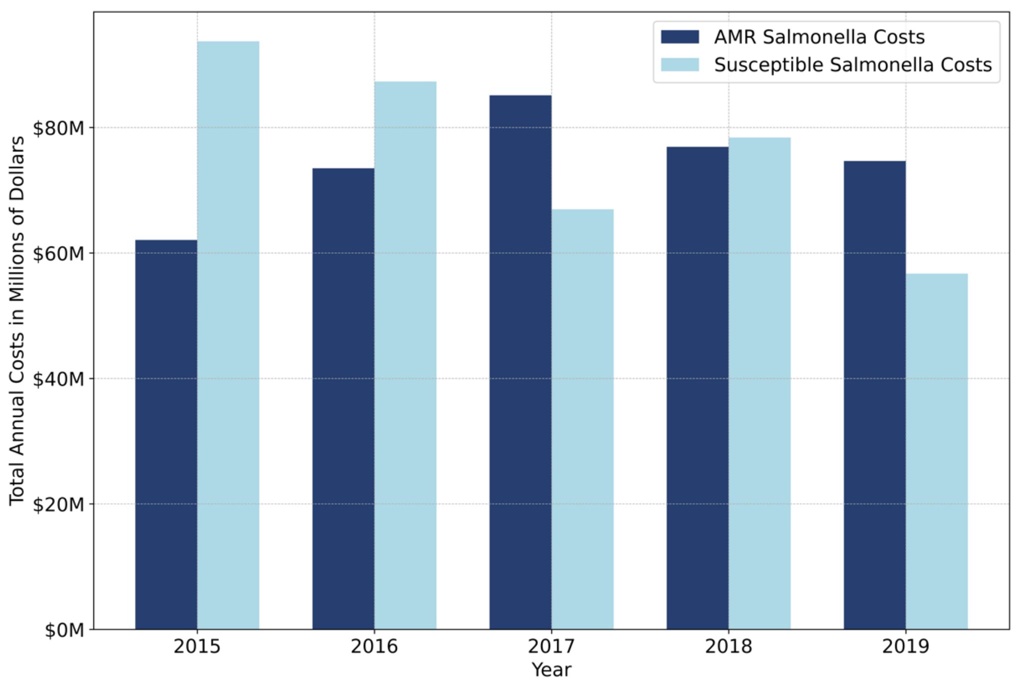
Susceptible Campylobacter Cases Mean (95% CI)							
Year	**Case Number**	**Hospitalization**	**Physician Visit**	**IBS**	**GBS**	**RA**	**Death**
2017	61,775 (61,330 to 62,219)	1,137 (1,071 to 1,203)	10,058 (9,864 to 10,251)	(2,596 to 2,798)	50 (36 to 63)	362 (324 to 399)	3 (0 to 6)
2018	63,904 (63,453 to 64,354)	1,143 (1,076 to 1,209)	(10,375 to 10,772)	(2,666 to 2,871)	44 (31 to 57)	380 (241 to 418)	5 (1 to 9)
2019	51,451 (51,037 to 51,864)	948 (887 to 1,008)	8,463 (8,284 to 8,641)	(2,157 to 2,342)	43 (30 to 56)	291 (257 to 324)	3 (0 to 6)

Total Campylobacter Cases Mean (95% CI)							
Year	**Case Number**	**Hospitalization**	**Physician Visit**	**IBS**	**GBS**	**RA**	**Death**
2017	146,008 (145,063 to 146,951)	2,764 (2,619 to 2,908)	(25,277 to 26,143)	(6,508 to 6,957)	122 (91 to 152)	987 (900 to 1,072)	9 (1 to 17)
2018	144,367 (143,424 to 145,308)	2,669 (2,525 to 2,811)	(25,117 to 25,983)	(6,315 to 6,759)	132 (100 to 163)	1,005 (817 to 1,091)	10 (2 to 18)
2019	144,986 (144,052 to 145,918)	2,751 (2,606 to 2,894)	(25,458 to 26,320)	(6,444 to 6,888)	132 (101 to 163)	947 (862 to 1030)	10 (2 to 18)

4.1.2. Annual and Lifetime Costs

The chart in Figure 4.1 shows the total annual costs of foodborne AMR and susceptible *Salmonella* infections from 2015 to 2019. The costs of AMR *Salmonella* infections fluctuated, increasing substantially from $62 million in 2015 to a peak of $85 million in 2017, before declining to $74.6 million in 2019. The costs of susceptible *Salmonella* infections also varied, starting at $93.7 million in 2015, going to $87.3 million in 2016, and declining to $56.7 million in 2019. The total costs of *Salmonella* infections ranged from $131 million to $160 million per year. This cost increase correlates with the predicted number of AMR cases, which peaked in 2017 with 48,077 cases.

Figure 4.1 Total annual costs of foodborne AMR and susceptible *Salmonella* infections



Per case costs for AMR *Salmonella* were consistently higher than for susceptible cases (Table 4.5). In 2015, the cost per case for AMR cases was $1,783, compared to $1,108 for susceptible cases. This difference continues over the years, with AMR costs per case peaking at

$1,798 in 2018 before declining slightly to $1,751 in 2019. For susceptible cases, costs per case ranged from $1,070 in 2017 to $1,165 in 2018. Similar results were obtained for *Campylobacter* infections (Table 4.6), where per case costs for AMR *Campylobacter* infections were consistently higher than for susceptible cases. In 2017, the cost per AMR *Campylobacter* case was $994, compared to $864 for susceptible cases. This trend continued, with AMR costs per case reaching $984 in 2019, compared to $878 for susceptible cases. The total annual costs for AMR *Campylobacter* cases decreased from $83,758,063 in 2017 to $78,218,592 in 2018, then increased to $92,028,806 in 2019. Similarly, the total annual costs for susceptible *Campylobacter* cases also fluctuated, starting at $53,355,371 in 2017, increasing to $54,843,480 in 2018, and then decreasing to $45,186,974 in 2019. Overall, the total annual cost of *Campylobacter* infections has remained relatively stable, with slight variations at around $137 million.

Table 4.5 Total annual and per case costs of foodborne *Salmonella* infections (in dollars)

	AMR Salmonella Costs ($) Mean (95% CI)		Susceptible Salmonella Costs ($) Mean (95% CI)		Total Costs ($) Mean (95% CI)	
Year	**Annual**	**Per Case**	**Annual**	**Per Case**	**Annual**	**Per Case**
2015	62,068,114 (60,081,970 to 64,054,258)	1,783 (1,744 to 1,822)	93,735,084 (90,735,615 to 96,734,553)	1,108 (1,078 to 1,136)	155,803,198 (150,817,586 to 160,788,811)	1,305 (1,263 to 1,346)
2016	73,502,882 (71,188,457 to 75,817,308)	1,693 (1,654 to 1,731)	87,325,981 (84,576,300 to 90,075,662)	1,145 (1,116 to 1,173)	160,828,863 (155,764,758 to 165,892,971)	1,343 (1,301 to 1,386)
2017	85,131,215 (82,337,979 to 87,924,452)	1,770 (1,727 to 1,813)	66,966,135 (64,768,912 to 69,163,358)	1,070 (1,042 to 1,097)	152,097,350 (147,106,891 to 157,087,810)	1,374 (1,329 to 1,419)
2018	76,912,714 (74,415,864 to 79,409,563)	1,798 (1,755 to 1,840)	78,395,577 (75,850,588 to 80,940,565)	1,165 (1,135 to 1,195)	155,308,291 (150,266,452 to 160,350,129)	1,411 (1,365 to 1,457)
2019	74,660,561 (72,024,361 to 77,296,761)	1,751 (1,704 to 1,796)	56,714,215 (54,711,685 to 58,716,745)	1,122 (1,091 to 1,152)	131,374,776 (126,736,046 to 136,013,507)	1,410 (1,359 to 1,459)

Table 4.6 Total annual and per case costs of foodborne *Campylobacter* infections (in dollars)

	AMR Campylobacter Costs ($) Mean (95% CI)		Susceptible Campylobacter Costs ($) Mean (95% CI)		Total Costs ($) Mean (95% CI)	
Year	**Annual**	**Per Case**	**Annual**	**Per Case**	**Annual**	**Per Case**
2017	83,758,063 (81,698,244 to 85,817,882)	994 (975 to 1,012)	53,355,371 (52,043,230 to 54,667,512)	864 (848 to 879)	137,113,434 (133,741,475 to 140,485,394)	939 (915 to 962)
2018	78,218,592 (76,294,299 to 80,142,884)	972 (954 to 989)	54,843,480 (53,494,249 to 56,192,710)	858 (843 to 873)	133,062,072 (129,788,549 to 136,335,595)	922 (899 to 944)
2019	92,028,806 (89,779,834 to 94,277,779)	984 (965 to 1,002)	45,186,974 (44,082,708 to 46,291,240)	878 (863 to 892)	137,215,780 (133,862,542 to 140,569,020)	946 (923 to 969)

Table 4.7 shows the lifetime costs associated with foodborne *Salmonella* infections, distinguishing between AMR and susceptible strains over four-time horizons: 10, 40, 70, and 100 years. The total cost of *Salmonella* infections over 10 years was approximately $17.6 million, with AMR infections accounting for $9.8 million and susceptible infections accounting for $7.8 million. As the time frame extended to 40 years, the total cost increased to nearly $22 million, with AMR infections accounting for $12.3 million and susceptible infections accounting for $9.7 million. This trend continued over the 70 and 100-year periods, with total costs remaining stable at around $22 million. Over these more extended time periods, AMR infections continue to impose a higher economic burden (Figure 4.2), with costs consistently exceeding $12.3 million, compared with costs of $9.7 million for susceptible infections. The figure also shows that the cumulative costs of AMR and susceptible infections rise sharply in the first few years and then stabilize over time. This pattern suggests that most of the economic burden is incurred early in the infection. Costs remain relatively stable over the long term, likely due to higher mortality rates among older individuals, reducing ongoing expenses.

Table 4.7 Lifetime costs of foodborne *Salmonella* infections (in dollars)

Time Horizon	AMR Salmonella Costs	Susceptible Salmonella Costs	Total Costs
10 years	9,795,321	7,833,170	17,628,492
40 years	12,289,999	9,683,638	21,973,637
70 years	12,317,359	9,721,461	22,038,819
100 years	12,317,359	9,721,835	22,039,194

Figure 4.2 Comparison of lifetime costs of AMR and Susceptible *Salmonella* infections

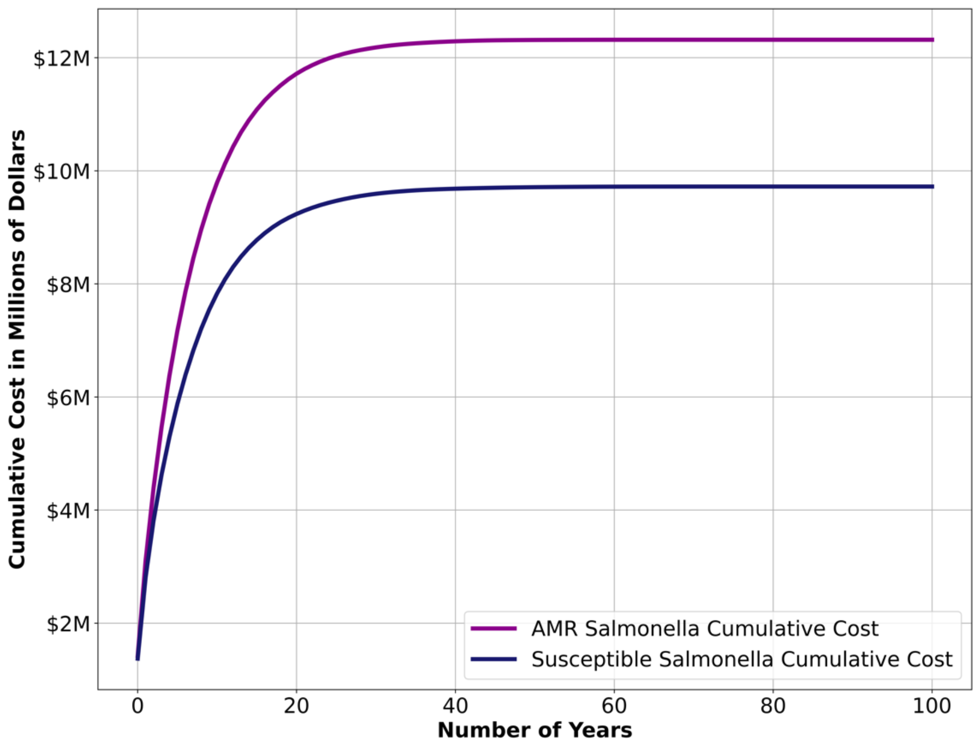


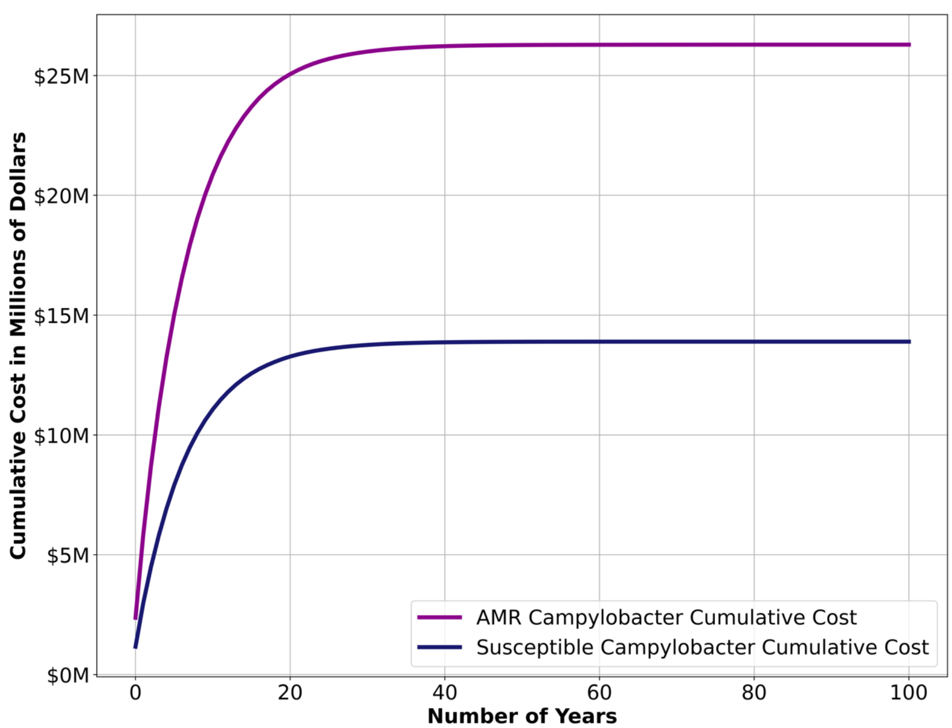
Table 4.8 presents the estimated lifetime costs associated with foodborne *Campylobacter* infections, distinguishing between AMR and susceptible strains over the same four-time frames. Over the 10 years, the total costs for *Campylobacter* infections were higher than for *Salmonella*, at approximately $31.4 million. Of this total, $20.9 million were for AMR infections and $10.5 million for susceptible infections. As the time frame was extended to 40 years, the total costs increased to approximately $40.1 million, of which $26.2 million was for AMR infections and $13.9 million was for susceptible infections. Costs remained stable over the 70- and 100-year

periods, with total costs of approximately $40.2 million. AMR infections consistently accounted for a larger share of the economic burden (Figure 4.3), with costs exceeding $26.2 million, compared with $13.9 million for susceptible infections.

Table 4.8 Lifetime costs of foodborne *Campylobacter* infections (in dollars)

Time Horizon	AMR Campylobacter Costs	Susceptible Campylobacter Costs	Total Costs
10 years	20,885,974	10,508,696	31,394,670
40 years	26,223,536	13,866,557	40,090,093
70 years	26,285,346	13,894,855	40,180,201
100 years	26,287,698	13,894,855	40,182,553

Figure 4.3 Comparison of lifetime costs of AMR and Susceptible *Campylobacter* infections



4.1.3. QALY Loss

Table 4.9 shows the total annual QALY loss and QALY loss per case for foodborne *Salmonella* infections from 2015 to 2019, distinguishing between AMR and susceptible strains. In 2015, AMR *Salmonella* infections resulted in a total annual QALY loss of 710.92, or 0.02042 per case. In contrast, susceptible *Salmonella* infections resulted in a higher total annual QALY loss of 1,071.03, or 0.01266 per case. The total annual QALY loss for AMR and susceptible infections was 1,781.95, or 0.01492 per case, in 2015. In subsequent years, the total annual QALY loss for resistant *Salmonella* infections increased, peaking at 964.11 in 2017 before declining slightly to 870.32 in 2019. The QALY loss per case for resistant *Salmonella* infections remained relatively stable. The total annual QALY loss for susceptible *Salmonella* infections decreased from 1,071.03 in 2015 to 644.61 in 2019. The total annual QALY loss for all *Salmonella* infections fluctuated, peaking at 1,862.49 in 2016 before declining to 1,514.93 in 2019.

Table 4.9 Total annual and per case QALYs losses of foodborne *Salmonella* infections

	AMR Salmonella		Susceptible		Total QALYs losses	
Year	**Annual**	**Per Case**	**Annual**	**Per Case**	**Annual**	**Per Case**
2015	710.92	0.02042	1,071.03	0.01266	1,781.95	0.01492
2016	878.58	0.02024	983.91	0.01290	1,862.49	0.01556
2017	964.11	0.02005	782.41	0.01250	1,746.52	0.01578
2018	850.02	0.01988	864.96	0.01286	1,714.98	0.01559
2019	870.32	0.02041	644.61	0.01275	1,514.93	0.01625

Similarly, for *Campylobacter* infections, the total annual QALY loss for AMR strains showed a slight decline in 2018 before increasing in 2019 (Table 4.10). In 2017, the total QALY loss was 2,528.49, of which 1,534.87 were due to AMR strains and 993.62 to susceptible strains. The total QALY loss decreased slightly to 2,502.97 in 2018. By 2019, the total QALY loss for resistant *Campylobacter* infections increased to 1,696.37, and the total QALY loss for susceptible infections decreased to 842.26. The total QALY loss for *Campylobacter* infections in 2019 was 2,538.63.

Table 4.10 Total annual and per case QALYs loss of foodborne *Campylobacter* infections

	AMR Campylobacter		Susceptible Campylobacter		Total QALYs losses	
Year	**Annual**	**Per Case**	**Annual**	**Per Case**	**Annual**	**Per Case**
2017	1,534.87	0.01822	993.62	0.01608	2,528.49	0.01732
2018	1,468.78	0.01825	1,034.19	0.01618	2,502.97	0.01734
2019	1,696.37	0.01814	842.26	0.01637	2,538.63	0.01751

Table 4.11 presents the total lifetime QALY loss in the first ten years due to AMR *Salmonella* infection was 4,326.88, while the total QALY loss due to susceptible infection was 5,142.39. Extending the time frame to 40 years, the total QALY loss increased to 13,911.71, with 6,361.78 due to AMR infection and 7,549.93 due to susceptible infection. The QALY loss per case also increased to 0.1421. Over 70 years, the total QALY loss was 15,129.20, of which AMR infection accounted for 6,918.95 and susceptible infection accounted for 8,210.26. The QALY loss per case rose to 0.1623. Over 100 years, the total QALY loss reached 15,365.06. AMR infection accounted for 7,027.73 and susceptible infection accounted for 8,337.33, resulting in a QALY loss per case of 0.1649.

Table 4.11 Lifetime QALYs losses from foodborne *Salmonella* infections

Time Horizon	Salmonella QALYs Losses	Susceptible Salmonella QALYs Losses	Total QALYs Losses	Per Case QALYs Losses
10 years	4326.88	5142.39	9469.27	0.1016
40 years	6361.78	7549.93	13911.71	0.1493
70 years	6918.95	8210.26	15129.20	0.1623
100 years	7027.73	8337.33	15365.06	0.1649

Table 4.12 presents a similar analysis for *Campylobacter* infections. Over a 10-year timeframe, the total QALY loss was 19,125.73, of which AMR infections accounted for 12,299.32 and susceptible infections accounted for 6,826.41. The QALY loss per case was 0.1319. Over a

40-year timeframe, the total QALY loss increased to 31,660.75, of which AMR infections accounted for 20,343.67 and susceptible infections accounted for 11,317.08, resulting in a QALY loss per case of 0.2183. Over a 70-year timeframe, the total QALY loss was 35,943.66, of which AMR infections accounted for 23,096.06 and susceptible infections accounted for 12,847.60. The QALY loss per case was 0.247911. Over 100 years, the total QALY loss amounted to 36,868.32, of which 23,689.63 were from AMR infection and 13,178.69 were from susceptible infection, resulting in a QALY loss of 0.2543 per case.

Table 4.12 Lifetime QALYs losses from foodborne *Campylobacter* infections

Time Horizon	AMR Campylobacter QALYs Losses	Susceptible Campylobacter QALYs Losses	Total QALYs Losses	Per Case QALYs Losses
10 years	12299.32	6826.41	19125.73	0.1319
40 years	20343.67	11317.08	31660.75	0.2184
70 years	23096.06	12847.60	35943.66	0.2479
100 years	23689.63	13178.69	36868.32	0.2543

4.2. Macroeconomic Impacts

Foodborne illnesses have significant macroeconomic impacts, primarily through their effect on labour productivity and income. On the demand side, the direct effect is the loss of income due to absence from work for patients and caregivers, which decreases labour productivity and subsequently reduces spending on goods and services. This represents the direct effect of changes in final demand on industrial output. Supply and demand shocks are interdependent and interactions occur within and between industries. These interactions represent the indirect effects of changes in procurement between industries due to variations in industrial output. An input-output model is used to estimate the impact of these impacts on Canadian industrial output, GDP, and employment between 2015 and 2019.

Table 4.13 shows the estimated income loss associated with foodborne *Salmonella* infections. This was calculated using the number of cases and average income loss per case from the previous Markov model. These costs are then adjusted for the household savings rate to determine the change in final demand due to lost income. Household savings rates, derived from Statistics Canada (2024), were 4.55% in 2015, 1.95% in 2016, 2.00% in 2017, 0.63% in 2018, and 2.10% in 2019. In 2015, the total income loss from *Salmonella* infections was $27,396,850, of which $8,906,725 was due to AMR cases and $18,490,125 was due to susceptible cases. In 2019, total income losses decreased to $25,387,600, of which $12,627,219 was due to AMR cases and $12,760,382 was due to susceptible cases. An increased trend was observed for *Campylobacter* infections from 2017 onwards with income losses ranging around $34-36 million.

Table 4.13 Income lost due to foodborne *Salmonella* and *Campylobacter* infections

Year	AMR Salmonella	Susceptible Salmonella	Total	AMR Campylobacter	Susceptible Campylobacter	Total
2015	8,906,725	18,490,125	27,396,850	-	-	-
2016	11,756,170	17,618,089	29,374,259	-	-	-
2017	13,371,038	14,880,185	28,251,223	19,131,302	15,857,293	34,988,595
2018	12,467,117	16,739,887	29,207,004	19,086,664	17,141,783	36,228,447
2019	12,627,219	12,760,382	25,387,600	22,519,680	14,002,467	36,522,147

Any change in demand for goods and services generates direct and indirect economic impacts. The IO model uses inter-industry linkages to track the total output of goods and services required to meet a final demand shock. It determines which domestic industries directly meet this demand and how much is satisfied by foreign imports and other leakages, such as inventories and government services. This initial impact is called the direct impact. Direct suppliers subsequently purchase goods and services from other industries as inputs, which generates further economic activity. The model continues this process and identifies all indirect goods involved in the production chain until it has captured all indirect impacts. The accumulation of these impacts constitutes the indirect impacts. The combination of direct and indirect impacts forms the total impact.

For *Salmonella* infection, Table 4.14 indicates that the direct impact on industrial output led to a reduction of $27.2 million in 2015, and this reduction decreased to $25.2 million in 2019. The direct effect on GDP shows a minimal fluctuation, with a reduction ranging from $15.4 million in 2015 to $14.4 million in 2019. Regarding employment, the direct impact resulted in a loss of 140 jobs in 2015, decreasing to 120 jobs in 2019. The total employment impact, including direct and indirect effects, changed from a reduction of 191 jobs in 2015 to 149 jobs in 2019.

Table 4.14 Direct effect and direct plus indirect effect of the income loss due to *Salmonella* infection

Year	Effect Type	Industrial Output ('000$)	GDP ('000$)	Employment (jobs)
2015	Direct Effect	-27,193	-15,448	-140
	Direct + Indirect Effect	-35,959	-20,839	-191
2016	Direct Effect	-29,143	-16,624	-147
	Direct + Indirect Effect	-35,636	-20,797	-171
2017	Direct Effect	-28,018	-15,904	-138
	Direct + Indirect Effect	-34,786	-20,172	-164
2018	Direct Effect	-28,953	-16,448	-140
	Direct + Indirect Effect	-36,336	-21,072	-170
2019	Direct Effect	-25,165	-14,388	-120
	Direct + Indirect Effect	-31,865	-18,602	-149

In contrast, Table 4.15 shows that *Campylobacter* infections have a different pattern of economic impacts. In 2017, the direct effects included a decrease of $34.7 million in industrial output, $19.7 million in GDP, and a loss of 172 jobs. The combined direct and indirect effects were even more substantial, with industrial output decreasing by $43.1 million, GDP by $25.0 million, and employment by 203 jobs. By 2019, the direct effects included a loss of $36.2 million in industrial output, $20.7 million in GDP, and 172 jobs. The combined effects for that year showed an even greater impact, with reductions of $45.8 million in industrial output, $26.8 million in GDP, and 214 job losses.

Table 4.15 Direct effect and direct plus indirect effect of the income loss due to *Campylobacter* infection

Year	Effect Type	Industrial Output ('000$)	GDP ('000$)	Employment (jobs)
2017	Direct Effect	-34,699	-19,697	-172
	Direct + Indirect Effect	-43,082	-24,983	-203
2018	Direct Effect	-35,913	-20,402	-173
	Direct + Indirect Effect	-45,072	-26,138	-211
2019	Direct Effect	-36,202	-20,698	-172
	Direct + Indirect Effect	-45,840	-26,761	-214

4.2.1. Industrial Output Impact

The decrease in total industrial output value due to *Salmonella* infections from 2015 to 2019 is shown in Table 4.16. In 2015, the total industrial output value decreased by $36.0 million, with AMR strains causing $11.7 million and susceptible strains causing $24.3 million. The percentage decrease in total output value was 0.001026%. In 2019, the total reduction in industrial output decreased to $31.9 million, with AMR strains accounting for $15.8 million and susceptible strains $16.0 million, leading to a 0.000781% decrease. Figure 4.4 visually compares the decline in industrial output due to AMR and susceptible *Salmonella* infections. In 2015, the decrease from susceptible strains was higher than that of AMR strains. However, from 2016 onwards, the gap between the output decrease caused by AMR and susceptible strains narrowed. By 2019, the total decrease in industrial output was balanced between AMR and susceptible strains. This trend shows that while the overall industrial losses caused by *Salmonella* infections are decreasing, the proportion of losses caused by AMR strains is increasing.

Table 4.16 Decrease in total industrial output due to *Salmonella* infection

Year	AMR Salmonella spp.		Susceptible Salmonella spp.		Total Salmonella spp.	
	Δ Output ('000$)	Δ Output	Δ Output ('000$)	Δ Output (%)	Δ Output ('000$)	Δ Output (%)
2015	11,690	0.000334	24,269	0.000692	35,959	0.001026
2016	14,262	0.000401	21,374	0.000600	35,636	0.001001
2017	16,464	0.000436	18,322	0.000485	34,786	0.000922
2018	15,510	0.000392	20,826	0.000527	36,336	0.000919
2019	15,849	0.000388	16,016	0.000393	31,865	0.000781

Figure 4.4 Comparison of decrease in industrial output due to AMR and Susceptible *Salmonella* infections from 2015 to 2019

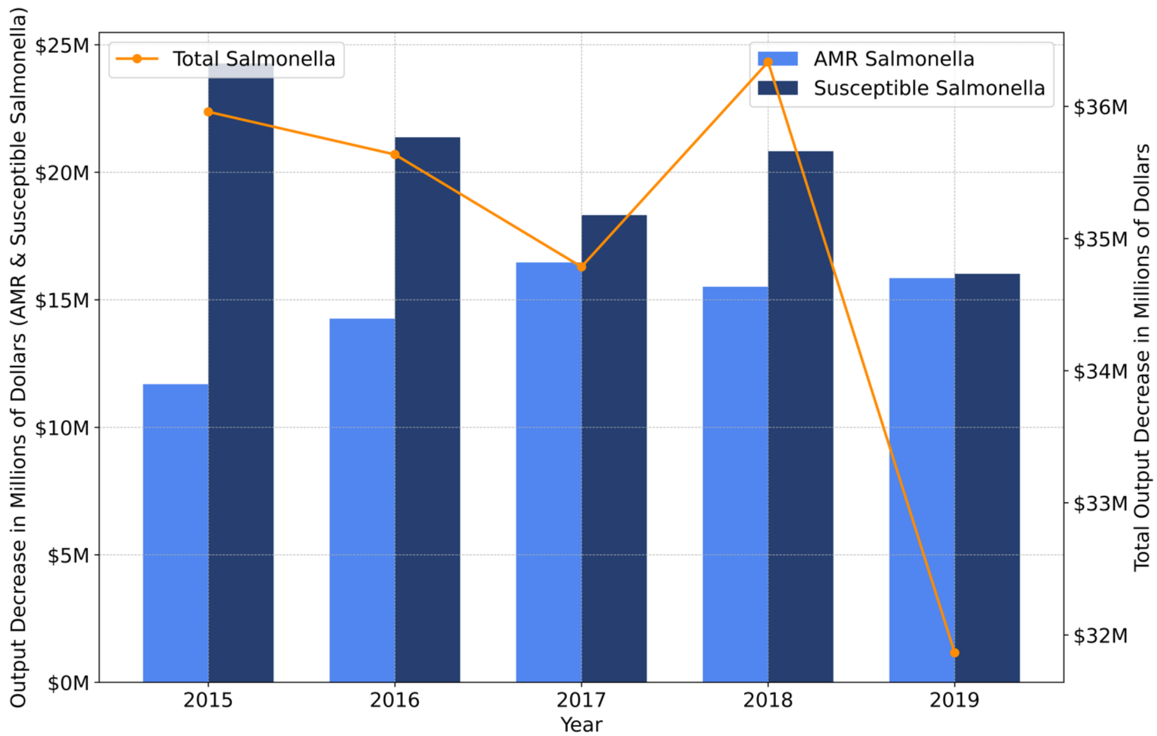


Table 4.17 presents the total industrial output value decrease due to *Campylobacter* infections from 2017 to 2019. The total industrial output reduction due to *Campylobacter* infections was consistently higher, ranging from $43.1 million to $45.8 million between 2017 and 2019. The largest reduction occurred in 2019, and the AMR strains consistently caused a larger reduction in industrial output compared to susceptible strains. The percentage decrease in total industrial output due to *Campylobacter* infections remained relatively stable, around 0.001140%.

Table 4.17 Decrease in total industrial output due to *Campylobacter* infection

Year	AMR Campylobacter spp.		Susceptible Campylobacter spp.		Total Campylobacter spp.	
	Δ Output ('000$)	Δ Output (%)	Δ Output ('000$)	Δ Output (%)	Δ Output ('000$)	Δ Output (%)
2017	23,557	0.000624	19,525	0.000517	43,082	0.001141
2018	23,746	0.000601	21,326	0.000539	45,072	0.001140
2019	28,265	0.000693	17,575	0.000431	45,840	0.001124

The 20 industries with the highest percentage decreases in output due to foodborne *Salmonella* and *Campylobacter* infections are presented in Table 4.18 and Table 4.19. The recreational vehicle parks, recreational campgrounds, and boarding houses industry experienced the most significant impact for *Salmonella* infections, with a total output reduction of $71,450. Other heavily impacted industries included recreation and entertainment, owner-occupied residential, and private households, with total output reductions of $203,010, $4,345,510, and $75,950, respectively. Additionally, cannabis stores (licensed and unlicensed), urban transportation systems, and funeral services also faced output reductions. Industries such as clothing and accessories stores, food and beverage stores, and food services and drinking establishments experienced substantial economic impacts, with total output reductions ranging from $374,460 to $1,511,120.

Table 4.18 Highest percentage decrease in industrial output due to *Salmonella* infection in 2019

		AMR Salmonella spp.		Susceptible Salmonella spp.		Total Salmonella spp.	
	Industry	**Δ Output ('000$)**	**Δ Output (%)**	**Δ Output ('000$)**	**Δ Output (%)**	**Δ Output ('000$)**	**Δ Output (%)**
1	Recreational vehicle (RV) parks, recreational camps, and rooming and boarding houses	35.54	0.001807	35.91	0.001826	71.45	0.003633
2	Amusement and recreation industries	100.97	0.001083	102.04	0.001094	203.01	0.002177
3	Owner-occupied dwellings	2161.36	0.001067	2184.15	0.001078	4345.51	0.002145
4	Private households	37.78	0.001067	38.18	0.001078	75.95	0.002145
5	Cannabis stores (unlicensed)	13.03	0.001067	13.17	0.001078	26.20	0.002145
6	Cannabis stores (licensed)	3.90	0.001065	3.94	0.001076	7.85	0.002141
7	Urban transit systems	53.30	0.001039	53.86	0.001050	107.15	0.002089
8	Funeral services	23.37	0.001032	23.62	0.001043	46.99	0.002074
9	Clothing and clothing accessories stores	186.25	0.001002	188.21	0.001013	374.46	0.002015
10	Motion picture and video exhibition	16.12	0.001002	16.29	0.001012	32.41	0.002014
11	Food and beverage stores	324.18	0.000998	327.59	0.001009	651.77	0.002007
12	Food services and drinking places	751.60	0.000997	759.52	0.001008	1511.12	0.002005
13	Personal care services and other personal services	118.84	0.000991	120.09	0.001002	238.92	0.001993
14	Gambling industries	68.37	0.000988	69.09	0.000999	137.46	0.001987
15	Offices of dentists	177.44	0.000981	179.32	0.000991	356.76	0.001973
16	Sporting goods, hobby, book and music stores	51.06	0.000966	51.60	0.000976	102.67	0.001942
17	Dairy product manufacturing	147.56	0.000938	149.12	0.000948	296.69	0.001886
18	Air transportation	193.30	0.000938	195.34	0.000948	388.63	0.001886
19	Gasoline stations	94.11	0.000920	95.10	0.000929	189.20	0.001849
20	General merchandise stores	166.52	0.000905	168.27	0.000915	334.79	0.001820

Campylobacter infections similarly impacted a wide range of industries. The RV parks, recreational campgrounds, and boarding houses industry was the most impacted, with a total output reduction of $1,027,800. The entertainment and recreation industry, private households, and owner-occupied residences also saw declines in output, with total output decreasing by $2,920,400, $1,092,700, and $62,513,700, respectively. The economic burden of *Campylobacter* infections extends to cannabis stores, urban transportation systems, and funeral services, which saw declines in output. Clothing and accessory stores, food and beverage stores, and food service and drinking establishments were the most affected industries, with total output decreases ranging from $5,386,900 to $21,738,700. Overall, *Campylobacter* infections generally resulted in higher output reductions across most of the top impacted industries compared to *Salmonella* infections.

Table 4.19 Highest percentage decrease in industrial output due to *Campylobacter* infection in 2019

		AMR Campylobacter spp.		Susceptible Campylobacter spp.		Total Campylobacter spp.	
	Industry	**Δ Output ('000$)**	**Δ Output (%)**	**Δ Output ('000$)**	**Δ Output (%)**	**Δ Output ('000$)**	**Δ Output (%)**
1	Recreational vehicle (RV) parks, recreational camps, and rooming and boarding houses	63.37	0.003223	39.41	0.002004	102.78	0.005227
2	Amusement and recreation industries	180.07	0.001931	111.97	0.001201	292.04	0.003132
3	Private households	67.37	0.001903	41.89	0.001183	109.27	0.003086
4	Owner-occupied dwellings	3854.61	0.001903	2396.75	0.001183	6251.37	0.003086
5	Cannabis stores (unlicensed)	23.24	0.001903	14.45	0.001183	37.70	0.003086
6	Cannabis stores (licensed)	6.96	0.001899	4.33	0.001181	11.29	0.003080
7	Urban transit systems	95.05	0.001853	59.10	0.001152	154.15	0.003005
8	Funeral services	41.68	0.001840	25.92	0.001144	67.60	0.002984
9	Clothing and clothing accessories stores	332.16	0.001787	206.53	0.001111	538.69	0.002898
10	Motion picture and video exhibition	28.75	0.001786	17.88	0.001111	46.62	0.002897
11	Food and beverage stores	578.14	0.001780	359.48	0.001107	937.62	0.002887
12	Food services and drinking places	1340.42	0.001778	833.45	0.001106	2173.87	0.002884
13	Personal care services and other personal services	211.93	0.001768	131.78	0.001099	343.71	0.002867
14	Gambling industries	121.94	0.001763	75.82	0.001096	197.75	0.002859
15	Offices of dentists	316.46	0.001750	196.77	0.001088	513.23	0.002838
16	Sporting goods, hobby, book and music stores	91.07	0.001723	56.63	0.001071	147.69	0.002794
17	Dairy product manufacturing	263.17	0.001673	163.64	0.001040	426.81	0.002714
18	Air transportation	344.73	0.001673	214.35	0.001040	559.08	0.002713
19	Gasoline stations	167.83	0.001640	104.35	0.001020	272.18	0.002660
20	General merchandise stores	296.97	0.001614	184.65	0.001004	481.62	0.002618

4.2.2. GDP Impact

Table 4.20 outlines the total decrease in GDP from 2015 to 2019 due to *Salmonella* infections. In 2015, the GDP decreased by $20.8 million due to *Salmonella* infections, with AMR strains contributing $6.8 million and susceptible strains $14.0 million, representing a total percentage decrease of 0.001122%. In 2019, the total GDP impact dropped to $18.6 million, with AMR strains contributing $9.3 million and susceptible strains $9.4 million, leading to a 0.00086% decrease. As shown in Figure 4.5, the GDP decrease was more substantial for susceptible strains compared to AMR strains. This trend continues in subsequent years, with susceptible strains consistently causing a higher GDP reduction. However, the gap between the GDP impact of AMR and susceptible strains narrows over the years. By 2017, the contribution of AMR strains to GDP decrease increases substantially, nearly matching that of susceptible strains by 2019.

Table 4.20 Total decrease in GDP from 2015 – 2019 due to *Salmonella* infection

Year	AMR Salmonella spp.		Susceptible Salmonella spp.		Total Salmonella spp.	
	Δ GDP ('000$)	Δ GDP (%)	Δ GDP ('000$)	Δ GDP (%)	Δ GDP ('000$)	Δ GDP (%)
2015	6,775	0.000365	14,064	0.000757	20,839	0.001122
2016	8,323	0.000441	12,474	0.000661	20,797	0.001103
2017	9,547	0.000479	10,625	0.000534	20,172	0.001013
2018	8,995	0.000432	12,077	0.000580	21,072	0.001011
2019	9,252	0.000428	9,350	0.000432	18,602	0.000860

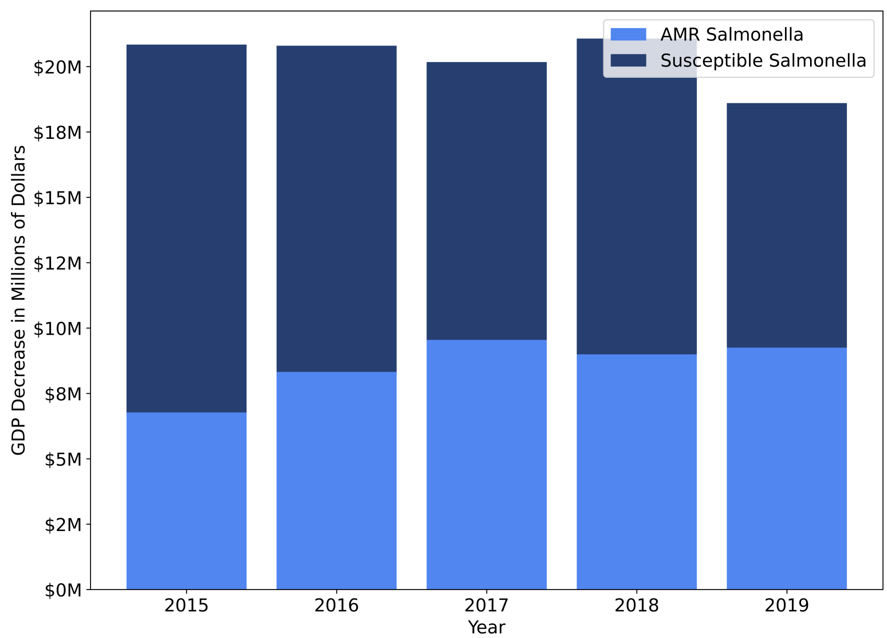
For *Campylobacter* infections, the impact on GDP remained high from 2017 to 2019 (Table 4.21). In 2017, the total GDP loss was $25.0 million, of which AMR strains caused $13.7 million and susceptible strains caused $11.3 million. The impact increased to $26.1 million in 2018 and further increased to $26.8 million in 2019. The percentage reduction in GDP for *Campylobacter* infections was slightly higher than for *Salmonella* infections, indicating a greater economic burden.

The percentage reduction in GDP for *Campylobacter* infections ranged from 0.001254% to 0.001238%.

Table 4.21 Total decrease in GDP from 2017 – 2019 due to *Campylobacter* infection

	AMR Campylobacter spp.		Susceptible Campylobacter spp.		Total Campylobacter spp.	
Year	Δ GDP ('000$)	Δ GDP (%)	Δ GDP ('000$)	Δ GDP (%)	Δ GDP ('000$)	Δ GDP (%)
2017	13,660	0.0006859	11,323	0.0005685	24,983	0.001254
2018	13,771	0.0006610	12,367	0.0005936	26,138	0.001255
2019	16,501	0.0007632	10,260	0.0004746	26,761	0.001238

Figure 4.5 Comparison of decrease in GDP due to AMR and Susceptible *Salmonella* infections from 2015 to 2019



4.2.3. Employment Impact

Table 4.22 illustrates the employment losses across 20 aggregated industries in 2019 due to the income loss from *Salmonella* and *Campylobacter* infections. The result shows the number of jobs lost and the percentage decrease in employment for each sector. For *Salmonella* infections, the retail trade sector experienced the highest employment loss, with 41 jobs lost, representing a

0.00179% decrease. Other affected sectors include finance and insurance with 11 jobs lost (0.00151%); healthcare and social assistance, with ten jobs lost (0.00047%), and administrative and support services, with seven jobs lost (0.00086%). *Campylobacter* infections had a more substantial impact on employment, with the retail trade sector experiencing the highest job loss at 59 jobs, which is a 0.00257% decrease. The finance and insurance sector lost 16 jobs (0.00218%), healthcare and social assistance lost 14 jobs (0.00068%), and administrative and support services lost 11 jobs (0.00124%). Overall, the total employment loss across all sectors due to *Salmonella* infections was 149 jobs (0.00087%), whereas *Campylobacter* infections resulted in a higher total employment loss of 214 jobs (0.00125%).

Table 4.22 Employment losses of aggregated 20 industries in 2019

	Salmonella spp.		Campylobacter spp.	
Sector	**Δ Employment (jobs)**	**Δ Employment (%)**	**Δ Employment (jobs)**	**Δ Employment (%)**
Agriculture, forestry, fishing and hunting	2.98	0.00083	4.29	0.00120
Mining, quarrying, and oil and gas extraction	0.38	0.00019	0.54	0.00027
Utilities	1.49	0.00117	2.14	0.00168
Construction	1.85	0.00018	2.66	0.00026
Manufacturing	7.29	0.00046	10.49	0.00066
Wholesale trade	5.38	0.00081	7.74	0.00117
Retail trade	40.69	0.00179	58.53	0.00257
Transportation and warehousing	6.23	0.00080	8.97	0.00115
Information and cultural industries	4.33	0.00123	6.22	0.00176
Finance and insurance	11.33	0.00151	16.31	0.00218
Real estate and rental and leasing	5.22	0.00175	7.50	0.00252
Professional, scientific and technical services	5.48	0.00056	7.88	0.00081
Management of companies and enterprises	0.80	0.00073	1.15	0.00105
Administrative and support, waste management and remediation services	7.27	0.00086	10.46	0.00124
Educational services	5.83	0.00043	8.39	0.00062
Health care and social assistance	9.86	0.00047	14.19	0.00068
Arts, entertainment and recreation	4.55	0.00147	6.55	0.00212
Accommodation and food services	19.17	0.00143	27.57	0.00205
Other services (except public administration)	6.73	0.00121	9.69	0.00174
Public administration	2.00	0.00017	2.88	0.00025
Total	**148.86**	**0.01806**	**214.15**	**0.02599**

Figures 4.6 and 4.7 clearly show the employment losses attributed to AMR and susceptible *Salmonella* and *Campylobacter* infections. The total employment losses caused by *Salmonella* infections fluctuated over the years. The highest total job loss occurred in 2016, and the lowest in 2019. In 2015 and 2016, the employment losses from susceptible infections were higher than AMR infections. By 2019, the contributions of both AMR and susceptible infections to total job losses were almost equal. In contrast, the total employment losses caused by *Campylobacter* infections increased over the three years, with the highest total job losses in 2019. Each year, from 2017 to 2019, AMR infections contributed more to the total job losses than susceptible infections. The gap between employment losses caused by resistant *Campylobacter* infection and employment losses caused by susceptible infection widens year after year, indicating that the impact of resistant *Campylobacter* infection on employment is increasing.

Figure 4.6 Comparison of employment losses due to AMR and Susceptible *Salmonella* infections from 2015 to 2019

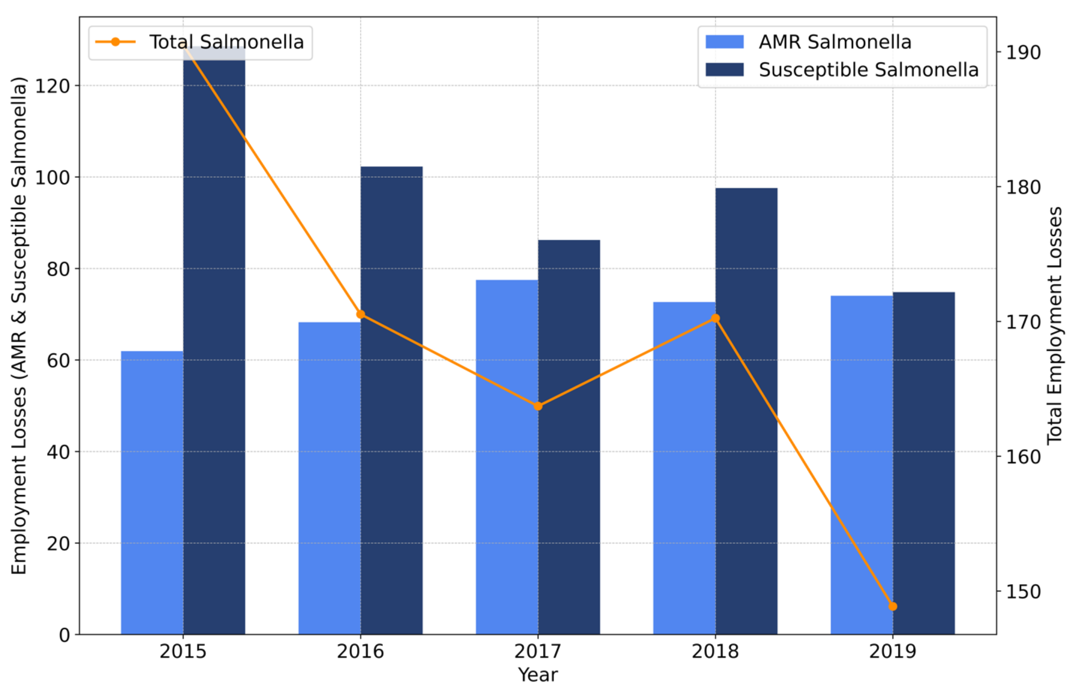
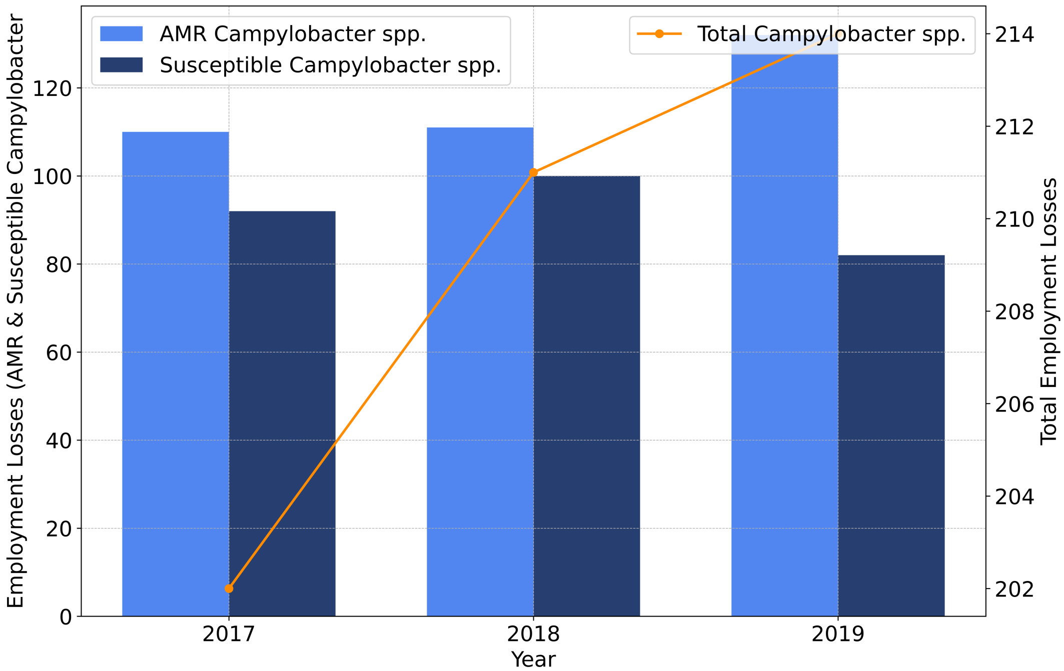


Figure 4.7 Comparison of employment losses due to AMR and Susceptible *Campylobacter* infections from 2017 to 2019



4.3. Case Study Results

The reduction in the use of Category I and Category II antimicrobials in the Canadian poultry industry has resulted in a decrease in the number of predicted chicken-associated *Salmonella* cases. For resistant *Salmonella* cases, Table 4.23 shows fluctuations in the number of cases from 2015 to 2019, with the highest number of cases in 2017 (39,624) and the lowest number in 2019 (30,969). There has been a clear decrease in case counts over the years for susceptible *Salmonella* cases, with the highest number of cases in 2015 (67,881) and the lowest in 2019 (36,128). This decrease is reflected in the associated hospitalizations, physician visits, and severe health outcomes. Considering the total number of *Salmonella* cases associated with chicken, the data show a peak in 2016 (97,570 cases) and a decrease in 2019 (67,097 cases).

Table 4.23 Predicted number of cases of chicken related *Salmonella* infection

	AMR Salmonella Cases Related to Chicken Mean (95% CI)					
Year	Case Number	Hospitalization	Physician Visit	IBS	RA	Death
2015	28,543 (28,225 to 28,860)	1,418 (1,344 to 1,491)	8,126 (7,818 to 8,433)	844 (787 to 901)	214 (185 to 242)	6 (1 to 11)
2016	35,180 (34,830 to 35,529)	1,767 (1,684 to 1,849)	10,130 (9,781 to 10,478)	1,030 (967 to 1,092)	209 (181 to 237)	7 (2 to 12)
2017	39,624 (39,255 to 39,992)	1,932 (1,846 to 2,017)	11,430 (11,061 to 11,798)	1,165 (1,098 to 1,231)	258 (226 to 289)	8 (2 to 13)
2018	32,955 (32,615 to 33,294)	1,647 (1,567 to 1,726)	9,486 (9,151 to 9,820)	959 (898 to 1,019)	217 (188 to 245)	7 (2 to 12)
2019	30,969 (30,639 to 31,299)	1,540 (1,463 to 1,616)	8,729 (8,408 to 9,049)	882 (823 to 940)	209 (180 to 237)	6 (1 to 11)

	Susceptible Salmonella Cases Related to Chicken Mean (95% CI)					
Year	Case Number	Hospitalization	Physician Visit	IBS	RA	Death
2015	67,881 (67,421 to 68,340)	2,256 (2,163 to 2,348)	13,223 (12,822 to 13,623)	891 (832 to 949)	222 (192 to 251)	6 (1 to 11)
2016	62,390 (61,944 to 62,835)	2,052 (1,963 to 2,140)	12,245 (11,858 to 12,631)	886 (827 to 944)	172 (146 to 197)	9 (3 to 15)
2017	51,615 (51,202 to 52,027)	1,810 (1,726 to 1,893)	10,311 (9,955 to 10,666)	663 (612 to 713)	172 (146 to 198)	7 (2 to 12)
2018	52,571 (52,154 to 52,987)	1,785 (1,702 to 1,867)	10,294 (9,937 to 10,650)	681 (629 to 732)	147 (123 to 170)	4 (0 to 8)
2019	36,128 (35,773 to 36,482)	1,210 (1,141 to 1,278)	6,915 (6,625 to 7,204)	473 (430 to 515)	125 (103 to 147)	4 (0 to 8)

	Total Salmonella Cases Related to Chicken Mean (95% CI)					
Year	Case Number	Hospitalization	Physician Visit	IBS	RA	Death
2015	96,424 (95,646 to 97,200)	3,674 (3,507 to 3,839)	21,349 (20,640 to 22,056)	1,735 (1,619 to 1,850)	436 (377 to 493)	12 (2 to 22)
2016	97,570 (96,774 to 98,364)	3,819 (3,647 to 3,989)	22,375 (21,639 to 23,109)	1,916 (1,794 to 2,036)	381 (327 to 434)	16 (5 to 27)
2017	91,239 (90,457 to 92,019)	3,742 (3,572 to 3,910)	21,741 (21,016 to 22,464)	1,828 (1,710 to 1,944)	430 (372 to 487)	15 (4 to 25)
2018	85,526 (84,769 to 86,281)	3,432 (3,269 to 3,593)	19,780 (19,088 to 20,470)	1,640 (1,527 to 1,751)	364 (311 to 415)	11 (2 to 20)
2019	67,097 (66,412 to 67,781)	2,750 (2,604 to 2,894)	15,644 (15,033 to 16,253)	1,355 (1,253 to 1,455)	334 (283 to 384)	10 (1 to 19)

The economic impact of chicken-associated *Salmonella* infections also changed substantially (Table 4.24). For resistant *Salmonella*, the total annual costs increased from

$51,222,400 in 2015 to a peak of $72,273,850 in 2017 before declining to $54,664,767 in 2019. Costs per case remained relatively stable at around $1,800. The total annual costs for susceptible *Salmonella* decreased from $71,524,231 in 2015 to $38,898,591 in 2019. Costs per case remained constant at about $1,100. The total cost of resistant and susceptible strains peaked in 2016 ($130,895,363) and declined in 2019 ($93,563,358).

Table 4.24 Total annual and per case costs of chicken related *Salmonella* infections (in dollars)

	AMR Salmonella Costs ($) Mean (95% CI)		Susceptible Salmonella Costs ($) Mean (95% CI)		Total Costs ($) Mean (95% CI)	
Year	**Annual**	**Per Case**	**Annual**	**Per Case**	**Annual**	**Per Case**
2015	51,222,400 (49,401,238 to 53,043,561)	1795 (1750 to 1837)	71,524,231 (68,981,258 to 74,067,203)	1,054 (1,023 to 1,083)	122,746,630 (118,382,497 to 127,110,764)	1,273 (1,227 to 1,318)
2016	65,581,502 (63,275,595 to 67,887,409)	1,864 (1,816 to 1,910)	65,313,861 (63,017,365 to 67,610,357)	1,047 (1,017 to 1,075)	130,895,363 (126,292,960 to 135,497,767)	1,342 (1,294 to 1,388)
2017	72,273,850 (69,691,280 to 74,856,420)	1,824 (1,775 to 1,871)	57,716,111 (55,653,734 to 59,778,487)	1,118 (1,086 to 1,148)	129,989,961 (125,345,015 to 134,634,908)	1,425 (1,373 to 1,475)
2018	60,174,578 (57,942,539 to 62,406,615)	1,826 (1,776 to 1,874)	57,580,453 (55,454,267 to 59,726,639)	1,095 (1,063 to 1,127)	117,755,031 (113,396,806 to 122,133,255)	1,377 (1,325 to 1,428)
2019	54,664,767 (52,400,943 to 56,928,589)	1,765 (1,710 to 1,818)	38,898,591 (37,287,690 to 40,509,492)	1,077 (1,042 to 1,110)	93,563,358 (89,688,634 to 97,438,081)	1,394 (1,336 to 1,452)

QALY losses due to *Salmonella* infections in chicken measures the health impact, including the number and quality of life years affected. For resistant *Salmonella*, the annual total QALY losses peaked in 2017 (806.19) and then declined to 637.79 in 2019 (See Table 4.25). The QALY losses per case remained around 0.0205. For susceptible *Salmonella*, the annual total QALY losses decreased from 872.14 in 2015 to 466.53 in 2019, and the QALY losses per case remained around 0.0128. Total QALY losses for resistant and susceptible strains decreased from 1,458.83 in 2015 to 1,104.32 in 2019.

Table 4.25 Total annual and per case QALYs losses of chicken related *Salmonella* infections

	AMR Salmonella QALYs losses		Susceptible Salmonella QALYs losses		Total QALYs losses	
Year	**Annual**	**Per Case**	**Annual**	**Per Case**	**Annual**	**Per Case**
2015	586.69	0.02055	872.14	0.01285	1,458.83	0.01513
2016	713.97	0.02029	796.47	0.01277	1,510.44	0.01548
2017	806.19	0.02035	660.93	0.01280	1,467.12	0.01608
2018	689.33	0.02092	678.64	0.01291	1,367.97	0.01599
2019	637.79	0.02059	466.53	0.01291	1,104.32	0.01646

Chapter 5. Discussion

5.1. Insights From Results

The study estimated the economic cost and health burden of foodborne illness related to foodborne nontyphoidal *Salmonella* and *Campylobacter* species in Canada. This represents the first study in Canada that differentiates between AMR and susceptible strains of these pathogens. Glass-Kaastra et al. (2022) reported a substantial reduction in the number of nontyphoidal *Salmonella* cases in Canada in 2019, with an estimated 25,821 fewer cases, 213 fewer hospitalizations, and two fewer deaths than in the previous five years. This reduction equates to an estimated economic savings of $26.9 million, attributed to strategic public health actions and enhanced genomic surveillance. Our study supports these findings, showing a reduction in *Salmonella* cases from 119,432 in 2015 to 93,199 in 2019. The economic impact observed in our study further confirms the reduction in economic burden, with the total cost of resistant and susceptible *Salmonella* strains decreasing from $155.8 million in 2015 to $131.3 million in 2019. However, this overall decline contrasts with the increase in AMR *Salmonella* infections, which rose from 34,807 in 2015 to 42,645 in 2019. AMR *Salmonella* infections also had higher rates of severe outcomes including hospitalization, IBS, RA, and mortality compared to susceptible cases.

The cumulative costs of infections with resistant strains of *Salmonella* and *Campylobacter* were higher than those with susceptible strains, suggesting that infections with resistant strains carry a greater economic burden over time. For *Salmonella* infections, the total costs over 100 years remained stable at approximately $22 million, with resistant strains accounting for $12.3 million and susceptible strains for $9.7 million. In contrast, the total costs of *Campylobacter* infections were higher, remaining stable at about $40.2 million, with resistant strains accounting for $26.3 million and susceptible strains for $13.9 million.

Salmonella and *Campylobacter* infections resulted in substantial QALY losses, with AMR strains contributing more to total QALY losses than susceptible strains. For *Salmonella* infections, the total annual QALYs loss for AMR strains peaked in 2017 and then declined slightly, while the QALY loss per case remained stable. In contrast, the QALY loss for susceptible strains showed a decreasing trend over the years. *Campylobacter* infections resulted in higher total QALY losses than *Salmonella* infections across all time frames. Over 10 years, *Campylobacter* infections resulted in 19,125.73 total QALY losses compared to 9,469.27 total QALY losses for *Salmonella* infections. This trend continued over longer periods, with *Campylobacter* infections resulting in more than twice as many QALY losses as *Salmonella* infections over 100 years (36,868.32 compared to 15,365.06 total QALY losses for *Salmonella* infections). This discrepancy is likely due to the higher number of *Campylobacter* cases each year.

There is a substantial economic burden from foodborne *Salmonella* and *Campylobacter* infections on labour productivity in Canada. The total income loss from *Salmonella* infections peaked in 2016 at $29,374,259, with AMR cases contributing a higher proportion of these losses over the years. The overall trend shows a slight decrease in total income loss by 2019. Similar trends were observed for *Campylobacter* infections from 2017 onwards, with total income losses remaining stable around $28-29 million, followed by a slight decrease in 2019. The input-output analysis shows that *Salmonella* and *Campylobacter* infections cause substantial economic losses across various industries. Income loss leads to reduced consumer spending, with the most significant impact on industries such as caravan parks, recreational campgrounds and boarding houses. Other heavily affected industries include recreation and leisure, owner-occupied residential and private households. Both resistant and susceptible strains of these pathogens have a substantial impact on the economic burden on these industries.

Previous studies have examined the impact of WGS on industrial output, GDP, and employment across four scenarios in Canada (Jain, Mukhopadhyay, and Thomassin 2018). The changes in GDP ranged from $2.6 million to $23.2 million, with the highest increase in employment (201 jobs) observed in scenarios with increased consumer expenditure. This is consistent with our findings that *Salmonella* and *Campylobacter* infections cause substantial economic losses across various industries, leading to reductions in industrial output and GDP. Specifically, our study observed total industrial output reductions due to *Salmonella* infections ranging from $20.8 million to $18.6 million between 2015 and 2019. In terms of employment impact, they reported that WGS adoption led to positive net benefits, increasing industrial output ($15.88 million) and employment (116). Similarly, our study showed that the total number of jobs lost due to reduced income from *Salmonella* infections was 149 in 2019, with substantial impacts on various sectors such as retail trade, finance, insurance, healthcare, and administrative support services.

For *Campylobacter* infections, the percentage decrease in total industrial output due to *Campylobacter* infections remained relatively stable, around 0.001140%, indicating a consistent economic impact over the observed years. However, *Campylobacter* infections generally impose a greater economic burden than *Salmonella* infections, mainly due to the higher impact of AMR strains. The GDP impact of *Campylobacter* infections was consistently higher than that of *Salmonella* infections. In 2019, the GDP decrease due to *Campylobacter* infections was $26.8 million, much more than *Salmonella* infections ($18.6 million). While the GDP impact of *Salmonella* infections showed a slight decline over the years, the impact of *Campylobacter* infections remained consistently high, with a slight increase in 2019. In addition, the total number of jobs lost caused by reduced income from *Campylobacter* infections (214) was higher than that caused by *Salmonella* infection (149). The retail trade sector experienced the highest employment loss, with 41 jobs lost due to *Salmonella* infections and 59 jobs due to *Campylobacter* infections. Similar trends were observed in other industries such as finance and insurance, healthcare and social assistance, and administrative and support services, where the impact of *Campylobacter* infection on employment was even more severe.

The voluntary reduction of Categories I and II antimicrobials used by Canadian poultry farmers has led to public health and economic benefits. The result shows a clear trend of decreasing *Salmonella* cases, physician visits, hospitalizations, and deaths, alongside a reduction in economic costs and QALY. This aligns with findings from Hurst et al. (2023) and (Huber et al. 2021), which observed a decline in the incidence rate of salmonellosis from chicken. Huber et al. (2021) found that antimicrobial resistance in foodborne bacteria, including *Salmonella*, Escherichia coli, and *Campylobacter*, decreased as a result of reduced prophylactic antimicrobial use. Specifically, antimicrobial resistance in broiler chickens decreased by 6%–38%. This decrease is consistent with our findings, with the total number of *Salmonella* cases associated with chicken decreasing from 96,424 in 2015 to 67,097 in 2019. This can translate to a total cost reduction from $122 million in 2015 to $93 million in 2019. However, a greater decline was observed for susceptible strains compared to AMR strains.

5.2. Policy Implications

The findings of this study have several important policy implications. First, the success of antimicrobial use reduction strategies in the poultry industry suggests the potential benefits of similar interventions in other areas of food production and animal husbandry. Policymakers should consider expanding antimicrobial stewardship programs to other sectors to replicate the positive public health outcomes observed in this study. Regulations along the food supply chain can also play a role in reducing foodborne pathogens. For example, regulations requiring frozen breaded chicken to have no *Salmonella* required firms to adopt new processes and technology. Targeted intervention regulations, particularly those implemented at the beginning of the food supply chain, can be a cost-effective way to mitigate the spread of foodborne pathogens. These regulations can improve food safety and incentivize the food industry to innovate and adopt safer practices.

The substantial economic savings and reductions in QALY losses highlight the value of investing in public health interventions to reduce foodborne illness. Governments and health organizations should prioritize funding such programs, as the long-term economic and health benefits far outweigh the initial costs. In addition, it is important to continue ongoing monitoring and surveillance of antimicrobial resistance in the food supply chain. A strong surveillance system can help detect and mitigate antimicrobial resistance early, thereby preventing outbreaks and reducing the associated health and economic burdens. In addition, incorporating advanced technologies such as WGS into routine surveillance can provide more precise and timely data to further aid in detecting and managing foodborne pathogens. Improved data collection and transparency across federal and provincial agencies will strengthen research and policy analysis, leading to better-informed decisions.

Investing savings from direct healthcare costs into public awareness campaigns is vital. Educating consumers and producers about the risks of AMR and the importance of appropriate antibiotic use can promote more responsible practices. Raising awareness can support the overall goal of reducing AMR in the food industry by promoting behavioural changes consistent with public health goals. In addition, policies should encourage research and development of alternatives to antimicrobials, such as vaccines, probiotics, and other preventive health strategies. Supporting innovation in these areas can provide sustainable solutions to maintain animal health and productivity without heavy reliance on antibiotics.

5.3. Limitations and Future Research

A limitation of the current model is the reliance on reported cases and underreporting multipliers, which may only partially reflect the overall infection exposure in the Canadian population. Many patients do not seek medical care or do lab tests, and constant underreporting and antimicrobial resistance rates were assumed over these years, which may ignore real-world variation. The probability of patients seeking physician care, hospitalization, and death were determined through meta-analysis, which showed wide variability in transition probabilities. In addition, some Canada-specific data were not available, and the use of data from comparable countries, such as the United States, could affect the accuracy of the model. The sensitivity analyses found that variations in the probability of developing chronic sequelae had a substantial effect on the total QALY losses. Changes in hospitalization costs and productivity losses impacted the total economic burden substantially.

This study used data from FoodNet Canada from 2017 to 2019 to assess *Campylobacter*'s impact during this period. The limitation of data availability is mainly because there was no comprehensive, integrated dataset on *Campylobacter* before 2017. Human *Campylobacter* data are generally more difficult to process than *Salmonella* data. Although CIPARS provides AMR rates for human *Salmonella*, similar data for *Campylobacter* were not systematically collected or integrated into a single dataset prior to 2017. The process of collecting *Campylobacter* isolates from provincial sites and sending them to the National Microbiology Laboratory (NML) for AMR testing began around 2014. Furthermore, these data were not linked to the FNC questionnaire until 2017, resulting in incomplete AMR data for *Campylobacter* that were unsuitable for this study.

The model also does not account for age and sex. Our analysis of AMR rates for *Salmonella* and *Campylobacter* using the FoodNet Canada dataset showed overlapping trends, but age is a predictor of physician visits, hospitalizations, and deaths. The WHO reports that approximately one-third (30%) of all deaths from foodborne diseases occur in children (World Health Organization 2015). Due to limited data on age and gender in Canada, separate transition probabilities for different age and sex groups could not be estimated. Markov models have age-specific analytical power but require age-specific case estimates or age distributions of patients. Future studies should incorporate these variables to improve accuracy.

Another limitation is the assumption that illnesses progress through all relevant health states before death. This ignores the possibility that patients may be hospitalized without a prior physician visit or die without hospitalization. The Markov model needs further refinement to incorporate these possibilities. Comprehensive estimates of the provincial costs of outbreak investigations are also lacking. Provincial laboratories and local agencies play an essential role in outbreak investigations and enforcement of food safety regulations. Understanding the temporal and spatial variation of costs is critical for a comprehensive economic analysis.

Due to time and data constraints, this study did not evaluate the economic cost of *Campylobacter* infections attributed to chicken. Dramé et al. (2020) found that 53% of *Campylobacter* isolates from broiler chickens in different regions of Canada were resistant to at least one antibiotic, indicating that a substantial proportion of resistant *Campylobacter* is present in chicken products, which may expose the Canadian population to this bacterium. Future studies should evaluate the economic impact and changes in resistance rates of *Campylobacter* pathogens after implementing the antimicrobial reduction strategies in the Canadian poultry industry.

While the input-output model is a valuable decision-making tool, it also has limitations. The input-output analysis assumes fixed technical coefficients, meaning that the inputs required per unit of output are constant and do not account for price effects, substitution, technological change, or economies of scale. In addition, the model assumes that resource supply is infinite and perfectly elastic, ignoring potential resource constraints. The input-output model is a flow model that does not explicitly account for additions to the capital stock and assumes that there are no capital changes in the production of goods. Finally, it assumes full and efficient use of local employment resources and does not account for underemployment.

Future research should focus on enhancing surveillance data by expanding patient follow-up and improving access to detailed medical records. Improved reporting systems are essential to reduce underreporting and more accurately reflect the burden of infection. Detailed surveillance data on patient outcomes following infection would be particularly valuable. Age and sex should be incorporated into future models to account for their substantial impact on health outcomes. This would require the collection of age-specific and sex-specific case estimates or distributions. Future research should also investigate the reasons why patients seek medical care during foodborne outbreaks and how antimicrobial resistance and susceptibility to *Salmonella* and *Campylobacter* affect these decisions. In addition, research should focus on whether outbreaks of these pathogens are more severe and require different medical responses.

Chapter 6. Conclusion

This study presents a novel application of Markov models to estimate the economic costs and health burden of nontyphoidal *Salmonella* and *Campylobacter* associated with foodborne illnesses in Canada from 2015 to 2019. To our knowledge, this is the first comprehensive economic analysis using Markov models to assess these infections in Canada, differentiated by antimicrobial-resistant and susceptible strains. The innovation lies in the dual-time frame approach of Markov models which is applicable to both annual and lifetime analyses to provide a comprehensive understanding of the short and long-term impacts of these infections. Combining these models with input-output analysis, the study quantifies the macroeconomic impacts on industrial output, GDP, and employment, bridging a critical gap between health outcomes and economic analysis.

Key findings show a downward trend in *Salmonella* cases, physician visits, hospitalizations, and mortality, with costs falling from $155 million in 2015 to $131 million in 2019. Chicken-associated *Salmonella* cases fell from 96,424 to 67,097, translating to a cost reduction from $122 million to $93 million. In contrast, the annual cost of *Campylobacter* infections remained stable at about $137 million, with AMR strains having a greater impact. The total annual QALY losses for *Salmonella* decreased to 1,514.93 and increased to 2,538.63 for *Campylobacter* in 2019. *Campylobacter* infection maintained a higher output reduction and GDP impact, with $26.8 million in GDP loss in 2019 compared to $18.6 million for *Salmonella*, and higher employment losses (214 jobs for *Campylobacter* and 149 jobs for *Salmonella*).

The data used for our study was extracted from FoodNet Canada questionnaires, which collects systematic and uniform data from multi-partner sentinel sites. This surveillance system captures data from human cases and various non-human sources like retail meats and environmental samples across Canada. This robust data collection supported the development of the Markov models to better represent the Canadian situation. The core of the Markov model, which incorporates self-treatment, physician treatment, hospitalization, recovery, sequelae, and death as health states, is adaptable to any disease with similar health states. By adjusting transition probabilities and cost parameters, this model could supplement the existing iAM.AMR developed by the Public Health Agency of Canada and be applied to other pathogens such as *E. coli* or Norovirus.

References

Adhikari, Bishwa B, Frederick Angulo, and Martin Meltzer. 2004. "Economic Burden of Salmonella Infections in the United States." AgEcon Search. https://ageconsearch.umn.edu/record/20050/.

Ahmed, Syud Amer, Enis Barış, Delfin S. Go, Hans Lofgren, Israel Osorio-Rodarte, and Karen Thierfelder. 2018. "Assessing the Global Poverty Effects of Antimicrobial Resistance." *World Development* 111 (July): 148–60. https://doi.org/10.1016/j.worlddev.2018.06.022.

Akil, Luma, H. Anwar Ahmad, and Remata S Reddy. 2014. "Effects of Climate Change on Salmonella Infections." *Foodborne Pathogens and Disease* 11 (12): 974–80. https://doi.org/10.1089/fpd.2014.1802.

Aminov, Rustam. 2010. "A Brief History of the Antibiotic Era: Lessons Learned and Challenges for the Future." *Frontiers in Microbiology* 1 (January). https://doi.org/10.3389/fmicb.2010.00134.

Augusto, Marcelo, Diana Oliveira, Dália dos, and Daniel Roberto. 2011. "Prevalence and Antimicrobial Resistance of Salmonella in Chicken Carcasses at Retail in 15 Brazilian Cities." *Revista Panamericana de Salud Pública* 30 (6): 555–60. https://doi.org/10.1590/s1020-49892011001200010.

Avery, Brent P, E. Jane Parmley, Richard J Reid-Smith, Danielle Daignault, Rita Finley, and Rebecca Irwin. 2014. "Canadian Integrated Program for Antimicrobial Resistance Surveillance: Retail Food Highlights, 2003–2012." *Canada Communicable Disease Report* 40 (S2): 29–35. https://doi.org/10.14745/ccdr.v40is2a05.

Batz, Michael, Evan Henke, and Barbara Kowalcyk. 2013. "Long-Term Consequences of Foodborne Infections." *Infectious Disease Clinics of North America* 27 (3): 599–616. https://doi.org/10.1016/j.idc.2013.05.003.

Batz, Michael, Sandra Hoffmann, and J. Glenn Morris. 2014. "Disease-Outcome Trees, EQ-5D Scores, and Estimated Annual Losses of Quality-Adjusted Life Years (QALYs) for 14 Foodborne Pathogens in the United States." *Foodborne Pathogens and Disease* 11 (5): 395–402. https://doi.org/10.1089/fpd.2013.1658.

Brent, Robert J. 2023. "Cost-Benefit Analysis versus Cost-Effectiveness Analysis from a Societal Perspective in Healthcare." *International Journal of Environmental Research and Public Health* 20 (5): 4637–37. https://doi.org/10.3390/ijerph20054637.

Briggs, A., and M. Sculpher. 1998. "An introduction to markov modelling for economic evaluation." *Pharmacoeconomics* 13(4):397–409.

Bushnik, Tracey, Michael Tjepkema, and Laurent Martel. 2018. "Health-Adjusted Life Expectancy in Canada." Government of Canada, Statistics Canada. April 18, 2018. https://www150.statcan.gc.ca/n1/pub/82-003-x/2018004/article/54950-eng.htm.

"Canadian Antimicrobial Resistance Surveillance System (CARSS) Report 2022". 2022. https://www.canada.ca/en/public-health/services/publications/drugs-health-products/canadian-antimicrobial-resistance-surveillance-system-report-2022.html.

Canadian Food Inspection Agency. 2019. "Questions and Answers: New Measures to Reduce Salmonella in Frozen Raw Breaded Chicken Products." Canada.ca. 2019. https://inspection.canada.ca/en/preventive-controls/meat/salmonella-frozen-raw-breaded-chicken/faq.

Canadian Institute for Health Information (CIHI). 2022. "An overview of physician payments and cost per service." CIHI. https://www.cihi.ca/en/health-workforce-in-canada-in-focus-including-nurses-and-physicians/an-overview-of-physician.

Chauhan, Akashdeep Singh, Isha Kapoor, Saroj Kumar Rana, Dilesh Kumar, Madhu Gupta, Jacob John, Gagandeep Kang, and Shankar Prinja. 2021. "Cost Effectiveness of Typhoid Vaccination in India." *Vaccine* 39 (30): 4089–98. https://doi.org/10.1016/j.vaccine.2021.06.003.

Chhatwal, Jagpreet, Suren Jayasuriya, and Elamin H Elbasha. 2016. "Changing Cycle Lengths in State-Transition Models." *Medical Decision Making* 36 (8): 952–64. https://doi.org/10.1177/0272989x16656165.

Chicken Farmers of Canada. 2020. "Category III Reduction – Everything You Need to Know." March 10, 2020. https://www.chickenfarmers.ca/category-3-reduction/.

Council of Canadian Academies (CCA). 2019. "Forecasting the Future of Antimicrobial Resistance (AMR) in Canada". https://cca-reports.ca/forecasting-the-future-of-amr/.

Drabo, Emmanuel F., and William V. Padula. 2023. "Introduction to Markov Modeling." In *Handbook of applied health economics in vaccines*. 264-78. Oxford University Press. https://doi.org/10.1093/oso/9780192896087.003.0022.

Dramé Ousmane, Daniel Leclair, E. Jane Parmley, Anne Deckert, Blaise Ouattara, Danielle Daignault, and André Ravel. 2020. "Antimicrobial Resistance of Campylobacter in Broiler Chicken along the Food Chain in Canada." *Foodborne Pathogens and Disease* 17 (8): 512–20. https://doi.org/10.1089/fpd.2019.2752.

Drudge, Christopher, S. Greco, Jinhee Kim, and R. Copes. 2019. "Estimated Annual Deaths, Hospitalizations, and Emergency Department and Physician Office Visits from Foodborne Illness in Ontario." *Foodborne Pathogens and Disease*. https://doi.org/10.1089/fpd.2018.2545.

Ebrahim, M., D. Gravel, C. Thabet, K. Abdesselam, S. Paramalingam, and C. Hyson. 2016. "Antimicrobial Use and Antimicrobial Resistance Trends in Canada: 2014." *Canada Communicable Disease Report* 42 (11): 227–31. https://doi.org/10.14745/ccdr.v42i11a02.

Economic Research Service. 2017. "Cost estimates of foodborne illnesses." https://www.ers.usda.gov/data-products/cost-estimates-of-foodborne-illnesses/.

Eng, Shu Kee, Priyia Pusparajah, Syakima Ab, Hooi-Leng Ser, Kok-Gan Chan, and Learn-Han Lee. 2015. "Salmonella: A Review on Pathogenesis, Epidemiology and Antibiotic Resistance." *Frontiers in Life Science* 8 (3): 284–93. https://doi.org/10.1080/21553769.2015.1051243.

Esan, Oluwaseun B., Madison E. Pearce, Oliver van Hecke, Nia Roberts, Dylan Collins, Mara Violato, Noel D. McCarthy, Rafael Perera, and Thomas R. Fanshawe. 2017. "Factors Associated with Sequelae of Campylobacter and Non-Typhoidal Salmonella Infections: A Systematic Review." *EBioMedicine* 15 (February): 100–111. https://doi.org/10.1016/j.ebiom.2016.12.006.

Gebretekle, Gebremedhin Beedemariam, Damen Haile Mariam, Stephen Mac, Workeabeba Abebe, Tinsae Alemayehu, Wondwossen Amogne Degu, Michael Libman, et al. 2021. "Cost–Utility Analysis of Antimicrobial Stewardship Programme at a Tertiary Teaching Hospital in Ethiopia." *BMJ Open* 11 (12): e047515. https://doi.org/10.1136/bmjopen-2020-047515.

Ghanem, Ziad. 2010. *The Canadian and Inter-Provincial Input-Output Models: The Mathematical Framework*. Industry Accounts Division. Ottawa: Statistics Canada.

Gidwani, Risha, and Louise B. Russell. 2020. "Estimating Transition Probabilities from Published Evidence: A Tutorial for Decision Modelers." *PharmacoEconomics* 38 (11): 1153–64. https://doi.org/10.1007/s40273-020-00937-z.

Glass-Kaastra, Shiona, Brendan Dougherty, Andrea Nesbitt, Mythri Viswanathan, Nadia Ciampa, Stephen Parker, Celine Nadon, Diane MacDonald, and M. Kate Thomas. 2022. "Estimated Reduction in the Burden of Nontyphoidal Salmonella Illness in Canada circa 2019." *Foodborne Pathogens and Disease* 19 (11): 744–49. https://doi.org/10.1089/fpd.2022.0045.

Government of Canada. 2009. *Economic valuation of mortality risk reduction: Review and recommendations for policy and regulatory analysis*. https://publications.gc.ca/collection_2009/policyresearch/PH4-51-2009E.pdf

Government of Canada. 2016. "Yearly Food-Borne Illness Estimates for Canada". Canada.ca. https://www.canada.ca/en/public-health/services/food-borne-illness-canada/yearly-food-borne-illness-estimates-canada.html#shr-pg0.

Herrick, Robert L., Steven G. Buchberger, Robert M. Clark, Margaret Kupferle, Regan Murray, and Paul Succop. 2011. "A Markov model to estimate Salmonella morbidity, mortality, illness duration, and cost." *Health Economics* 21 (10): 1169–82. https://doi.org/10.1002/hec.1779.

Hessel, Franz. 2008. "Burden of Disease." Springer EBooks, January, 94–96. https://doi.org/10.1007/978-1-4020-5614-7_297.

Hoffmann, S., Michael B. Batz, and J. Morris. 2012. "Annual Cost of Illness and Quality-Adjusted Life Year Losses in the United States due to 14 Foodborne Pathogens." *Journal of Food Protection*. https://doi.org/10.4315/0362-028X.JFP-11-417.

Hoffmann, Sandra, and Elaine Scallan Walter. 2020. "Acute Complications and Sequelae from Foodborne Infections: Informing Priorities for Cost of Foodborne Illness Estimates." *Foodborne Pathogens and Disease* 17 (3): 172–77. https://doi.org/10.1089/fpd.2019.2664.

Holmes, Alison, Luke Moore, Arnfinn Sundsfjord, Martin Steinbakk, Sadie Regmi, Abhilasha Karkey, Philippe J Guérin, and Laura. 2016. "Understanding the Mechanisms and Drivers of Antimicrobial Resistance." *The Lancet* 387 (10014): 176–87. https://doi.org/10.1016/s0140-6736(15)00473-0.

Huber, Laura, Agnes Agunos, Sheryl P. Gow, Carolee A. Carson, and Thomas P. Van Boeckel. 2021. "Reduction in Antimicrobial Use and Resistance to Salmonella, Campylobacter, and Escherichia Coli in Broiler Chickens, Canada, 2013–2019." *Emerging Infectious Diseases* 27 (9): 2434–44. https://doi.org/10.3201/eid2709.204395.

Hurst, Matt, Andrea Nesbitt, Stefanie Kadykalo, Brendan Dougherty, Juan Carlos Arango-Sabogal, and André Ravel. 2023. "Attributing Salmonellosis Cases to Foodborne, Animal Contact and Waterborne Routes Using the Microbial Subtyping Approach and Exposure Weights." *Food Control* 148 (June): 109636–36. https://doi.org/10.1016/j.foodcont.2023.109636.

Jain, Sonali, Kakali Mukhopadhyay, and Paul J. Thomassin. 2019. "An Economic Analysis of Salmonella Detection in Fresh Produce, Poultry, and Eggs Using Whole Genome Sequencing Technology in Canada." *Food Research International* 116 (February): 802–9. https://doi.org/10.1016/j.foodres.2018.09.014.

Jain, Sonali, Kakali Mukhopadhyay, and Paul Thomassin. 2018. "An Economic Analysis of Salmonella Detection in Fresh Produce, Poultry, and Eggs Using Whole Genome Sequencing Technology in Canada." McGill University. https://escholarship.mcgill.ca/concern/theses/pg15bh50g.

Jo, Changik. 2014. "Cost-of-Illness Studies: Concepts, Scopes, and Methods." *Clinical and Molecular Hepatology* 20 (4): 327–27. https://doi.org/10.3350/cmh.2014.20.4.327.

José Luis Martínez. 2014. "General Principles of Antibiotic Resistance in Bacteria." *Drug Discovery Today: Technologies* 11 (March): 33–39. https://doi.org/10.1016/j.ddtec.2014.02.001.

Kaakoush, Nadeem O., Natalia Castaño-Rodríguez, Hazel M. Mitchell, and Si Ming Man. 2015. "Global Epidemiology of Campylobacter Infection." *Clinical Microbiology Reviews* 28 (3): 687–720. https://doi.org/10.1128/cmr.00006-15.

Keithlin, Jessica, Jan M. Sargeant, M.K. Thomas, and A. Fazil. 2014. "Systematic Review and Meta-Analysis of the Proportion of Non-Typhoidal Salmonella Cases That Develop Chronic Sequelae." *Epidemiology and Infection* 143 (7): 1333–51. https://doi.org/10.1017/s0950268814002829.

Lin, Iris, Erik Muser, Michael Munsell, Carmela Benson, and Joseph Menzin. 2014. "Economic Impact of Psychiatric Relapse and Recidivism among Adults with Schizophrenia Recently Released from Incarceration: A Markov Model Analysis." *Journal of Medical Economics* 18 (3): 219–29. https://doi.org/10.3111/13696998.2014.971161.

Lindsay, James. 1997. "Chronic Sequelae of Foodborne Disease." *Emerging Infectious Diseases* 3 (4): 443–52. https://doi.org/10.3201/eid0304.970405.

Lobanovska, Mariya, and Giulia Pilla. 2017. "Penicillin's Discovery and Antibiotic Resistance: Lessons for the Future?" *The Yale Journal of Biology and Medicine* 90 (1): 135–45. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5369031/.

McCubbin, Kayley D., R. Michele Anholt, Ellen de Jong, Jennifer A. Ida, Diego B. Nóbrega, John P. Kastelic, John M. Conly, et al. 2021. "Knowledge Gaps in the Understanding of Antimicrobial Resistance in Canada." *Frontiers in Public Health*. https://doi.org/10.3389/fpubh.2021.726484.

McGowan Jr, John E. 2001. "Economic Impact of Antimicrobial Resistance." *Emerging Infectious Diseases* 7 (2): 286–92. https://doi.org/10.3201/eid0702.010228.

McGuire, T. G., Kenneth B. Wells, Martha L. Bruce, Jeanne Miranda, Richard M. Scheffler, Mary Durham, Daniel E. Ford, et al. 2002. *Mental Health Services Research* 4 (4): 179–85. https://doi.org/10.1023/a:1020956313890.

McLinden, Taylor. 2013. "A Scoping Review of Component Costs of Foodborne Illness and Analysis of the Association between Study Methodologies and Component Costs to the Cost of a Foodborne Illness." M.Sc. thesis, University of Guelph. https://atrium.lib.uoguelph.ca/items/a9ff34d9-5d50-4623-8072-02193778c958.

Miller, Ronald E., and Peter D. Blair. 2009. *Input-Output Analysis*, https://doi.org/10.1017/cbo9780511626982.

Murphy, Colleen P., Carolee Carson, Ben A. Smith, Brennan Chapman, Jayme Marrotte, Maggie McCann, Courtney Primeau, Parth Sharma, and E. Jane Parmley. 2018. "Factors Potentially Linked with the Occurrence of Antimicrobial Resistance in Selected Bacteria from Cattle, Chickens and Pigs: A Scoping Review of Publications for Use in Modelling of Antimicrobial Resistance (IAM.AMR Project)." *Zoonoses and Public Health* 65 (8): 957–71. https://doi.org/10.1111/zph.12515.

Nair, Divek V. T., Kumar Venkitanarayanan, and Anup Kollanoor Johny. 2018. "Antibiotic-Resistant Salmonella in the Food Supply and the Potential Role of Antibiotic Alternatives for Control." *Foods* 7 (10): 167. https://doi.org/10.3390/foods7100167.

Naushad, Sohail, Dele Ogunremi, and Hongsheng Huang. 2023. "Salmonella: A Brief Review." IntechOpen EBooks. https://doi.org/10.5772/intechopen.112948.

Naylor, Nichola Rochelle. 2019. "The Burden of Antimicrobial Resistance: The Case of Escherichia Coli." PhD diss., Imperial College London, https://doi.org/alma.

Otto, S. J. G., C. A. Carson, R. L. Finley, M. K. Thomas, R. J. Reid-Smith, and S. A. McEwen. 2014. "Estimating the Number of Human Cases of Ceftiofur-Resistant Salmonella Enterica Serovar Heidelberg in Quebec and Ontario, Canada." *Clinical Infectious Diseases* 59 (9): 1281–90. https://doi.org/10.1093/cid/ciu496.

Phillips, Charly, Brennan Chapman, Agnes Agunos, Carolee A Carson, E. Jane Parmley, Richard J Reid-Smith, Ben A Smith, and Colleen P Murphy. 2022. "A Scoping Review of Factors Potentially Linked with Antimicrobial-Resistant Bacteria from Turkeys (IAM.AMR Project)." *Epidemiology and Infection* 150 (January). https://doi.org/10.1017/s0950268822001224.

Porooshat Dadgostar. 2019. "Antimicrobial Resistance: Implications and Costs." *Infection and Drug Resistance* Volume 12 (December): 3903–10. https://doi.org/10.2147/idr.s234610.

Prestinaci, Francesca, Patrizio Pezzotti, and Annalisa Pantosti. 2015. "Antimicrobial Resistance: A Global Multifaceted Phenomenon." *Pathogens and Global Health* 109 (7): 309–18. https://doi.org/10.1179/2047773215y.0000000030.

Public Health Agency of Canada. 2020. *FoodNet Canada Tables and Figures 2019*. https://publications.gc.ca/collections/collection_2020/aspc-phac/HP40-279-2019-eng.pdf.

Public Health Agency of Canada. 2022. *Canadian Antimicrobial Resistance Surveillance System Report 2021*. https://www.canada.ca/en/public-health/services/publications/drugs-health-products/canadian-antimicrobial-resistance-surveillance-system-report-2021.html.

Public Health Agency of Canada. 2022. "Reported Cases from 1991 to 2022 in Canada - Notifiable Diseases On-Line." https://diseases.canada.ca/notifiable/charts?c=yl.

Public Health Agency of Canada. 2023. “Antimicrobial Resistance and Animals - Actions” Canada.ca. https://www.canada.ca/en/public-health/services/antibiotic-antimicrobial-resistance/animals/actions.html.

Public Health Agency of Canada. 2023. “Canadian Integrated Program for Antimicrobial Resistance Surveillance (CIPARS)” Canada.ca. https://www.canada.ca/en/public-health/services/surveillance/canadian-integrated-program-antimicrobial-resistance-surveillance-cipars.html.

Regula, G., D.M.A. Lo Fo Wong, U. Ledergerber, R. Stephan, J. Danuser, B. Bissig-Choisat, and K.D.C. Stärk. 2005. “Evaluation of an Antimicrobial Resistance Monitoring Program for Campylobacter in Poultry by Simulation.” *Preventive Veterinary Medicine* 70 (1-2): 29–43. https://doi.org/10.1016/j.prevetmed.2005.02.017.

Reygaert, Wanda. 2018. “An Overview of the Antimicrobial Resistance Mechanisms of Bacteria.” *AIMS Microbiology* 4 (3): 482–501. https://doi.org/10.3934/microbiol.2018.3.482.

Rigby, D., K. Payne, S. Wright, M. Burton, S. O'Brien, J. Hardstaff, Ece Özdemiroğlu, Erin Gianferrera, and R. Mistry. 2017. *Estimating Quality Adjusted Life Years and Willingness to Pay Values for Microbiological Foodborne Disease (Phase 2)*. Food Standards Agency. https://www.food.gov.uk/research/foodborne-disease/estimating-quality-adjusted-life-years-and-willingness-to-pay-values-for-microbiological-foodborne-disease-phase-2.

Roope, Laurence, Richard Smith, Koen B. Pouwels, James Buchanan, Lucy Abel, Peter Eibich, Christopher Collett Butler, et al. 2019. “The Challenge of Antimicrobial Resistance: What Economics Can Contribute.” *Science* 364 (6435). https://doi.org/10.1126/science.aau4679.

Sahin, Orhan, Teresa Y. Morishita, and Qijing Zhang. 2002. “CampylobacterColonization in Poultry: Sources of Infection and Modes of Transmission.” *Animal Health Research Reviews* 3 (2): 95–105. https://doi.org/10.1079/ahrr200244.

Sanyal, Chiranjeev, Armen Aprikian, Fabio Cury, Simone Chevalier, and Alice Dragomir. 2014. “Clinical Management and Burden of Prostate Cancer: A Markov Monte Carlo Model.” *PLoS ONE* 9 (12): e113432–32. https://doi.org/10.1371/journal.pone.0113432.

Sapkota, Amy R., Erinna L. Kinney, Ashish George, R. Michael Hulet, Raul Cruz-Cano, Kellogg J. Schwab, Guangyu Zhang, and Sam W. Joseph. 2014. “Lower Prevalence of Antibiotic-Resistant Salmonella on Large-Scale U.S. Conventional Poultry Farms That Transitioned to Organic Practices.” *Science of the Total Environment* 476-477 (April): 387–92. https://doi.org/10.1016/j.scitotenv.2013.12.005.

Schorling, Elisabeth, Sonja Lick, Pablo Steinberg, and Dagmar Brüggemann. 2023. "Health Care Utilizations and Costs of Campylobacter Enteritis in Germany: A Claims Data Analysis." *PLOS ONE* 18 (4): e0283865. https://doi.org/10.1371/journal.pone.0283865.

Schwartz, Kevin L, Bradley J Langford, Nick Daneman, Branson Chen, Kevin E Brown, Warren J McIsaac, Karen Tu, et al. 2020. "Unnecessary Antibiotic Prescribing in a Canadian Primary Care Setting: A Descriptive Analysis Using Routinely Collected Electronic Medical Record Data." *CMAJ Open* 8 (2): E360–69. https://doi.org/10.9778/cmajo.20190175.

Shrestha, Poojan, Ben S. Cooper, Joanna Coast, Raymond Oppong, Nga Do Thi Thuy, Tuangrat Phodha, Olivier Celhay, Philippe J. Guerin, Heiman Wertheim, and Yoel Lubell. 2018. "Enumerating the Economic Cost of Antimicrobial Resistance per Antibiotic Consumed to Inform the Evaluation of Interventions Affecting Their Use." *Antimicrobial Resistance & Infection Control* 7 (1). https://doi.org/10.1186/s13756-018-0384-3.

Smith, Richard, Milton Yago, Michael Millar, and Joanna Coast. 2006. "A Macroeconomic Approach to Evaluating Policies to Contain Antimicrobial Resistance." *Applied Health Economics and Health Policy* 5 (1): 55–65. https://doi.org/10.2165/00148365-200605010-00007.

Song, Hyun Jin, Jin-Won Kwon, Nayoung Kim, and Young Soo Park. 2013. "Cost Effectiveness Associated with Helicobacter Pylori Screening and Eradication in Patients Taking Nonsteroidal Anti-Inflammatory Drugs And/or Aspirin." *Gut and Liver* 7 (2): 182–89. https://doi.org/10.5009/gnl.2013.7.2.182.

Sonnenberg, Frank A., and J. Robert Beck. 1993. "Markov Models in Medical Decision Making." *Medical Decision Making* 13 (4): 322–38. https://doi.org/10.1177/0272989x9301300409.

Statistics Canada. 2022. "Supply and Use Tables." Government of Canada, Statistics Canada. https://www150.statcan.gc.ca/n1/pub/15-602-x/15-602-x2017001-eng.htm.

Statistics Canada. 2022. "Estimating the economic value of unpaid household work in Canada, 2015 to 2019." Government of Canada, Statistics Canada. March 17, 2022. https://www150.statcan.gc.ca/n1/pub/13-605-x/2022001/article/00001-eng.htm.

Statistics Canada. 2024. "Current and Capital Accounts - Households, Canada, Quarterly." Government of Canada, Statistics Canada. May 31, 2024. https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3610011201.

Sundström, Kristian. 2018. "Cost of Illness for Five Major Foodborne Illnesses and Sequelae in Sweden." *Applied Health Economics and Health Policy* 16 (2): 243–57. https://doi.org/10.1007/s40258-017-0369-z.

Taylor, Jirka, Marco Hafner, Erez Yerushalmi, Richard Smith, Jacopo Bellasio, Raffaele Vardavas, Teresa Bienkowska-Gibbs, and Jennifer Rubin. 2014. *Europe Estimating the Economic Costs of Antimicrobial Resistance Model and Results.* RAND Corporation https://www.rand.org/content/dam/rand/pubs/research_reports/RR900/RR911/RAND_RR911.pdf.

Thomas, M. Kate, Regan Murray, Logan Flockhart, Katarina Pintar, Aamir Fazil, Andrea Nesbitt, Barbara Marshall Joanne Tataryn, and Frank Pollari. 2015. "Estimates of Foodborne Illness–Related Hospitalizations and Deaths in Canada for 30 Specified Pathogens and Unspecified Agents." *Foodborne Pathogens and Disease*. https://doi.org/10.1089/fpd.2015.1966.

Thomas, M. Kate, Regan Murray, Logan Flockhart, Katarina Pintar, Frank Pollari, Aamir Fazil, Andrea Nesbitt, and Barbara Marshall. 2013. "Estimates of the Burden of Foodborne Illness in Canada for 30 Specified Pathogens and Unspecified Agents, circa 2006." *Foodborne Pathogens and Disease* 10 (7): 639–48. https://doi.org/10.1089/fpd.2012.1389.

TreeAge Software, Inc. *TreeAge Pro 2024, R1*. Williamstown, MA: TreeAge Software, 2024. https://www.treeage.com/

Uddin, Tanvior Mahtab, Arka Chakraborty, Ameer Khusro, Redwan Matin, Saikat Mitra, Talha Bin Emran, Kuldeep Dhama, et al. 2021. "Antibiotic Resistance in Microbes: History, Mechanisms, Therapeutic Strategies and Future Prospects." *Journal of Infection and Public Health* 14 (12): 1750–66. https://doi.org/10.1016/j.jiph.2021.10.020.

UNEP. 2020. "Antimicrobial Resistance: A Global Threat." UN Environment Programme. https://www.unep.org/topics/chemicals-and-pollution-action/pollution-and-health/antimicrobial-resistance-global-threat.

Van Cauteren, Dieter, Yann Le Strat, Cécile Sommen, Mathias Bruyand, Mathieu Tourdjman, Nathalie Jourdan Da Silva, Elisabeth Couturier, Nelly Fournet, Henriette de Valk, and Jean-Claude Desenclos. 2017. "Estimated Annual Numbers of Foodborne Pathogen–Associated Illnesses, Hospitalizations, and Deaths, France, 2008–2013." *Emerging Infectious Diseases* 23 (9): 1486–92. https://doi.org/10.3201/eid2309.170081.

Velazquez-Meza, Maria Elena, Miguel Galarde-López, Berta Carrillo-Quiróz, and Celia Mercedes Alpuche-Aranda. 2022. "Antimicrobial Resistance: One Health Approach." *Veterinary World* 15 (3): 743–49. https://doi.org/10.14202/vetworld.2022.743-749.

Virk, Sohrab, Harvinder S. Sandhu, and Safdar N. Khan. 2012. "Cost Effectiveness Analysis of Graft Options in Spinal Fusion Surgery Using a Markov Model." *Journal of Spinal Disorders & Techniques* 25 (7): E204–10. https://doi.org/10.1097/bsd.0b013e3182692990.

World Health Organization. 2015. *WHO Estimates of the Global Burden of Foodborne Diseases: Foodborne Disease Burden Epidemiology Reference Group 2007-2015*. https://doi.org/9789241565165.

World Health Organization. 2015. “WHO’s First Ever Global Estimates of Foodborne Diseases Find Children under 5 Account for Almost One Third of Deaths.” Who.int. World Health Organization: WHO. December 3, 2015. https://www.who.int/news/item/03-12-2015-who-s-first-ever-global-estimates-of-foodborne-diseases-find-children-under-5-account-for-almost-one-third-of-deaths.

World Health Organization. 2020. “The Top 10 Causes of Death.” December 9, 2020. https://www.who.int/news-room/fact-sheets/detail/the-top-10-causes-of-death

World Health Organization, Rob M. P. M. Baltussen, Taghreed Adam, Tessa Tan-Torres Edejer, Raymond C. W. Hutubessy, Arnab Acharya, David B. Evans, Christopher J. L. Murray, and WHO-CHOICE. *Making Choices in Health: WHO Guide to Cost-Effectiveness Analysis*. Edited by Tessa Tan-Torres Edejer et al. Geneva: World Health Organization, 2003. https://iris.who.int/handle/10665/42699.

Appendix A.

Table A.1 Labour productivity costs per case for *Salmonella* infections

	AMR Salmonella		
	Self treatment	**Visited physician**	**Hospitalized**
Proportion of miss work	0.2889	0.3728	0.2553
Number of work days missed	3.9182	4.1556	6.2857
Proportion of care miss work	0.0889	0.2485	0.4468
Number of care work days missed	2.3537	2.5301	2.5076
Average daily earnings	$ 183.76	$ 183.76	$ 183.76
Productivity lost per case	**$ 246.44**	**$ 400.20**	**$ 500.79**

	Susceptible Salmonella		
	Self treatment	**Visited physician**	**Hospitalized**
Proportion of miss work	0.2842	0.3269	0.2424
Number of days miss work	3.9400	4.1805	4.2341
Proportion of care miss work	0.0479	0.2216	0.2727
Number of days care miss work	2.4455	2.7450	2.6116
Average daily earnings	$ 183.76	$ 183.76	$ 183.76
Productivity lost per case	**$ 227.34**	**$ 362.87**	**$ 319.49**

Table A.2 Labour productivity costs per case for *Campylobacter* infections

	AMR Campylobacter		
	Self treatment	**Visited physician**	**Hospitalized**
Proportion of miss work	0.3313	0.4183	0.3846
Number of work days missed	3.3380	3.7864	3.8085
Proportion of care miss work	0.0429	0.1373	0.2308
Number of care work days missed	2.1579	2.0879	2.1587
Average daily earnings	$ 183.76	$ 183.76	$ 183.76
Productivity costs per case	**$ 220.23**	**$ 343.70**	**$ 360.71**

	Susceptible Campylobacter		
	Self treatment	**Visited physician**	**Hospitalized**
Proportion of miss work	0.3652	0.4065	0.3000
Number of days miss work	3.7825	3.8170	3.8154
Proportion of care miss work	0.0337	0.1179	0.2333
Number of days care miss work	2.1091	2.1011	2.1313
Average daily earnings	$ 183.76	$ 183.76	$ 183.76
Productivity costs per case	**$ 266.88**	**$ 330.63**	**$ 301.71**

Appendix B.

Table B.1 Industrial sector aggregation based on North American Industry Classification System (NAICS) and IIOC

NAICS		IIOC	
Code	**Industry**	**Code**	**Industry**
11	Agriculture, forestry, fishing and hunting	BS111110	Soybean farming
		BS111121	Canola farming
		BS1111Y0	Oilseed (except soybean and canola) and pulse farming
		BS111140	Wheat farming
		BS1111X0	Grain farming
		BS111211	Potato farming
		BS111900	Other crop farming
		BS111W00	Vegetable (except potato), melon, fruit and tree nut farming
		BS1114A0	Greenhouse, nursery and floriculture production (except cannabis)
		BS111CL0	Cannabis production (licensed)
		BS111CU0	Cannabis production (unlicensed)
		BS112110	Beef cattle ranching and farming, including feedlots
		BS112120	Dairy cattle and milk production
		BS112200	Hog and pig farming
		BS112300	Poultry and egg production
		BS112X00	Other animal production
		BS112500	Aquaculture
		BS113000	Forestry and logging
		BS114000	Fishing, hunting and trapping
		BS115A00	Support activities for crop and animal production
		BS115300	Support activities for forestry
21	Mining, quarrying, and oil and gas extraction	BS211110	Oil and gas extraction (except oil sands)
		BS211140	Oil sands extraction
		BS212100	Coal mining
		BS212210	Iron ore mining
		BS212220	Gold and silver ore mining
		BS212230	Copper, nickel, lead and zinc ore mining
		BS212290	Other metal ore mining
		BS212310	Stone mining and quarrying
		BS212320	Sand, gravel, clay, and ceramic and refractory minerals mining and quarrying
		BS212392	Diamond mining
		BS21239A	Other non-metallic mineral mining and quarrying (except diamond and potash)
		BS212396	Potash mining

		BS21311A	Support activities for oil and gas extraction
		BS21311B	Support activities for mining
22	Utilities	BS221100	Electric power generation, transmission and distribution
		BS221200	Natural gas distribution
		BS221300	Water, sewage and other systems
23	Construction	BS23A000	Residential building construction
		BS23B000	Non-residential building construction
		BS23C100	Transportation engineering construction
		BS23C200	Oil and gas engineering construction
		BS23C300	Electric power engineering construction
		BS23C400	Communication engineering construction
		BS23C500	Other engineering construction
		BS23D000	Repair construction
		BS23E000	Other activities of the construction industry
31-33	Manufacturing	BS311111	Dog and cat food manufacturing
		BS311119	Other animal food manufacturing
		BS3112X0	Grain and oilseed milling (except oilseed processing)
		BS311224	Oilseed processing
		BS311310	Sugar manufacturing
		BS3113X0	Confectionery product manufacturing
		BS311410	Frozen food manufacturing
		BS311420	Fruit and vegetable canning, pickling and drying
		BS311500	Dairy product manufacturing
		BS3116X0	Meat product manufacturing (except poultry processing)
		BS311615	Poultry processing
		BS311700	Seafood product preparation and packaging
		BS3118X0	Tortilla and pasta manufacturing
		BS3118Y0	Bread, cookie, cracker and bakery product manufacturing
		BS311919	Other snack food manufacturing
		BS3119X0	Other food manufacturing (except other snack foods)
		BS312110	Soft drink and ice manufacturing
		BS312120	Breweries
		BS3121A0	Wineries and distilleries
		BS312200	Tobacco manufacturing
		BS31A000	Textile and textile product mills
		BS31B000	Clothing and leather and allied product manufacturing
		BS321100	Sawmills and wood preservation
		BS321200	Veneer, plywood and engineered wood product manufacturing
		BS321900	Other wood product manufacturing
		BS322100	Pulp, paper and paperboard mills
		BS322200	Converted paper product manufacturing
		BS323000	Printing and related support activities
		BS324110	Petroleum refineries

		BS3241A0	Petroleum and coal product manufacturing (except petroleum refineries)
		BS325100	Basic chemical manufacturing
		BS325200	Resin, synthetic rubber, and artificial and synthetic fibres and filaments manufacturing
		BS325300	Pesticide, fertilizer and other agricultural chemical manufacturing
		BS325400	Pharmaceutical and medicine manufacturing
		BS325500	Paint, coating and adhesive manufacturing
		BS325600	Soap, cleaning compound and toilet preparation manufacturing
		BS325900	Other chemical product manufacturing
		BS326100	Plastic product manufacturing
		BS326200	Rubber product manufacturing
		BS327A00	Non-metallic mineral product manufacturing (except cement and concrete products)
		BS327300	Cement and concrete product manufacturing
		BS331100	Iron and steel mills and ferro-alloy manufacturing
		BS331200	Steel product manufacturing from purchased steel
		BS331300	Alumina and aluminum production and processing
		BS331400	Non-ferrous metal (except aluminum) production and processing
		BS331500	Foundries
		BS332100	Forging and stamping
		BS332A00	Cutlery, hand tools and other fabricated metal product manufacturing
		BS332300	Architectural and structural metals manufacturing
		BS332400	Boiler, tank and shipping container manufacturing
		BS332500	Hardware manufacturing
		BS332600	Spring and wire product manufacturing
		BS332700	Machine shops, turned product, and screw, nut and bolt manufacturing
		BS332800	Coating, engraving, cold and heat treating and allied activities
		BS333100	Agricultural, construction and mining machinery manufacturing
		BS333200	Industrial machinery manufacturing
		BS333300	Commercial and service industry machinery manufacturing
		BS333400	Ventilation, heating, air-conditioning and commercial refrigeration equipment manufacturing
		BS333500	Metalworking machinery manufacturing
		BS333600	Engine, turbine and power transmission equipment manufacturing
		BS333900	Other general-purpose machinery manufacturing

		BS334100	Computer and peripheral equipment manufacturing
		BS334200	Communications equipment manufacturing
		BS334A00	Other electronic product manufacturing
		BS334400	Semiconductor and other electronic component manufacturing
		BS335100	Electric lighting equipment manufacturing
		BS335200	Household appliance manufacturing
		BS335300	Electrical equipment manufacturing
		BS335900	Other electrical equipment and component manufacturing
		BS336110	Automobile and light-duty motor vehicle manufacturing
		BS336120	Heavy-duty truck manufacturing
		BS336200	Motor vehicle body and trailer manufacturing
		BS336310	Motor vehicle gasoline engine and engine parts manufacturing
		BS336320	Motor vehicle electrical and electronic equipment manufacturing
		BS336330	Motor vehicle steering and suspension components (except spring) manufacturing
		BS336340	Motor vehicle brake system manufacturing
		BS336350	Motor vehicle transmission and power train parts manufacturing
		BS336360	Motor vehicle seating and interior trim manufacturing
		BS336370	Motor vehicle metal stamping
		BS336390	Other motor vehicle parts manufacturing
		BS336400	Aerospace product and parts manufacturing
		BS336500	Railroad rolling stock manufacturing
		BS336600	Ship and boat building
		BS336900	Other transportation equipment manufacturing
		BS337100	Household and institutional furniture and kitchen cabinet manufacturing
		BS337200	Office furniture (including fixtures) manufacturing
		BS337900	Other furniture-related product manufacturing
		BS339100	Medical equipment and supplies manufacturing
		BS339900	Other miscellaneous manufacturing
41	Wholesale trade	BS411000	Farm product merchant wholesalers
		BS412000	Petroleum and petroleum products merchant wholesalers
		BS413000	Food, beverage and tobacco merchant wholesalers
		BS414000	Personal and household goods merchant wholesalers
		BS415000	Motor vehicle and motor vehicle parts and accessories merchant wholesalers
		BS416000	Building material and supplies merchant wholesalers
		BS417000	Machinery, equipment and supplies merchant wholesalers
		BS418000	Miscellaneous merchant wholesalers

		BS419000	Business-to-business electronic markets, and agents and brokers
44-45	Retail trade	BS441000	Motor vehicle and parts dealers
		BS442000	Furniture and home furnishings stores
		BS443000	Electronics and appliance stores
		BS444000	Building material and garden equipment and supplies dealers
		BS445000	Food and beverage stores
		BS446000	Health and personal care stores
		BS447000	Gasoline stations
		BS448000	Clothing and clothing accessories stores
		BS451000	Sporting goods, hobby, book and music stores
		BS452000	General merchandise stores
		BS453A00	Miscellaneous store retailers (except cannabis)
		BS453BL0	Cannabis stores (licensed)
		BS453BU0	Cannabis stores (unlicensed)
		BS454000	Non-store retailers
48-49	Transportation and warehousing	BS481000	Air transportation
		BS482000	Rail transportation
		BS483000	Water transportation
		BS484000	Truck transportation
		BS485100	Urban transit systems
		BS48A000	Other transit and ground passenger transportation and scenic and sightseeing transportation
		BS485300	Taxi and limousine service
		BS486A00	Crude oil and other pipeline transportation
		BS486200	Pipeline transportation of natural gas
		BS488000	Support activities for transportation
		BS491000	Postal service
		BS492000	Couriers and messengers
		BS493000	Warehousing and storage
51	Information and cultural industries	BS511110	Newspaper publishers
		BS5111A0	Periodical, book and directory publishers
		BS511200	Software publishers
		BS5121A0	Motion picture and video industries (except exhibition)
		BS512130	Motion picture and video exhibition
		BS512200	Sound recording industries
		BS515100	Radio and television broadcasting
		BS515200	Pay and specialty television
		BS517000	Telecommunications
		BS518000	Data processing, hosting, and related services
		BS519000	Other information services
52	Finance and insurance	BS521000	Monetary authorities - central bank
		BS5221A0	Banking and other depository credit intermediation

		BS522130	Local credit unions
		BS522200	Non-depository credit intermediation
		BS522300	Activities related to credit intermediation
		BS52A000	Financial investment services, funds and other financial vehicles
		BS524100	Insurance carriers
		BS524200	Agencies, brokerages and other insurance related activities
53	Real estate and rental and leasing	BS531100	Lessors of real estate
		BS531A00	Offices of real estate agents and brokers and activities related to real estate
		BS5311A0	Owner-occupied dwellings
		BS532100	Automotive equipment rental and leasing
		BS532A00	Rental and leasing services (except automotive equipment)
		BS533000	Lessors of non-financial intangible assets (except copyrighted works)
54	Professional, scientific and technical services	BS541100	Legal services
		BS541200	Accounting, tax preparation, bookkeeping and payroll services
		BS541300	Architectural, engineering and related services
		BS541400	Specialized design services
		BS541500	Computer systems design and related services
		BS541600	Management, scientific and technical consulting services
		BS541700	Scientific research and development services
		BS541800	Advertising, public relations, and related services
		BS541900	Other professional, scientific and technical services
55	Management of companies and enterprises	BS551113	Holding companies
56	Administrative and support, waste management and remediation services	BS561100	Office administrative services
		BS561A00	Facilities and other support services
		BS561300	Employment services
		BS561400	Business support services
		BS561500	Travel arrangement and reservation services
		BS561600	Investigation and security services
		BS561700	Services to buildings and dwellings
		BS562000	Waste management and remediation services
61	Educational services	BS610000	Educational services
		NP610000	Educational services
		GS611100	Elementary and secondary schools
		GS611200	Community colleges and C0E0G0E0P0s

		GS611300	Universities
		GS611A00	Other educational services
62	Health care and social assistance	BS621100	Offices of physicians
		BS621200	Offices of dentists
		BS621A00	Miscellaneous ambulatory health care services
		BS623000	Nursing and residential care facilities
		BS624000	Social assistance
		GS622000	Hospitals
		GS623000	Nursing and residential care facilities
		NP621000	Ambulatory health care services
		NP624000	Social assistance
71	Arts, entertainment and recreation	BS71A000	Performing arts, spectator sports and related industries, and heritage institutions
		BS713A00	Amusement and recreation industries
		BS713200	Gambling industries
		NP710000	Arts, entertainment and recreation
		NP999999	Other non-profit institutions serving households
72	Accommodation and food services	BS721100	Traveller accommodation
		BS721A00	Recreational vehicle (RV) parks, recreational camps, and rooming and boarding houses
		BS722000	Food services and drinking places
81	Other services (except public administration)	BS811100	Automotive repair and maintenance
		BS811A00	Repair and maintenance (except automotive)
		BS812A00	Personal care services and other personal services
		BS812200	Funeral services
		BS812300	Dry cleaning and laundry services
		BS813000	Business, professional and other membership organizations
		BS814000	Private households
		NP813100	Religious organizations
		NP813A00	Grant-making, civic, and professional and similar organizations
	Fictional	FC110000	Repair and maintenance
		FC120000	Operating supplies
		FC130000	Office supplies
		FC210000	Advertising, promotion, meals and entertainment
		FC220000	Travel, meetings and conventions
		FC300000	Transportation margins
91	Public administration	GS911100	Defence services
		GS911A00	Other federal government services (except defence)
		GS912000	Other provincial and territorial government services
		GS913000	Other municipal government services
		GS914000	Other aboriginal government services