An Economic Analysis of *Salmonella* Detection in Fresh Produce, Poultry, and Eggs Using Whole Genome Sequencing Technology in Canada

Sonali Jain

Department of Agricultural Economics

McGill University, Montreal

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Abstract

Foodborne illnesses cause a significant socio-economic burden worldwide. Nontyphoidal *Salmonella* is one of the major foodborne disease agents in Canada. To date, there is hardly any research on the cost and benefits of the Whole Genome Sequencing (WGS) compared to the traditional technology for the detection of *Salmonella* from specific food products and the macroeconomic impact of the improved technology in outbreak detection. The current study is an attempt to make a contribution in that direction. The study estimates the annual costs of *Salmonella* from fresh produce, poultry and eggs in Canada and the economic benefits from the introduction of WGS in the detection of *Salmonella* clusters and outbreaks. The results from the cost-benefit analysis are then used to measure the impact on industrial output, gross domestic product (GDP) and employment. Cost-of-illness and Health Adjusted Quality Life Years are used to estimate the monetary and non-monetary costs of *Salmonella* respectively. Probability models are used to account for uncertainty in the cost-of-illness estimates. The input-output framework is used to measure the macroeconomic impact. Four scenarios are exercised to measure the macroeconomic impact: i) productivity improvement, ii) decrease in direct healthcare cost, iii) decrease in federal cost and iv) total net benefits from WGS. The estimated number of cases is 47,082 annually, which represents a cost of $287.78 million from PFGE. The non-monetary estimates from current technology are 529.20 years (Disability Adjusted Life Years) and 289.90 years (Quality Adjusted Life Years), annually. The total net benefits from the introduction of WGS are estimated at $90.25 million (in 2013 CAD). These microeconomic net benefits are then used to measure the macroeconomic impacts of WGS. Positive net benefits from WGS lead to increased industrial output ($15.88 million), GDP ($13.38 million) and labour (116). Overall, WGS will help in reducing the economic burden from *Salmonella*. The monetary savings from the reduction in direct healthcare cost (medical intervention) and laboratory costs can be invested in further research and development, however, a proper intervention of federal and provincial government is required. A holistic approach to food safety will improve the benefits from WGS in outbreak containment.

Résumé

Les maladies d’origine alimentaire imposent un fardeau socioéconomique substantiel sur les économies du monde. La *salmonella* est l’un des vecteurs de maladie les plus importants au Canada. Jusqu’à maintenant, peu de recherches ont été effectuées sur les coûts et bénéfices de l’utilisation du Séquençage de Génome Entier (SGE) par rapport aux autres techniques plus standards de dépistage de la *salmonella*. De plus, les effets macroéconomiques que pourrait avoir l’adoption de cette technologie sur la détection de foyers de cette bactérie n’ont pas encore été analysés. La présente étude a pour objectif de contribuer à faire progresser les connaissances dans ces deux domaines. Cette recherche évalue les coûts annuels liés à la *salmonella* dans les produits frais, la volaille et les œufs au Canada et estime les bénéfices économiques de l’introduction du SGE dans la détection de la bactérie. Les résultats de l’analyse coût-bénéfice sont ensuite utilisés pour mesurer l’impact de l’adoption du SGE sur la production industrielle, le produit intérieur brut (PIB) et le taux de chômage. Les coûts monétaires et non monétaires sont évalués. Les coûts de sante (Cost-of-Illness) et l’Année de Vie Pondérée par la Qualité (AVPQ) sont utilisés comme mesures des coûts monétaire et non monétaire, respectivement. Des modèles probabilistes sont utilisés de manière à tenir compte de l’incertitude découlant des estimations de coûts de sante. Les coûts macroéconomiques, quant à eux, sont évalués à l’aide d’un modèle entrée-sortie. Avec ce modèle, quatre scénarios sont simulés pour rendre compte de i) l’amélioration de la productivité, ii) l’abaissement des coûts directs, iii) l’abaissement des coûts au niveau fédéral et iv) le bénéfice net retiré de l’utilisation du SGE. L’apparition annuelle de la bactérie est estimée à 47 082 cas, ce qui représente un coût total de 287,78 milliards de dollars. L’estimateur non monétaire annuel de la technologie de détection actuellement utilisée est de 529,20 années (Espérance de vie corrigée de l’incapacité) et de 289,90 années (AVPQ). Le bénéfice total net de l’introduction du SGE est estimé à 90,25 millions de dollars (CAD de 2013). Ces bénéfices nets microéconomiques sont ensuite employés afin de mesurer l’impact macroéconomique du SGE: il accroit la valeur de la production industrielle de 15.88 millions de dollars, le PIB de 13,38 millions de dollars et génère 116 emplois. Globalement, le SGE réduirait le fardeau économique que représente la *salmonella*. Les épargnes faites sur les coûts de l’intervention médicale et les frais de laboratoire pourraient être investies dans davantage de recherche et développement, cependant, une intervention des gouvernements provinciaux et du gouvernement fédéral serait nécessaire. Une approche holistique visant à contenir la prolifération de la *salmonella* améliorerait les bénéfices tirés de la mise en œuvre du SGE dans sa détection.

Abbreviations

1. World Health Organization (WHO)
2. Centers for Disease Control and Prevention (CDC)
3. Pulsed Field Gel Electrophoresis (PFGE)
4. Hazard Analysis and Critical Control Point (HACCP)
5. Canadian Food Inspection Agency (CFIA)
6. Public Health Agency of Canada (PHAC)
7. Whole Genome Sequencing (WGS)
8. Cost and Benefit Analysis (CBA)
9. Cost-of- illness (COI)
10. Disability Adjusted Life Years (DALY)
11. Quality Adjusted Life Years (QALY)
12. Patient Cost Estimator (PCE)
13. Case Mix Group(CMG)
14. Length of Stay (LOS)
15. *Salmonella* Foodborne Syst-OMICS Database (SAlFoS)
16. Gross Domestic Product (GDP)
17. Willingness to Pay (WTP)
18. Health Adjusted Life Years (HALY)
19. Value of Statistical Life (VSL)
20. National Microbiology Laboratory (NML)

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Chapter 1: Introduction

1.1. Introduction

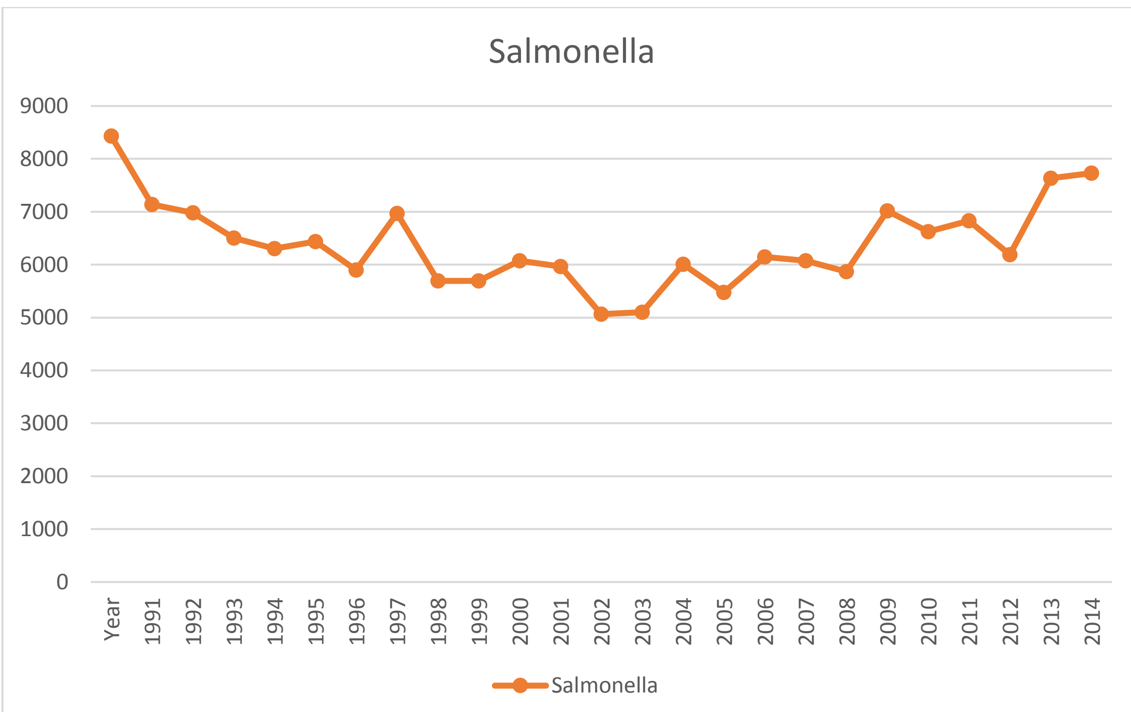
Foodborne diseases cause a significant socio-economic burden worldwide. World Health Organisation (WHO) reports that globally 600 million foodborne illnesses and 420,000 deaths occur annually (World Health Organization 2015). *Norovirus*, *Campylobacter* and nontyphoidal *Salmonella* are the top three causes of foodborne illness. Africa and South-East Asia have the highest burden per population of foodborne diseases. Nontyphoidal *Salmonella* is the leading cause of foodborne diseases in Africa. The report by WHO is the only source of information available which estimates the burden of foodborne diseases at a global level. Studies have been conducted by many countries to ascertain the burden of foodborne diseases at a national level (World Health Organization 2015).

Public health agencies have estimated the burden of illnesses for respective countries to ascertain the risk associated with different pathogens. National estimates of foodborne illnesses in the developing countries are almost non-existent (World Health Organization 2015). WHO's regional office for Europe estimates that approximately 22 million foodborne illnesses occur every year in Europe (World Health Organization 2015). The top three pathogens that contribute to foodborne illnesses in Europe are *norovirus, Campylobacter and* nontyphoidal *Salmonella* (World Health Organization 2015). Nontyphoidal *Salmonella* causes around two thousand out of three thousand deaths every year from foodborne disease agents in Europe (World Health Organization 2015). The Centers for Disease Control and Prevention (CDC) estimated that each year in the United States, 31 pathogens caused 9.4 million foodborne illnesses which resulted in

56,000 hospitalizations and 1,350 deaths (Scallan et al. 2011). *Norovirus*, nontyphoidal *Salmonella and Clostridium* caused the highest number of foodborne illnesses in the US (Scallan 2011). The most number of hospitalizations were caused by nontyphoidal *Salmonella* followed by *norovirus* (Scallan 2011). Public Health Agency of Canada reports that four million domestically acquired foodborne illnesses occur each year, which leads to 11,600 hospitalizations and 238 deaths every year in Canada (Thomas et al. 2013, Thomas et al. 2015a). *Norovirus, Clostridium perfringens, Campylobacter and* nontyphoidal *Salmonella* cause the highest number of foodborne illnesses in Canada (Thomas et al. 2013). Norovirus and nontyphoidal *Salmonella* cause the highest number of hospitalization in Canada (Thomas et al. 2015a). Each year, approximately 88,000 people become sick from consuming food that is contaminated with *Salmonella* in Canada (Thomas et al. 2013). Figure 1.1 shows the number of reported *Salmonella* illnesses in Canada every year from 1991-2014. The data shows an increase in the reported *Salmonella* illnesses since 2000.

Traditionally, *Salmonella* has been divided into two groups invasive typhoidal *Salmonella* and non-invasive nontyphoidal *Salmonella* (Feasey et al. 2012). *Salmonella enterica* is divided into six subspecies and has over 2500 serotypes which can cause human illness (Grimont and Weill 2007). The illness caused by *Salmonella* is known as *Salmonellosis*. Majority of the serotypes of *Salmonella* only cause gastroenteritis. Nontyphoidal *Salmonella* is one of the notable diarrhoeal disease agents. Nontyphoidal *Salmonella* has symptoms such as nausea, vomiting, severe diarrhea and abdominal pain (Acheson and Hohmann 2001, Bell et al. 2016). Though, only *Salmonella Typhi* and various types of *Salmonella Paratyphi* can cause typhoid fever (Bell et al. 2016). Treatment of non-life threating *Salmonella* in human beings is generally done using antibiotics, anti-nausea and anti-diarrheal medication. Some cases of *Salmonella* can result in long-term illnesses such as Reactive Arthritis and bacteremia (Pui et al. 2011). A dose as small as 1 to 10 cells of *Salmonella* can cause infection in humans, depending on the serovar (Pui et al. 2011). The ideal temperature for the growth of *Salmonella* ranges from 35 to 37° C, though it can sometimes grow in temperatures ranging from 5 to 47° C (Pui et al. 2011). This makes it easy for *Salmonella* to survive in natural conditions.

Figure 1.1: Number of reported nontyphoidal *Salmonella* illnesses in Canada from 1991 to 2014



Source: Canadian Notifiable Diseases Online, Public Health Agency Canada

Salmonella can survive in the environment for a long time. *Salmonella* has been known to transmit through food vehicles like eggs, cheese, poultry, processed meat, sprouts etc. Though, a very small percentage of *Salmonella* transmissions are from contact with pets, direct contact with chicken and contaminated water (Acheson and Hohmann 2001). *Salmonella* has been long associated with animal-based products but recently there has been an increase in number of cases from fresh produce (Fatica and Schneider 2011). Besides this, *Salmonella* can be transmitted through contaminated surfaces such as food processing equipment and inefficient handling while preparation of food (Pui et al. 2011). Health agencies rely on food attribution rate of illnesses to identify trends in the source of pathogenic contamination and formulating policies for implicated food products. Table 1.1 shows the nontyphoidal *Salmonella* (hereon referred to as *Salmonella* unless specified otherwise) outbreaks related to fresh produce, poultry and eggs in Canada from 2000-2016. In the recent years, there have been more outbreaks related to fresh produce than poultry. This could be due to surveillance and control strategies adopted by the poultry sector in Canada. Table 1.1 shows that recent outbreaks have lasted for a longer period (197 days and 117 days). To contain the outbreak and decrease the number of illnesses it is important to know the pathogenic source of illness and identify the food vehicle so that the implicated source can be removed from the market.

Table 1.1: Nontyphoidal *Salmonella* outbreaks related to fresh produce and poultry in Canada from 2000-2016

Year	Serotype	Location	Illnesses reported	Food Vehicle	start Date	End Date	Duration of Outbreak (days)	Reference
2000	*S. Enteritidis*	BC	62	Eggs	July, 2000	Sept, 2000	63	j
2001	*S. Enteritidis*	AB, BC, SK	84	Mung Bean Sprouts (suspected)	Feb 01, 2001	March 31, 2001	59	a, i
2002	*S. Newport*	ON	34	Fruit	N/A	N/A	N/A	a
2002	*S. Poona*	ON	2	Cantaloupe	March 30, 2002	May 31, 2002	63	a
2003	*S. Heidelberg*	BC	23	Chicken nuggets	January, 2003	April, 2003	90	l
2004	*S. Brandenberg*	BC	12	Cucumber	N/A	N/A	N/A	a
2004	*S. Javiana*	ON	7	Unknown	July 04,2004	July 08, 2004	5	a, k
2005	*S. Enteritidis PT 13*	AB, ON	560	Mung bean sprouts	Oct 27, 2005	Dec 14, 2005	49	a, i
2006	*S. Oranienburg*	ON	2	Fruit Salad	June 15, 2006	Jul 31, 2006	47	a, h
2007	*S. typhimurium*	ON	90	Chicken	Nov, 2007	Dec, 2007	30	f
2008	*S. Litchfield*	BC, AB, MB, ON, NB	9	Cantaloupe : Honduras	Jan 01, 2008	Apr 02, 2008	92	a, f
2008	*S. Saintpaul*	Unknown	N/A	Jalapeno; Tomatoes	April 16, 2008	Aug 11, 2008	117	d
2009	*S. Cubana*	AB, BC, NS, ON	20	Onion Sprouts	NA	NA	N/A	a
2012	*S. Brandenberg*	BC, AB	23	Mangoes imported Mexico	July 12, 2012	Aug 23, 2012	43	c
2014	*S. Newport, Hartford, Oranienburg, Saintpaul*	BC, ON, QC	63	Sprouted Chia seed	Dec 8, 2013	June 22, 2014	197	b, g

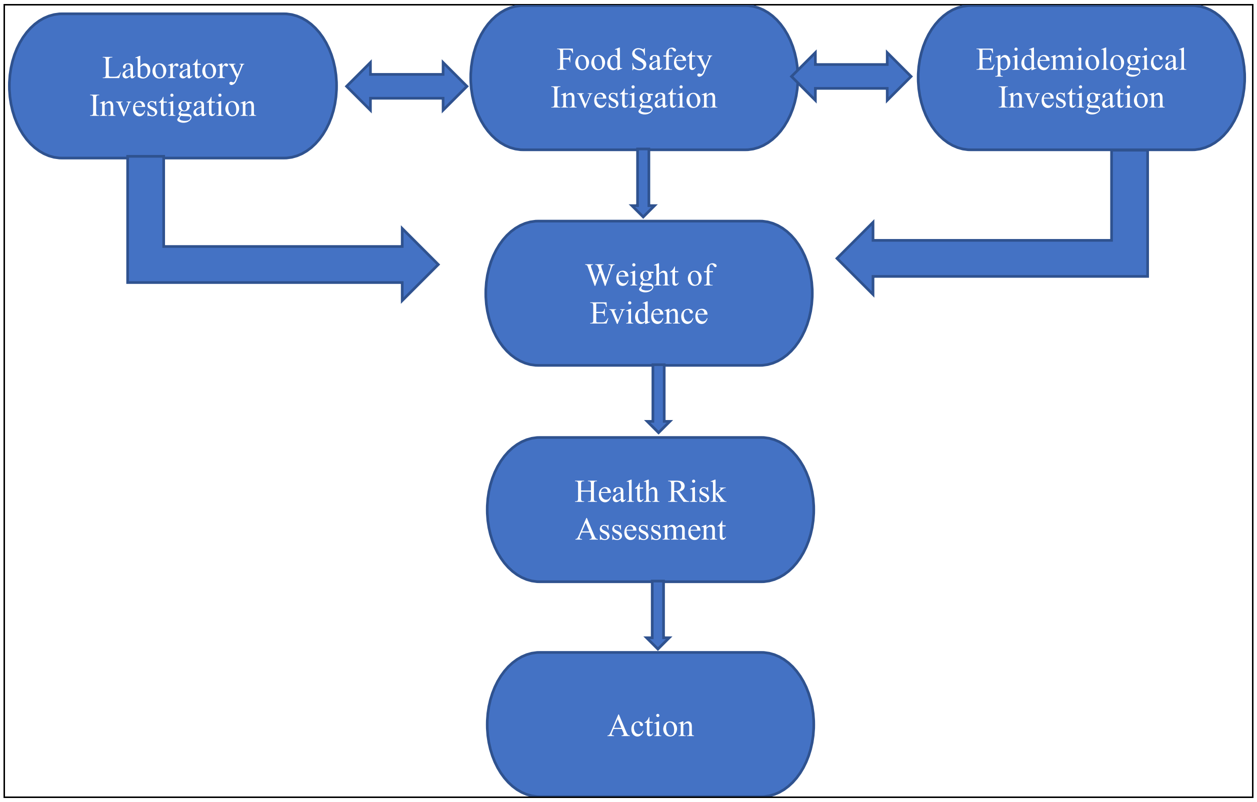
2015	*S. Enteritidis*	ON, QC, NS, NL	51	Frozen Chicken Products	Jan, 2015	July, 2015	210	m
2015	*S. Infantis*	BC, AB, SK, PE, NB, MB, ON, QC, NS	110	Raw Chicken	Mar, 2015	Jan, 2016	300	l

Notes: AB- Alberta, BC-British Columbia, ON-Ontario, SK- Saskatchewan, NS- Nova Scotia, QC- Quebec, MB-Manitoba, NB- New Brunswick

a) *Kozak, G., et al. (2013). "Foodborne outbreaks in Canada linked to produce: 2001 through 2009." J. Food Prot.76(1): 173-183.*
b) *Public Health Agency of Canada. Available at: http://www.phac-aspc.gc.ca/phn-asp/2014/salmonella-nh-053114-eng.php. Accessed 2016-12-31.*
c) *Public Health Agency of Canada. Available at: http://www.phac-aspc.gc.ca/fs-sa/phn-asp/osm-esm-eng.php. Accessed 2016-12-15.*
d) *Center for Disease Control. Available at https://www.cdc.gov/salmonella/2008/raw-produce-8-28-2008.html. Accessed 2016-12-10.*
e) *Center for Disease Control. Available at https://www.cdc.gov/salmonella/2006/tomatoes-11-2006.html. Accessed 2016-12-31.*
f) *Center for Disease Control. Available at: https://www.cdc.gov/salmonella/2008/cantaloupes-4-2-2008.html. Accessed 2016-12-31.*
g) *Public Health Ontario. Available at: https://www.publichealthontario.ca/en/BrowseByTopic/InfectiousDiseases/Pages/Chia-seed-powder.aspx. Accessed 2016-12-31.*
h) *Center for Disease Control. Available at: https://www.cdc.gov/mmwr/preview/mmwrhtml/mm5639a3.htm. Accessed 2016-12-31.*
i) *Nesbitt, A., et al. (2012). "Integrated surveillance and potential sources of Salmonella Enteritidis in human cases in Canada from 2003 to 2009." Epidemiology and infection 140(10): 1757.*
j) *Public Health Agency of Canada. Available at:http://www.phac-aspc.gc.ca/publicat/ccdr-rmtc/05vol31/dr3107a-eng.php*
k) *Public Health Agency of Canada. Available at: http://www.phac-aspc.gc.ca/publicat/ccdr-rmtc/05vol31/dr3121b-eng.php. Accessed 2017-01-03*
l) *Middlesex-London Health Unit. Salmonella Outbreak at the University of Western Ontario, London, Ontario, June 2008.*
m) *Public Health Agency of Canada. Available at: http://www.phac-aspc.gc.ca/fs-sa/phn-asp/2015/salm-0628-eng.php*

Given that *Salmonella* is majorly transmitted through food vehicles. Food safety is becoming one of the major concerns worldwide as the consumers become more aware and governments establish new rules to promote it. Foodborne Illness Outbreak Response Protocol (FIORP) defines a foodborne outbreak as following, in Canada, *"an incident in which two or more persons, from different households and therefore not linked, experience similar illness after a common source of exposure. An outbreak is often identified through laboratory surveillance or other surveillance* *mechanism demonstrating an increase in illness that is unusual in terms of time and/or place. An outbreak is confirmed through laboratory, food safety and/or epidemiological evidence"* (Health Canada et al. 2011). Providing the country with improved food safety protocols and technology has become an important task for the governments worldwide. Europe has food policy regulations related to control and monitoring of pathogens in food products. All members of the European Union must follow similar food safety rules laid out by the commission as agricultural and processed food products are unrestrictedly traded in all the member countries (European Union 2014). The European Union introduced *Salmonella* control programs in 2003 for poultry farms which included preventive actions, detection strategies and regulatory measures (European Union 2014). The US has three federal agencies that help in formulating and implementing food safety policies— Food and Drug Administration, the US Department of Agriculture and Food Safety Inspection Service. Apart from these three agencies, the responsibility to investigate, monitor and control a foodborne outbreak also lays with CDC (Susan Keenan et al. 2015). To help with these tasks the CDC introduced PulseNet US. PulseNet is defined as *"a molecular subtyping network of federal, state, and local public health laboratories designed to facilitate the identification of and response to outbreaks caused by bacterial foodborne pathogens"* (Scharff et al. 2016). PulseNet helps in real-time communication between outbreak coordinating agencies and helps in early identification of the source of the outbreak by standardization of tests using pulsed field gel electrophoresis (PFGE) patterns (Scharff et al. 2016). Canada follows similar food safety programs as the US. Canada has employed hazard analysis and critical control point (HACCP) principles to strengthen its food safety policies. These principles help in tracing the food vehicle from farm gate to plate. This method is an internationally accepted food safety practice but it has been implemented differently in different countries (Rajić et al. 2007). In Canada, food safety responsibilities are shared among federal agencies, provincial agencies, local agencies, industries and consumers (Bureau of Microbial Hazards 2014). Three federal agencies work together in Canada to ensure the food safety — Health Canada, Canadian Food Inspection Agency (CFIA) and Public Health Agency of Canada (PHAC) (Health Canada et al. 2011). The provincial agencies have provincial food safety legislation and are responsible for inspection, education and surveillance (Bureau of Microbial Hazards 2014). Local agencies are responsible for inspection of retail foodservice outlets and are involved in activities like licensing, inspection and resolution of local level complaints (Bureau of Microbial Hazards 2014). Industries are responsible for complying with food safety regulations laid out in the federal and provincial legislation. (Bureau of Microbial Hazards 2014). Consumers are responsible for educating themselves about various safe food handling practices (Bureau of Microbial Hazards 2014). Foodborne illness outbreak investigations are a combination of multidisciplinary activities, like data collection from affected persons, testing of the specimen by laboratories and recall of implicated food products, by the three agencies (Health Canada et al. 2011).

Figure 1.2: Simplified decision-diagram of the steps leading to a foodborne illness outbreak investigation.



Source: Weight of Evidence: Factors to Consider for Appropriate and Timely Action in a Foodborne Illness Outbreak Investigation, Health Canada

Canada has established a systematic process of investigating foodborne outbreaks. Figure 1.2 shows the main steps involved in the decision-making process during a foodborne outbreak investigation (Health Canada et al. 2011). The laboratory investigation, food safety investigation and epidemiological investigation all go hand in hand. As more pieces of evidence are gathered during the investigations, the strength of each evidence guides the investigations further. Accordingly, the risk posed by the outbreak is evaluated and remedial actions are taken. PulseNet Canada plays an important part in food safety investigations. It acts as a network for provincial and other partner laboratories (CFIA and Health Canada laboratory) for simultaneously sharing data on the isolates recovered from various pathogens (Reimer et al. 2016).

Various tools are being developed to help improve *Salmonella* detection in food products. Currently, PulseNet Canada uses Pulsed-Field Gel Electrophoresis (PFGE), a gold standard, for subtyping of *Salmonella* isolates. The technology has been termed as a gold standard because historically it was one of the first few methods which could subtype the DNA of *Salmonella* (Wattiau et al. 2011). PFGE helps find DNA fingerprint which is unique for each organism (Centers for Disease Control and Prevention 2016a). The process of extraction of the DNA follows five main steps. Initially, a bacterial culture is prepared and then the bacterial cells are poured into plug moulds (Centers for Disease Control and Prevention 2016a). Then, these plug moulds are used to break open the bacterial cells so that the DNA can be freed (Centers for Disease Control and Prevention 2016a). The plug is then placed in a gel and then in an electric field that separates DNA fragments with a specific pattern (Centers for Disease Control and Prevention 2016a). Next, the pattern is analyzed using a computer software and uploaded to PulseNet database. PFGE has more discrimination power than the earlier methods like ribotyping or multi-locus sequence typing (Centers for Disease Control and Prevention 2016a, Bell et al. 2016). Still, there are disadvantages of PFGE which make it less proficient. Firstly, the method is time-consuming as it can take up to weeks to get the whole DNA sequence (Bell et al. 2016, Centers for Disease Control and Prevention 2016a). This makes it especially difficult for detection of *Salmonella* in fresh produce because the time frame required for detection is too long which can lead to spoilage of the produce (Bell et al. 2016). This can also deter producers from testing the produce before sending it to the market. Secondly, PFGE does not discriminate between all isolates (Bell et al.

2016, Centers for Disease Control and Prevention 2016a). This makes it inefficient in the detecting presence of *Salmonella* in fresh produce due to the presence of indigenous microbial and antimicrobial in the produce (Bell et al. 2016). Thirdly, it is labour intensive with various plates required for samples and a large space is required for conducting the tests (Bell et al. 2016, Centers for Disease Control and Prevention 2016a). A new sequencing tool is being developed to allow public health officials to better determine the food source of *Salmonella*, which will allow for contaminated food vehicle to be removed from the market before it is purchased by the consumers. This technology is known as Whole Genome Sequencing (WGS), which is a highly automated genome sequencer (Bell et al. 2016). The technology is powerful enough to recognize the source of outbreak down to the food vehicle (Bell et al. 2016, Centers for Disease Control and Prevention 2016b). It can recognize the geographical location of the isolate and determine antimicrobial susceptibility, due to its high discriminatory power (Bell et al. 2016, Centers for Disease Control and Prevention 2016b). WGS is a fast and more precise way of detection of *Salmonella* which will lead to solving more outbreaks by identifying implicated food vehicles in short time. The process of WGS can be divided into four main steps. The first step involves preparing bacterial culture in an agar plate and breaking the cells to release the DNA (Centers for Disease Control and Prevention 2016b). Then the DNA is cut into fragments and the copies of these fragments are collected in a "DNA library" (Centers for Disease Control and Prevention 2016b). Next, the library is loaded onto a sequencer and a computer software is used to put the fragments in a correct order (Centers for Disease Control and Prevention 2016b). Currently, a multi-disciplinary team is investigating the use of genomics to address the problem of *Salmonella* in the Canadian food system. The team plans on sequencing 4,500 genomes of *Salmonella* and share the database with the federal and provincial agencies involved in the detection of foodborne outbreaks (Emond-Rheault et al. 2017). The data will help not only in outbreak detection but also in the attribution of an outbreak to a specific food vehicle. The genomic database is an online web application which is called *Salmonella* Foodborne Syst-OMICS Database (SAlFoS) and will be available to various laboratories on the PulseNet Canada network (Emond-Rheault et al. 2017). The database will provide isolate identification, geographical origin, phenotypic data and epidemiological data (Emond-Rheault et al. 2017). This database will help in antimicrobial testing, epidemiological investigations and clinical enquiries.

PulseNet Canada is in the phase of rolling-out WGS for routine molecular outbreak response activities and phasing out the conventional tests like PFGE (Reimer et al. 2016). The scientific benefits of the technology have been studied by many researchers and this makes it important to study the microeconomic benefits and macroeconomic impact of adoption of the technology. Economic analysis of foodborne diseases and their control strategies has important applications. The economic analysis helps in converting the risks related with foodborne diseases into a common monetary denominator which helps in ranking the diseases with the highest burden (Curtin and Krystynak 1991, Buzby and Roberts 2009). This further helps in estimating the costs and benefits of control strategies and various such strategies can be compared to find the most cost-effective method (Curtin and Krystynak 1991). Economic analysis helps in decision making at national organizations such as PHAC, CFIA etc. and international organizations such as WHO (Buzby and Roberts 2009). Economic analysis also helps in determining the costs to different groups like private costs, federal agency costs, provincial agency costs and producer costs. This helps in determining how the burden of the diseases fall on different groups in an economy. Due to the lack of economic analysis food safety has not been given essential importance in many countries (World Health Organization 2015). Towards this end, the study evaluates the economic impact of using WGS for the early detection of *Salmonella* as compared to the existing technology in Canada. To the best of the researcher's knowledge, none of the previous studies calculates the costs for *Salmonella* from fresh produce, poultry and eggs in Canada or conducts a cost-benefit analysis of technological improvement in outbreak detection. Further, translation of the impact from the cost and benefit analysis to the macroeconomic framework is rare in the literature. This study bridges the gap in the current literature by estimating the annual monetary and non-monetary burden of *Salmonella*[1] from fresh produce, poultry and eggs for Canada. Moreover, net benefits from one area of the economy are transformed into benefits for the whole economy through a multiplier effect, to measure the economy-wide impact of the technological improvement. The study estimates the impact on industrial output, gross domestic product (GDP) and employment in Canada. The economic analysis of new genome technology is helpful in informed decision-making.

1.2. Organisation of the study

The following is the outline of the thesis. Chapter 2 reviews the relevant literature concerning the economic analysis of the foodborne diseases. This is followed by the description of methodology and data used for economic evaluation of WGS in Chapter 3. This chapter presents the data sources and methodology for cost-benefit analysis and input-output modelling. Chapter 4 consists of the results and discussion of the microeconomic and macroeconomic

[1] Since, the clinical symptoms of typhoidal *Salmonella* are different from nontyphoidal *Salmonella* only costs for nontyphoidal *Salmonella* are accounted for.

impact from the adoption of the new technology. Chapter 5 presents the conclusion, policy recommendations and areas for further research.

Chapter 2: Literature Review

2.1. Introduction

Foodborne illnesses particularly *Salmonella* are an important public health issue, and priority setting for foodborne illness management requires health risks to be ranked according to defined burden of illness criteria (Bélanger et al. 2015). *Salmonella* is one of the most common source of illness among foodborne pathogens worldwide. An estimated 93.8 million cases of gastroenteritis caused by *Salmonella* occur globally each year and of these, nearly 80.3 million cases are foodborne (Majowicz et al. 2006). In the US, the leading cause of hospitalization (19,300 annually) among foodborne diseases is nontyphoidal *Salmonella* (Scallan et al. 2011). The number of illnesses due to nontyphoidal *Salmonella* in Canada are 87,500 and number of hospitalizations and deaths are 925 (24%) and 17 (16%) respectively (Thomas et al. 2015a, Thomas et al. 2013).

Foodborne *Salmonella* can be acquired from a range of food vehicles such as poultry, beef, eggs, deli meat, dairy, seafood, baked goods and complex goods (Batz et al. 2012). Ravel et al. (2009) found that in Canada, from 1976 to 2005, there were 6,908 foodborne outbreaks out of which the causative agent and a food vehicle was identified only in 2107 (40 percent) outbreaks. Out of these 79 outbreaks have recognized *Salmonella* as the causative agent. Out of these *Salmonella* infections 29 percent were attributed to produce, 15 percent were attributed to poultry and 5 percent were attributed to eggs.

Given the high number of illnesses caused by *Salmonella*, it is important to estimate the impact of the disease-causing pathogen on the economy. There are different ways of estimating the impact of foodborne diseases in the economy. Some of these are: Cost of Illness(COI), Willingness to Pay (WTP), Cost Effectiveness Analysis, Risk-Risk Analysis and Health-Health Analysis (Kuchler and Golan 1999). The paper critically reviews various studies that estimate the economic impact of foodborne diseases and *Salmonella* in particular. This study covers two types of estimates, monetary and non-monetary, and summarizes the existing literature on the topic.

2.2. Cost of Illnesses and Health Adjusted Life Years for Foodborne diseases

The costs and risks associated with foodborne diseases can be calculated using two methods: monetary methods like Cost of Illness (COI) and non-monetary methods like Health Adjusted Life Years (HALY). This section discusses these two methods and the empirical studies that have applied these methods to foodborne diseases.

Cost-of-illness (COI) studies aim to assess the economic burden of disease on a population, and they are estimated for an expanding range of illnesses and in many geographical settings. These studies identify and quantify all the costs incurred due to a single disease or for a range of diseases, at both the individual and societal levels. COI is a method which accounts for the direct medical costs, direct non-medical costs and indirect costs arising due to diseases (Buzby et al. 1996). It calculates the monetized loss to the economy (Kuchler and Golan 1999). Table 2.1 shows the various components of costs.

COI method is commonly used in foodborne illness studies. COI can be calculated using top-down approach or bottom-up approach. The top-down approach, also known as population based approach, uses aggregate values resource utilized whereas bottom-up approach, also known as person based, uses cost per person of resources used and multiplies it with total number of illnesses (Larg and Moss 2011). The COI for foodborne diseases have been calculated for various countries such as US, Canada, New Zealand and Netherlands. Todd (1989), Henson et al. (2008), Majowicz et al. (2006) estimated the costs of foodborne diseases in Canada. Buzby et al. (1996), Hoffmann et al. (2012), Batz et al. (2012), Scharff (2012) do the same for the US. Gadiel and Abelson (2010) and Lake et al. (2010) estimates the costs of foodborne illnesses for New Zealand. The economic analysis can be performed by calculating annual costs arising due to the disease (Majowicz et al. 2006, Henson et al. 2008, Hoffmann et al. 2012, Todd 1989, Buzby et al. 1996, Scharff 2012, Gadiel and Abelson 2010). Sometimes the analysis is done by calculating costs for one outbreak from a pathogen (Thomas et al. 2015b, Suijkerbuijk et al. 2016). While annual costs provide broader estimates as assumptions are made about the number of units of resource used, costs for a single outbreak are more detailed and precise as data for the number of patients using different resources is available. Table 2.2[2] shows the type of costs-monetary and non-monetary, methodology, time frame of the study: annual or single outbreak and final estimates of studies in the literature.

Productivity losses make up for a major component of COI in most of the studies. Productivity loss is the indirect cost that arises due to work days missed owing to the illness. Productivity losses can be calculated using two different approaches: Human Capital Method and Labor Market Method. The first approach, Human Capital[3] Method uses average wage adjusted for risk premium derived from life insurance. The second approach, Labor Market Method, uses estimates based on labor market studies where higher wages are provided for riskier jobs. There

[2] For the table check appendix

[3] The Human Capital Method was developed by J. Steven Landefeld and Eugene Seskin of the U.S. Department of Commerce.

is no consensus about which approach is the best for determining cost of illness (Frenzen et al. 1999).

While COI is widely accepted, Health Adjusted Life Years is also used to measure the burden of diseases as a non-monetary estimation (Hoffmann et al. 2012, Murray et al. 1996). Two types of integrated health metrics are gaining popularity: Quality Adjusted Life Years(QALY) and Disability Adjusted Life Years (DALY). For measuring these indices age distribution of the population affected by the disease should be known. QALY is measured by calculating the difference between health-related quality of life weight for a specific health state (with illness) and baseline health related quality of life weight, multiplied by the duration of disease (Batz et al. 2014). QALY is preferred by the federal agencies in the US as it provides country specific weights (Hoffmann et al. 2012). These measures are helpful in acquiring information about targeted pathogen, which in turn would help decrease the burden of diseases with the high losses to the society. The internationally standardized form of QALY is DALY (Murray et al. 1996). DALY is a summation of life years lost due to premature death and disability and discomfort due to a disease. Though, HALY matrices[4] are considered to be free of value judgement but assigning baseline weights to the population requires determining the ideal life expectancy of the population (Murray et al. 1996). There are also other considerations such as should the health of all socioeconomic groups be weighted equally, how the health of young and old should be weighted etc. which require value judgement (Murray et al. 1996).

[4] HALY is currently used by PHAC as an indicator of burden of illness.

There are many empirical studies that have been done to calculate COI and HALY for various foodborne diseases. Buzby and Roberts (1996) and Buzby et al. (1996) are two dated studies which calculate the costs for food borne illness for six pathogens in US. Todd (1989) estimated the cost of 67 incidents foodborne illness in US and Canada. The paper uses a unique approach of estimation by dividing the costs into two categories: food processing industry and food service industry. The estimates include costs related to medical care, travel, investigation of illness by public authorities, emotional loss, productivity losses, business losses and legal costs incurred by business but the paper does not state the sources and methodology of how the loss in each category of cost is calculated. Todd (1989) calculates total losses to be $1,334.6 million in 1985 US dollars ($3,945.54 million in 2017 US dollars).

More recently similar studies from the US have calculated COI for foodborne pathogens (Hoffmann et al. 2012, Scharff 2012). Hoffmann et al. (2012) estimates the costs for 14 foodborne pathogens to be at $14.0 billion and 61,000 QALYs. Scharff (2012) estimates costs to be $51.0 billion in the basic model and $77.7 billion in the enhanced model for the 31 pathogens and unidentified agents. All the costs are in 2010 US dollar estimates. Hoffmann et al. (2012), first, characterize the severity and associated probability of occurrence of different severities for each disease using disease trees. The COI estimate includes medical costs, productivity loss based on average daily wages and VSL including the cost of sequelae[5]. Hoffmann et al. (2012) also calculate Quality Adjusted Life Years (QALYs) for each of the disease pathogen. Scharff (2012) estimates the COI using two types of models: the basic and enhanced model. The basic model includes four

[5] Cost of sequelae-costs arising due to long term and chronic conditions

types of costs: medical costs, productivity losses, value of statistical life and the cost of sequelae. Productivity losses include losses due to own illness and losses due to informal caregiving in case of illness of a child. Value of Statistical Life (VSL) is adjusted for income elasticity. The second model of enhanced COI replaces own productivity losses with monetized QALY[6]. QALY represents the losses due to pain, suffering and functional disability arising from the illness and hence the monetized value of QALYs equals the WTP to avoid pain and suffering by the consumer. Production costs are assumed to be a part of QALY values. Scharff (2012) is the only paper which uses monetized value of QALY.

Other than these two studies US federal agencies also calculate COI for various foodborne diseases. Two types of models have been employed by US federal agencies till now to estimate economic burden of foodborne illnesses. Economic Research Service (ERS) of the U.S. Department of Agriculture (USDA) estimates the COI using basic cost of illness model which includes medical costs and productivity losses. The Center for Food Safety and Applied Nutrition at the U.S. Food and Drug Administration uses another model known as Enhanced Cost of Illness model, this includes values for pain and suffering (Scharff 2012). The COI study by Hoffmann et al. (2012) is like ERS except the calculation for VSL. Valuation of death by ERS is based on age at death whereas Hoffmann et al. (2012) is based on constant VSL for all deaths, not based on the age at death. On the other hand, Scharff (2012) calculates COI using both the models.

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[6] The monetized QALYs value is calculated by "*multiplying loss of well-being from a condition, the number of days with the condition, and the economic value of 1 day (derived from the value of statistical life)." Scharff, R. L. 2012. Economic burden from health losses due to foodborne illness in the United States. Journal of food protection, 75(1): 123-31.*

There are several differences between the two studies. The main difference between both the papers, apart from the number of pathogens, is that Scharff (2012) monetizes QALYs but Hoffmann et al. (2012) does not. Another difference is that Scharff (2012) uses more sophisticated estimates of QALY. Severity of illness is not considered while estimating the COI by Scharff (2012) whereas Hoffmann et al. (2012) estimates are based on severity. Also, Scharff (2012) calculates the cost of medication but Hoffmann et al. (2012) suggests that such costs are almost negligible. Both the papers incorporate uncertainty in the model using Monte Carlo Simulation. The use of income elasticity of VSL is unique in Scharff (2012) paper. Neither of the studies address the cost of foodborne pathogens to public health agencies and the industry.

Another method of calculating COI is by conducting phone surveys in a region and asking about episodes of illness and resources used for medical intervention. For Canada, Majowicz et al. (2006) and Henson et al. (2008) are two such studies that calculate the cost of gastrointestinal illness by conducting phone surveys for Hamilton, Ontario and British Columbia respectively. Instead of deriving point estimates both the articles use stochastic approaches that use known or hypothesized probability distributions for key variables. Both the studies are methodologically alike, phone surveys are conducted for the chosen cities and self-reporting by the sample is used as a tool to estimate the incidence of illness. Next, the cases are divided into three categories Mild cases, Moderate cases and Severe cases and then the resource use is assigned according to the severity. At last, probability distributions are assigned to a frequency of resource use variables and cost variables. The costs consist of the following component: direct costs and indirect costs. The direct costs incorporate the following physician costs, emergency room costs, travelling cost of treatment (excluded in Majowicz et al. 2012), hospitalization costs, laboratory test costs, medication costs. The indirect cost calculates the loss in productivity due to number of days missed from work by the patient and the care giver. It also includes the number of school days missed. Henson et al.(2008) calculates the cost of work days missed due to caregiver also. The daily earnings (based on statistics Canada data), number of cases and the number of days missed from paid work were represented in different distributions, in both the articles. The articles have comparable incidence of illness where Henson et al. (2008) estimates 112,193 cases of gastroenteritis per 100,000 population for British Columbia over the period of one year. Majowicz et al. (2006) estimates 123,300 cases per 100,000 of the population for Hamilton, Ontario. The estimated mean economic burden of gastrointestinal illness on British Columbia was CAN$514.2 million and a mean annual cost per case of CAN$1,342.57 at 2004 prices. The estimated mean economic burden for Hamilton was CAN$56 million and mean annual cost per case was Can$1,089, based on 2001 prices. The likely difference in the estimates of both the papers is because Majowicz et al. (2006) do not include travel costs. The cost per case is comparable in both the studies. The costs estimate of the studies are a lower bound because they do not include costs incurred due to inability to perform non-paid activities like household care and child care by the ill individuals, the costs associated with sequelae, public agency costs of investigation and industry costs. Due to these reasons, the estimates are biased downwards. None of the two studies calculate non-monetary measures like Health Adjusted Life years.

Very few studies include costs to the government and businesses from food safety monitoring and regulations. Gadiel and Abelson (2010) estimates such costs for New Zealand. Along with traditional costs such as treatment costs, productivity loss etc. estimates include cost incurring from regulation and surveillance; business compliance costs and costs of food incidence. The business compliance costs consist of three parts- the cost of general regulatory compliance, industry specific risk management practices and costs arising due to outbreaks. The estimated costs are $161.90 million based on 2009 prices. Compared to Australia and United States the costs for foodborne illnesses in New Zealand are low. Kemmeren et al. (2006) calculate the economic burden of foodborne diseases for Netherlands. The article calculates the COI and DALY for seven foodborne diseases causing pathogens. COI includes direct cost (physician costs, hospitalization costs and medication costs), direct non-healthcare costs (travel costs, informal care and co-payments from individuals) and indirect costs (productivity loss from work days missed due to own sickness and caregiving using fictional cost method). Productivity losses are the most important component of COI. Norovirus has the highest burden in terms of COI, followed by rotavirus, Campylobacter and *Salmonella* in order. In terms of DALY, Toxoplasmosis and Listeriosis have the highest burden.

Multifactorial Risk Analysis is another popular framework used to rank different foodborne diseases on multiple criteria. Ruzante et al. (2010) uses this framework for six pathogen-food combinations to rank them in a way which is flexible to help in decision making by different stakeholders. Six measures are adopted to measure the risk for four major factors, i.e., public health impact, market impact, consumer perception and acceptance of risk and social sensitivity. The impact on public health is measured using DALY[7] and COI. Economic importance of pathogen-food combination in the domestic market is measured in terms of size of the industry in the economy, exports etc. Consumer perception and acceptance of risk is measured by total normalized score. This score is calculated using expert opinion on the degree to which a

[7] See footnote 4.

particular food-pathogen risk is perceived as uncontrollable by consumers, unknown to the individual, unknown to scientists, involuntary, and known to have a severe outcome. Finally, consumer and firm scores are calculated to measure social sensitivity of the combinations. The framework is helpful in comparing associated risks from multiple point of view but does not consider the following. The paper does not justify why the given food-pathogen combinations have been chosen for the study. For calculating COI, the authors use estimates from Majowicz et al. (2006) which only represents costs from one region of Canada, Hamilton, this does not provide a comprehensive cost estimate for the whole country as the costs differ for different provinces. For calculating DALY cost disability weights are taken from a study from Netherlands as no study is available for Canada (Kemmeren et al. 2006). Uncertainty is not considered hence Monte-Carlo stimulations are not used. The risk analysis of consumer perception is not comprehensive and is being studied further by the authors to provide better insights.

2.3. Economic Analysis of *Salmonella* Estimates

Salmonella is one of the major foodborne diseases worldwide. This makes it important to analyze the economic effect of *Salmonella*. All the articles that calculate the cost of foodborne diseases also account for the cost of *Salmonella*. There are varied ways in which costs have been calculated in various studies. This section discusses various studies that have been conducted for calculating monetary and non-monetary costs of *Salmonella*.

The costs of *Salmonella* have been estimated since a long time. Cohen et al. (1978) calculates the cost for *Salmonella* using data from a survey of patients affected by a *Salmonella* Heidelberg outbreak from contaminated cheese in July and August 1976 in the US. 280 patients were surveyed to find costs related to doctor office visits, emergency room visits, hospitalization, medication, transportation, child care and loss of income due to work days missed. Hospitalization costs were the main contributors to the costs and these costs were highest for infants and elderly. A total loss of 151,000 is reported for 234 individuals. The authors extrapolate the cost for the number of cases not reported. The total estimated loss is due to US$4 million. The article is an initial attempt to economically analyze the costs of *Salmonella* outbreak and to bring to attention the importance of food safety and outbreak control in the economy.

Later on, Buzby et al. (1996) calculate costs for *Salmonella* in the US. It states that *Salmonella* has higher costs among all the foodborne diseases at that time. This is due to high prevalence of *Salmonella* in the population and massive milk related outbreak in Chicago at the time. The actual number of illnesses is extrapolated from the data of reported number of cases. Instead of calculating new cost estimates the article updates the costs calculation done by Cohen et al. (1978) with 1993 Consumer Price Index and the new incidence of illness estimates. The estimated cost of foodborne *Salmonella* ranges from $0.6 billion to $3.5 billion annually (1993 US$). The article does not calculate the cost of the sequel from *Salmonella*.

Another study that calculates COI of *Salmonella* for the US is Frenzen et al. (1999). Frenzen et al. (1999) calculate the cost of *Salmonella*, which includes medical costs and productivity loss, using FoodNet estimates. FoodNet estimates the annual number of *Salmonella* cases in the US then the multiplier is used to estimate the actual number of cases. The information regarding the type of medical care provided to the patients is extracted from MarketScan database. The database contains medical claims of 4 million patients. Of which claims for patients treated for

Salmonella from are examined. This makes the resource utilization calculations more actuate as the actual resources used are extracted from the database. The Patients are then divided into following four categories: patients that visited the physician, required hospitalization, and pre-mature deaths and the residual cases. Average medical costs are estimated for each case of severity separately. To estimate the number of work days lost telephone survey was conducted. Productivity loss was determined by the average number of work days lost by employed patients in each category of severity, the employment rate and average daily compensation for US workers in 1998. The income earning of people who died prematurely are calculated using two different methods the Human Capital Approach (HCA) and Labour Market Approach (LMA). For the HCA, average wage adjusted for risk premium derived from life insurance was used. For LMA, estimates based on labour market studies where higher wages are provided for riskier jobs was used. There is no consensus about which approach is the best for determining cost of illness but cost due to fatal cases constitutes a major part of the total COI.

Sockett and Roberts (1991) calculate the cost of *Salmonella* in England and Wales by conducting a survey of patients affected by Salmonellosis and a survey from public health authorities. The article divides the cost between public sector authorities, health sector authorities, individual and families and productivity losses to the economy. It is one of the few studies that tries to calculate costs to public health authorities for investigation of outbreaks. The costs to public health authorities consists of costs to Environment and Health Authorities and laboratory costs (staff and consumables). The costs to health sector consists of costs incurred by National Health Services department of the country which consists of physician costs, hospitalization costs, ambulance costs and prescription costs. The costs to individual and families consists of travel related costs to doctor, hospital and other expenditures incurred by the individuals. The productivity loss is the largest component of the total cost. The total costs come up to around £996,000. The limitations of the study are that it does not account for VSL or costs to industry implicated in the outbreak.

More recent estimates of COI from *Salmonella* show that it is ranked as one of the top economic loss causing foodborne pathogens. The cost estimates by Scharff et al. (2016) for *Salmonella* are US$4,430 million and US$11,391 million from basic cost of illness and the enhanced model respectively. Hoffmann et al. (2012) estimates the annual cost of *Salmonella* for US to be US$3.3 billion. Hoffmann et al. (2012) estimate the costs of nontyphoidal *Salmonella* to be highest among the 14-foodborne illness causing pathogens. *Salmonella* is the second most costly foodborne disease (27% of the total foodborne costs) in New Zealand (Gadiel and Abelson 2010). The study calculates VSL for *Salmonella* to be 13.3 million, second highest after Listeriosis ($14.44 million). In Netherlands, *Salmonella* costs £8.8 million annually and a loss of 670 DALY per year. Productivity loss makes up the most (55%) of total COI for *Salmonella* (Kemmeren et al. 2006). Economic Burden of Illness in Canada report calculates the cost of *Salmonella* to be CAD$5,636,200 which includes hospitalization costs to be CAD$3,644,200 and physician costs CAD$1,992,000, all estimates are at 2010 prices (Public Health Agency of Public Health Agency of Canada).

Apart from COI, non-monetary estimates like DALY and QALY have also been estimated for *Salmonella*. Globally, *Salmonella* is responsible for 4.0 million DALYs, highest among diarrheal agents such as *norovirus, Camphylobacter spp., Vibrio cholera and shigella spp.* (World Health

Organization 2015). Hoffmann et al. (2012) ranks *Salmonella* in top five foodborne pathogens that cause economic and QALY losses.

2.4. Cost- Benefit Analysis of *Salmonella* Control Program

Though a lot of papers calculate COI of *Salmonella* there is not much literature present when it comes to economic evaluation of the food safety policies associated with it. Two such studies that perform a Cost and Benefit Analysis (CBA) are Andersen and Christensen (2008) and Sundström et al. (2014). The articles undertake a CBA of *Salmonella* control policies in Denmark and Sweden receptivity. Scharff et al. (2016) analysis the benefits from technological improvements in food safety programs such as PulseNet in the US on the economy. Two methods were employed to check the impact of reduction of illness: the recall model and the process change model. The recall model measures the direct effect of PulseNet. The model calculates the difference between observed and expected cases of foodborne illnesses. The expected cases were calculated by modelling a negative binomial distribution for expected cases per week where the distribution was bounded by zero and highest number of cases reported in a week throughout the outbreak. The process change model measures the indirect benefits from PulseNet, i.e., improved food safety practices adopted by the industry due to improvement in outbreak detection. It is estimated that PulseNet US saves $500 million every year, in medical costs and productivity losses, by reducing the number of illnesses from foodborne pathogens (Scharff et al. 2016). The models used are unique to the paper and have not been used before.

Andersen and Christensen (2008) economically evaluate *Salmonella* control programs established by the Danish government. The programs were established to control the rising number of cases in 1980-1990. Two approaches are used to calculate the impact. The first approach uses COI method to compare direct costs and direct benefits of the programs, in short run. The second approach is Computable General Equilibrium (CGE) approach helps in calculating indirect benefits of the *Salmonella* control program, in the long run. Producer costs from the food safety regulations are divided into two categories direct costs and indirect costs. The direct costs to the producers are incurred due to improved hygiene, control and increased documentation, and indirect costs are incurred due to change in production possibilities. Public sector costs arise due to increased regulation and expenditure on R&D. The direct costs increase can be seen for the pork, poultry and egg production industry and the public sector. The direct costs are estimated at US$235 million from 1995-2002—at 2000 prices. Benefits arise from decreased public health sector expenditure and increased earnings due to increased labor productivity. Other benefits include an increase in demand for food products due to increased regulations which result in increased the food safety and hence, consumer confidence. For the COI analysis, the population is divided into seven categories according to the severity of illness and direct costs are calculated. The national database of patients is used. Then for each group the medical costs are calculated, these include hospital costs, doctor consultation and laboratory costs. To calculate the productivity increases average wage rate per person per day is used along with this estimate of average absenteeism for each group is used. These costs do not include costs arising due to chronic illness caused by the Salmonella, like reactive arthritis. It is estimated that the savings for public health sector are US$20 million from 1995-2002. The costs are more than the benefits from the *Salmonella* control program.

Limitation of analysis using COI method is that it considers costs which arise only after the illness and not the costs that arise before (ex-ante) the illness, i.e. the costs arising due to the risk associated with the consumption of food. Another strong assumption this method makes is that due to change in regulations there is no change in the supply or demand. This problem is solved by the general equilibrium analysis considers economy-wide adjustments.

Applied General Equilibrium (CGE) model is used to estimate the direct effect of the *Salmonella* programs on the producers who were impacted by the program (egg, pork and poultry) and indirect effects on producers who were not directly impacted by the program. This model takes into account the sales structures and price elasticities of consumer demand. The costs to the industry are incorporated by negatively shocking the total factor productivity of the three sectors— egg, pork and poultry. The reduction in the public health expenditure and increased labor productivity are also incorporated. Two scenarios are considered, baseline scenario-no program implementation and alternative scenario- with the program implementation. The final impact of the program on the industry can be positive or negative. Positive due to increase in labor productivity would decrease costs of production and negative due to the increase in prices will decrease the demand for commodities. The net effect from the model is negative as the prices increases and volume of output decreases. The net final impact on the economy is captured by GDP. The GDP could increase due to increased productivity and decrease due to decreased health care expenditure in the economy. The article shows that there is a positive accumulative effect on real GDP from 2003 onwards. This positive effect is due to increase in labor productivity which decreases the production costs for the economy. For the three industries that are directly affected the output costs increase due to increased regulation, even then the labor costs decrease. The analysis shows that GDP increases after 2003 as the prices in rest of the industries decreases which increases the exports and the substitution by consumers. These results are sensitive to the assumption of the percentage of registered illness for example if the percentage is low then GDP increases in the long run but if the percentage is high GDP decreases in the short run.

It can be seen from the above analysis that the estimating the net benefits of the food safety program can yield different results in different time horizons. The direct benefit analysis in the short run, using COI, yielded net costs to the society whereas the long-run analysis, i.e. CGE analysis yielded net benefits. Also, quantification of the economic consequences of the program is subject to uncertainties due to uncertainties arising from the actual burden of illness, impact of premature deaths and valuation of costs (medical). These estimates do not include consumer's willingness to pay for the program. The assumption that the number of illnesses from *Salmonella* would have remained the same had the program not been implemented is very strong, there could be factors other than the program that would impact the burden of illness for example technological change, development of antibiotics. The choice of the time horizon for which the cost-benefits are calculated impacts the estimates strongly.

Sundström et al. (2014) estimates the economic effects of changing the current *Salmonella* control strategy in Sweden to a hypothetically implementing the control strategies used by Denmark and Netherlands. For this purpose, the paper calculates the expected change in the number of cases of *Salmonella* with the change in policy. The paper uses COI method for analyzing the costs and benefits. The total costs are a sum of direct costs, indirect costs calculated using two different methods— friction cost method and human capital method and VSL were estimated for gender and age distribution of registered death cases due to *Salmonella*. The costs for surveillance and eradication of *Salmonella* the entire chain, from food to feed is divided between the producers and the government. Monte Carlo simulations were used to account for uncertainty and variability in the model.

The analysis shows that it would not be cost-effective to change the current strategy as in both the scenarios a change leads to negative effects. The authors argue that these costs are biased. The human capital approach used to measure indirect costs gives higher estimates of the productivity losses as it assumes that the sick employee cannot be replaced by a temporary one and therefore all the productivity in the economy is lost. On the other hand, friction cost approach assumes that a sick worker can be replaced by a temporary one in case of long-term illness. The costs incurred by the feed, animal and food producers are an underestimation. This is because the indirect costs arising due to supply shortages, hygiene measures and additional hours of labor are not accounted for. Costs incurred due to *Salmonella* presence in herds were not included as these depend on the number of farms tested positive and the steps taken by those to eradicate *Salmonella*. Many costs in the alternate policy scenario are difficult to predict, thus not included. If the alternative scenarios lead to decrease in costs for retailers the consumer and producer surpluses due to decreasing costs could not be calculated. Unlike Andersen and Christensen (2008) computable general equilibrium model is not used, hence the long term and economy-wide impact of alternative policy scenarios cannot be estimated. Also, time sensitive analysis of the CBA is not undertaken so much cannot be said about the long-term impact of the alternative scenarios.

Table 2.1: Components of COI and HALY found in literature

COI (Monetary valuation)	HALY (Non-monetary valuation)
Direct costs:	Disability Adjusted Life Years
Hospitalization	Years of life lost
Medication	Years lost due to disability
Physician	Quality Adjusted Life Years
Laboratory test	
Indirect costs:	
Productivity loss due to own-illness	
Productivity loss due to caregiving	
Direct non-health costs:	
Travel costs to seek medical help	
Lost leisure time	
Industry costs	
Public Agency costs	

2.5. Conclusion

Foodborne diseases are rising worldwide and it is important to study their impact on the economy to help decision making for policies. Monetary and non- monetary methods are used to calculate the impact of foodborne diseases on the economy. The COI method estimates monetary costs associated with the diseases. Most of the studies take into account direct and indirect costs. Economic analysis of foodborne illnesses and food-pathogen combinations have been studied in more detail for the US compared to Canada. Many European countries have annual monetary and non-monetary estimates for the foodborne pathogen. Few papers have studied benefits of alternative *Salmonella* policies for Europe, such research is required for North America. COI studies have been the subject of much critique and discussion, and the usefulness of COI studies as decision-making tools has been widely debated in the literature (Hodgson and Meiners 1982).

There are challenges while calculating COI for *Salmonella*. These include estimating the true incidence of *Salmonella* as many cases of illness do not seek medical help (Buzby and Roberts 2009). Another problem is distributing the number of cases into different categories of severity which in turn impacts the resource use by each case of illness, as not much factual data is available. While calculating costs and health adjusted estimates, it is important to make a distinction between nontyphoidal *and* typhoidal *Salmonella* as the number of cases and type of resource used for treating the two diseases are different.

There are areas which require further research so that cost estimates can be more comprehensive. Cost estimates for federal and provincial agencies involved in the outbreaks are not calculated by most of the studies (Majowicz et al. 2006, Henson et al. 2008, Hoffmann et al. 2012). Many producers undertake food safety management practices voluntarily or involuntarily such producer costs are difficult to estimate and information about the same has been sparsely included in studies. Disease specific disability weights are not available for Canada, articles in the past have used weights from a study in Netherland (Ruzante et al. 2010, Thomas et al. 2015b). CGE analysis is rarely seen in the literature, this analysis is important for understanding macroeconomic impacts. Many technological advances like Whole Genome Sequencing for outbreak detection and bacteriophage developments for fresh produce to eliminate foodborne illness causing pathogens are making an impact on the food safety policies. There is a need to study the impact of such advancement in the technologies and analyze the cost and benefit from them.

Chapter 3: Methodology and Data

3.1. Introduction

This chapter provides the description of the methodology, along with the sources of data employed, for calculating the costs from PFGE and the net benefits from WGS. It also describes the methodology for measuring the macroeconomic impact of the same on the economy of Canada. The Cost and Benefit Analysis (CBA) is used for estimating the microeconomic benefits from WGS. The CBA includes Cost-of-Illness (COI) and Health Adjusted Life Years which provide monetary and non-monetary estimates respectively. The COI is measured for PFGE. Then the net benefits from WGS are calculated accordingly. Input-Output analysis is used to measure the macroeconomic impacts. The change in industrial output, GDP and employment is measured for different scenarios. The chapter is divided into two parts: CBA and the input-output analysis.

3.2. Cost and Benefit Analysis (CBA)

Estimating the costs and benefits from the technologies involves following steps. First, the number of *Salmonella* illnesses from fresh produce, poultry and eggs in Canada are estimated. Then, these estimates of number of cases are used to calculate COI, Disability Adjusted Life Years (DALY) and Quality Adjusted Life Years (QALY) from current technology used to detect outbreaks and costs to the producers from implementing *Salmonella* detection strategies. Afterwards, net benefits from adopting the new technology, WGS, are estimated. Since, the clinical symptoms of typhoidal *Salmonella* are different from nontyphoidal *Salmonella* only costs for nontyphoidal *Salmonella* are accounted for.

3.2.1. Estimating the number of illnesses

To estimate the total number of illnesses Canadian Notifiable Diseases Online database is used to extract the annual number of *Salmonella* illnesses reported in Canada from 2000-2015 (Public Health Agency of Canada). Estimates of illnesses which are domestically acquired and attributable to food as a source are calculated based on Thomas et al. (2013). Under-reporting and under-diagnosis multiplier is then applied to account for patients who are not accounted for in the surveillance system. The multiplier is required because patients that experience mild symptoms do not seek medical care, those who seek medical care are not always tested for disease causing pathogen and not all samples are tested for each pathogen. Hence, a multiplier is required for estimation of true number of illnesses from disease (Frenzen et al. 1999, Buzby et al. 1996, Thomas et al. 2013). Ravel et al. (2009) estimate that 29 of the final *Salmonella* illnesses are attributable to fresh produce, 15 and 5 percent to poultry and eggs, respectively, in Canada. These estimates are used to calculate the illnesses attributable to respective food vehicles in the study.

Total number of illness attributable to fresh produce in Canada

= Average annual number of domestically acquired foodborne *Salmonella* infections per year

× Multiplier for under-reporting and under-diagnosis

× Percentage attributable to fresh produce

× Percentage attributable to poultry

× Percentage attributable to egg

For calculating the monetary and non-monetary estimates it is important to divide the total number of cases according to different health outcomes. So, the final estimates of number of illnesses are then divided into four categories of health outcomes: no doctor visit (mild cases of illnesses which do not seek medical intervention), doctor visit (outpatient cases of illnesses which do not require hospitalization) and hospitalized cases (inpatient cases that are severely ill). The hospitalization cases are further divided into two categories: first, hospitalizations which lead to recovery and second, hospitalization which lead to premature deaths. Disease outcome tree which specifies the duration of the disease and likelihood of each health outcome is derived from Hoffmann et al. (2012). The probability of death from *Salmonella* in Canada from total hospitalizations is derived from Thomas et al. (2015a).

3.2.2. Cost of Illness estimates

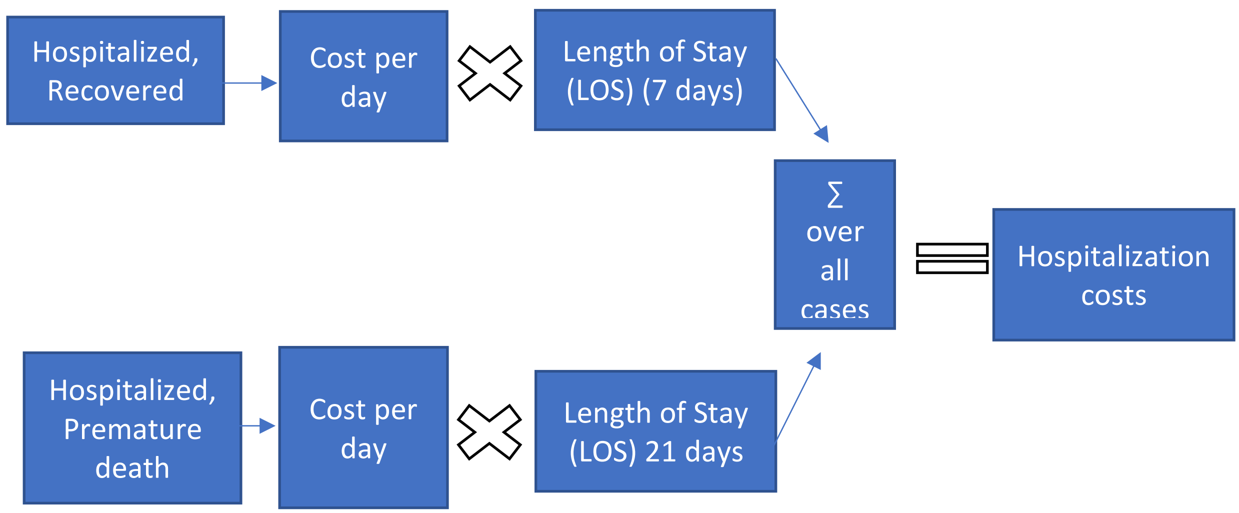
Cost of Illness identifies and measures all the economic costs associated with foodborne illnesses such as direct healthcare costs, indirect costs, federal costs and intangible losses (Byford et al. 2000). The direct healthcare costs include medication costs, hospitalization costs (excluding physician costs), physician costs including cost of consultation with specialists and laboratory test costs of blood and stool samples.

3.2.2.1 Direct healthcare costs

Direct healthcare costs are costs incurred to treat the medical condition. The direct healthcare costs are calculated by multiplying the cost per patient in each category with number of patients. The direct healthcare costs can be formally represented as $\sum_l \{\sum_i m_i \times p_i \times mc_i\}_l$, where m is the number of cases, p is the service being estimate and *mc* is the unit cost of service being estimated, summed across i healthcare services and l health categories (Kemmeren et al. 2006). The direct healthcare costs are divided into hospitalization costs, physician costs, medication costs and laboratory costs.

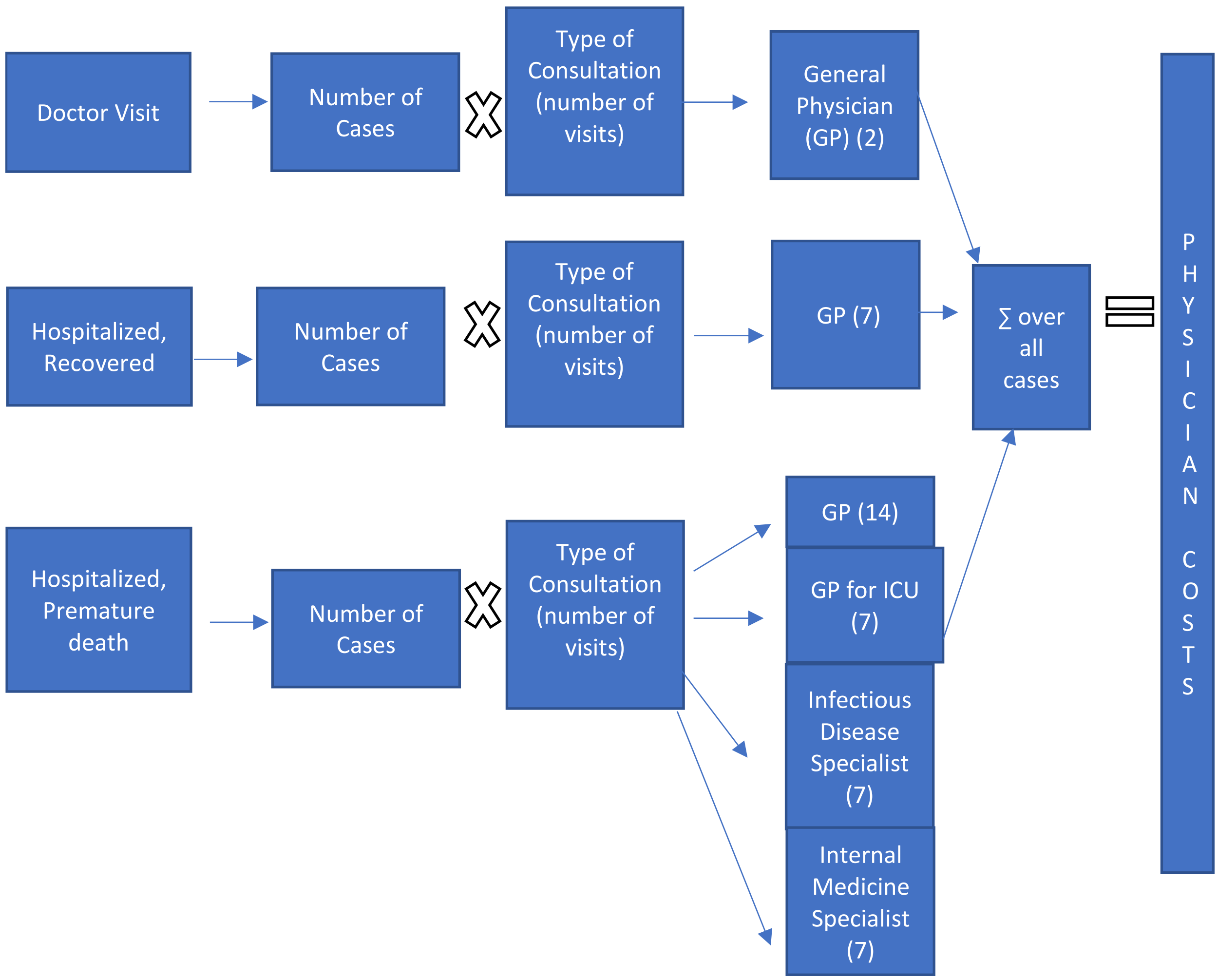
Hospitalization cost. The hospitalization costs are calculated for patients who were hospitalized (recovered and premature deaths) due to *Salmonella* and are based on the length of stay and per day cost at the hospital. Patient Cost Estimator (PCE) developed by Canadian Institute for Health Information was used to calculate the hospitalization costs per person. PCE provides estimates for the average costs of various services provided by hospitals to inpatients in acute facility care across Canada expect physician costs (Canadian Institute of Health Information 2016). PCE divides all the patients according to Case Mix Groups (CMG). Each CMG represents a unique type of treatment provided to the patient at the facility. The cost of standard hospital stay is based on the estimates provided by the hospital, the intensity of resource use and length of hospital stay. The PCE includes costs for medication and diagnostic services provided to the inpatients. For cases that were hospitalized and recovered Non-Severe Enteritis (CMG 249) was used to estimate the costs. For patients that died after hospitalization Severe Enteritis (CMG 250) was used. Since PCE provides costs per patient for average length of stay according to different age groups, cost per day was calculated and multiplied by length of stay which was assumed in the disease tree for the two categories- hospitalized and recovered and premature death (Figure 3.1).

Figure 3.1: Calculation of hospitalization costs



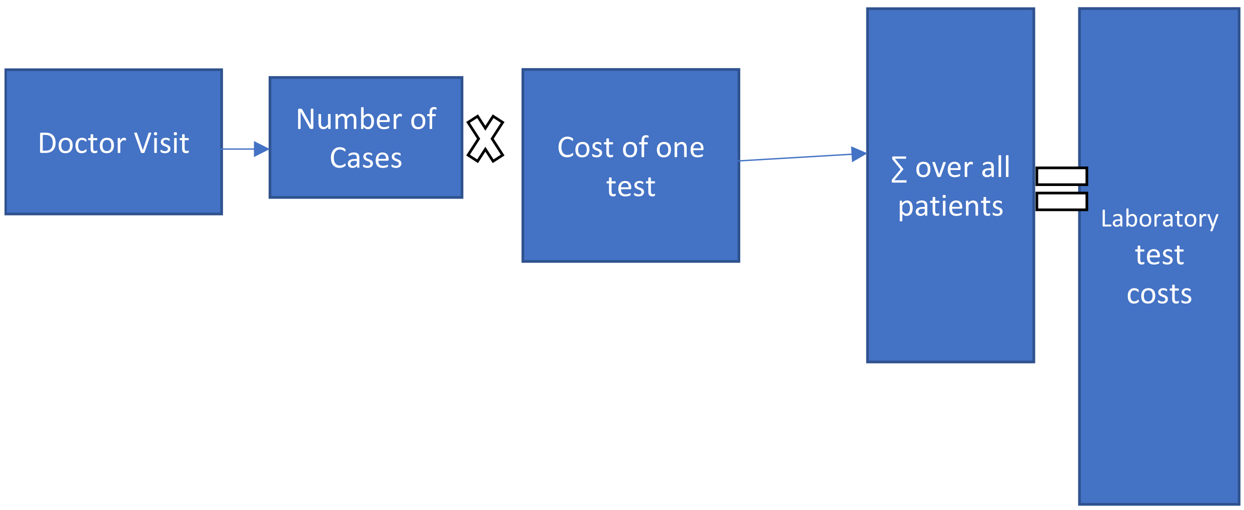
Physician costs. The physician costs are based on average physician fee in Canada and number of visits per patient. The average physician fee in Canada is calculated by taking an average of physician benefits listed for the four provinces: Ontario, British Columbia, Saskatchewan and Alberta (Alberta Medical Assosiation 2017, Ministry of Health 2016, Government of Saskatchewan 2017, Ministry of Health and Long Term Care 2015). The outpatient physician fee is calculated assuming physician consultation takes place twice within the duration of illness. The physician costs for inpatients are calculated separately because benefits for physicians who treat inpatients are different than those of outpatients. It is assumed that consultations for inpatients take place seven times during the illness. The physician fee for patients who die prematurely are calculated assuming services from general physician, internal medicine doctor and an infectious disease doctor are required. Further, it is assumed that general, internal medicine and infectious disease physicians visit the patient twenty-one times and seven times each respectively (Figure 3.2).

Figure 3.2: Calculation of physician costs



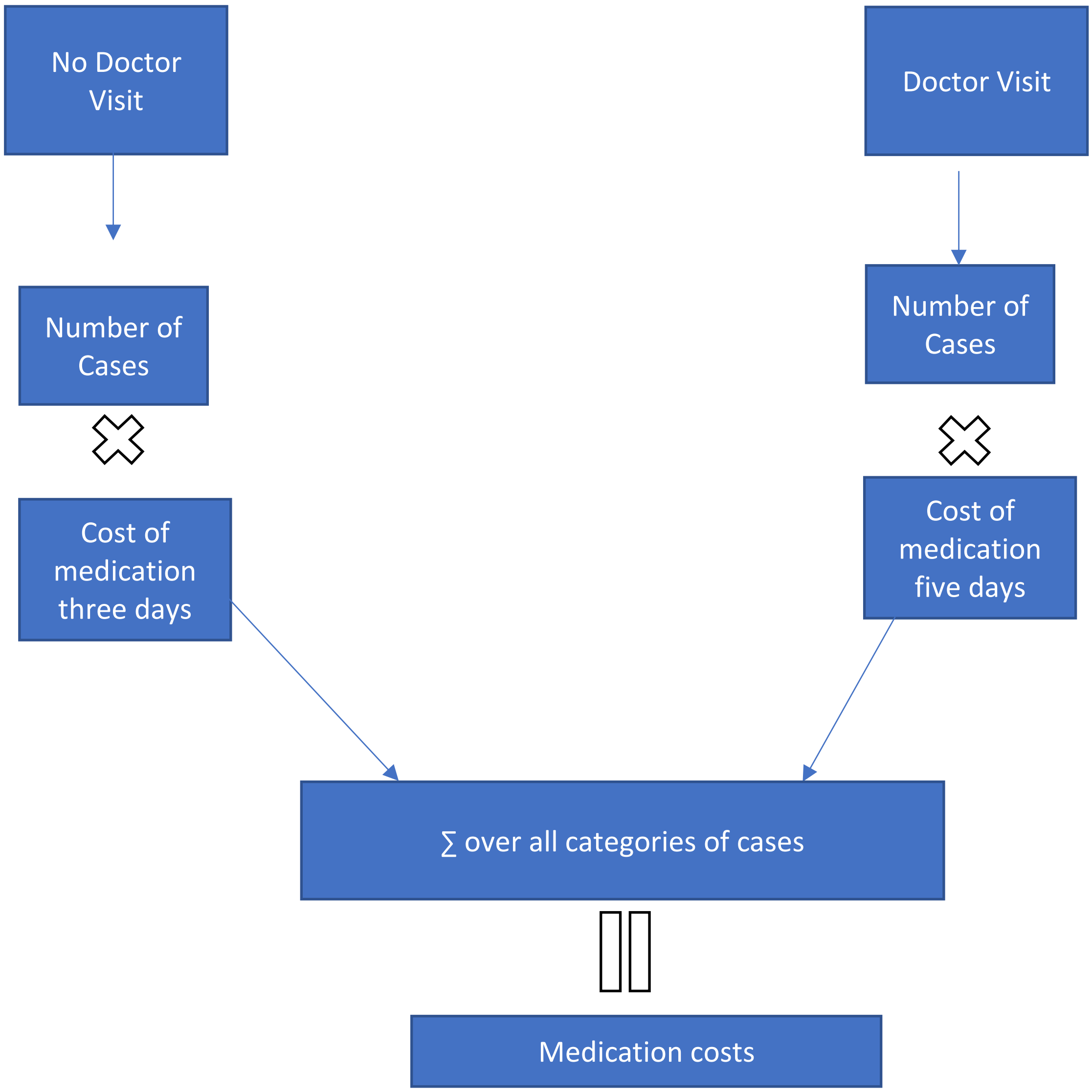
Laboratory test costs. Laboratory costs are incurred due to stool and blood tests conducted to determine the type of pathogen causing the disease. The cost for laboratory tests are based on average cost of the test and number of times the tests are conducted. The average cost of laboratory test is estimated using laboratory benefit schedule of Ontario, British Columbia and Saskatchewan. Figure 3.3 shows the calculation of laboratory test costs for patients who visited the doctor but were not hospitalized. It is assumed that laboratory tests are conducted once for out-patients. The costs for laboratory test for the patients who were hospitalized (recovered and died prematurely) are already included in the PCE. Hence, they are not calculated again to avoid double counting.

Figure 3.3: Calculation of laboratory test costs



Medication costs. Medicines like antacids, antinausea, analgesics, antidiarrheal and, in severe cases, antibiotics are used to treat patients suffering from *Salmonella*. Medication costs are calculated based on number of days the medication is required and type of medication (Figure 3.4). An average medication cost is calculated taking into consideration costs for Ontario Drug Benefit Formula/Comparative Drug Index and British Columbia Drug Formulary (Ontario Drug Benefit Formulary 2017, British Columbia Ministry of Health 2017). For people who do not visit the doctor and those who visit the doctor, an average cost of medicines (except antibiotics) and an average cost of antibiotics along with other medications is estimated.

Figure 3.4: Calculation of medication costs

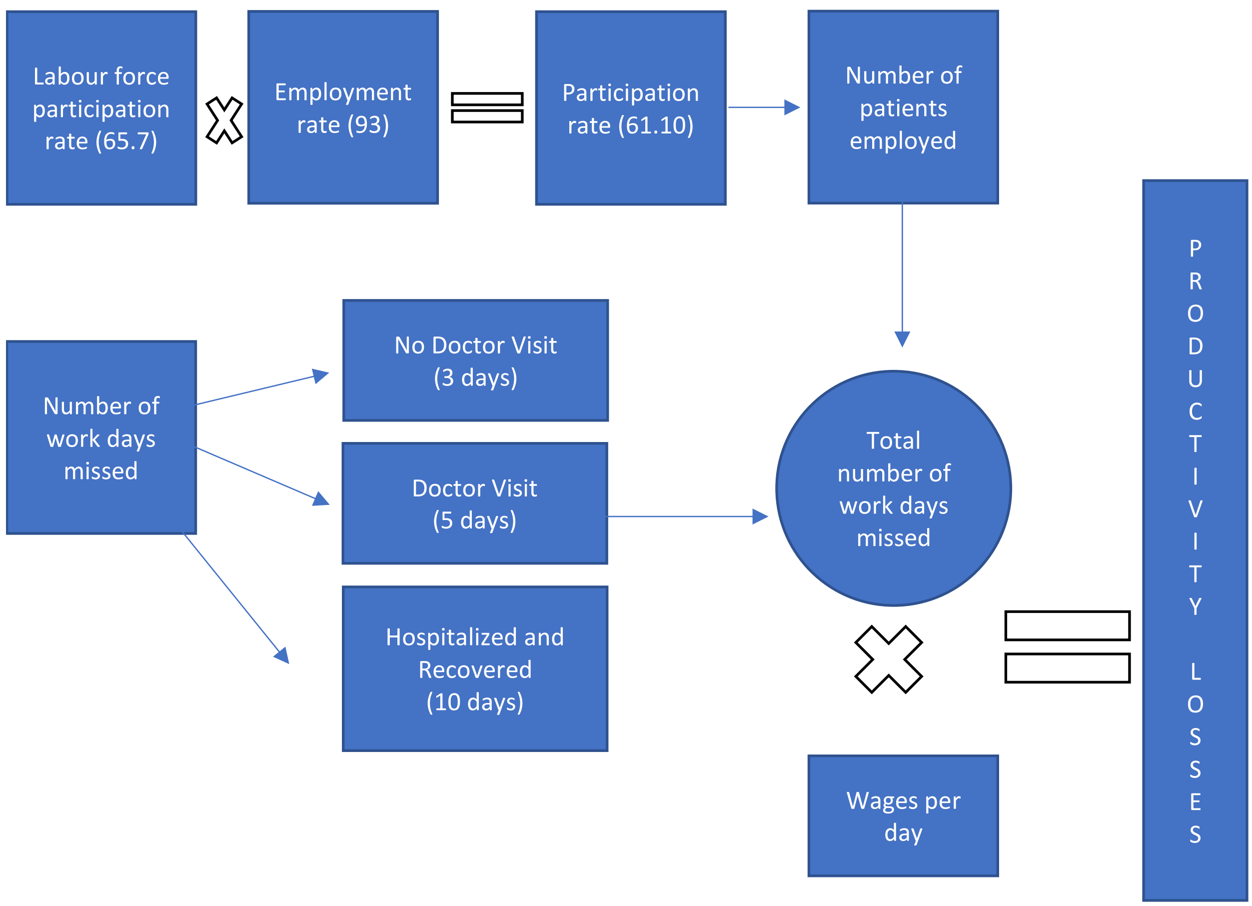


For individuals who do not visit the doctor a total of three days of medication (thrice every day) is assumed. For individuals who visit the doctor, a total of five days of medication (thrice every day) is assumed. The costs for medication provided to the patients who were hospitalized (recovered and died prematurely) are already included in the PCE. Hence, they are not calculated again to avoid double counting.

3.2.2.2 Indirect costs

Indirect costs arise due to missed work days which lead to decreased productivity in the economy. Indirect cost is divided into two categories a) productivity loss due to own-illness (ages 15 & above) and b) productivity loss due to caregiving for a child (ages 0-14). The productivity loss is calculated using a modified frictional cost method, for all categories except premature death, by multiplying daily wage loss by number of work days missed for own-illness and care-giving, adjusted for employment rate. Loss due to caregiver is calculated by assuming one sick day for a child (ages 0-14) is equal to one work day missed by an adult. The proportion of people employed out of total number of patients is calculated by multiplying the total number of patients with labor force participation rate and employment rate for Canada (Statistics Canada 2017b). Assumptions made to estimate the productivity loss are as following: a) those who did not visit the doctor missed three days of work, b) those who visited the doctor missed five days of work, c) those who were hospitalized and recovered missed ten days of work and d) none of the workdays missed lay on holidays or weekends. Hence, all the work days missed resulted in productivity loss. The wage rate is calculated by fitted the average minimum daily wage rate ($92.52) and the mean daily wage rate ($193.52) in Canada (Statistics Canada 2017c) to a lognormal distribution. The daily wage loss is estimated to be $224.39 for all categories. The wage rate per day is then multiplied by the number of work days missed by different category of patients. Figure 3.5 shows how productivity losses due to missed work days is calculated. The productivity loss can be formally represented as $\sum_l (\sum_k s_k \times u_k \times v)_l$,where s is the number of cases, u is the duration of work days missed, v is the estimated wage per day and k is the health outcome (Kemmeren et al. 2006).

Figure 3.5: Productivity losses due to work days missed



3.2.2.3 Value of Statistical Life

Value of Statistical Life (VSL) estimates the economic loss from premature death. VSL shows the willingness to pay for preventing one death. Chestnut and De Civita (2009) review the literature and recommend the VSL based on a comprehensive review of revealed and stated preference studies on loss of life in Canada. The value of life is then multiplied by number of deaths to get the final estimate. This VSL does not depend on the age at death or the health state. The PERT distribution is applied to calculate the mean VSL per person. The mean VSL per premature death is calculated using the following minimum ($4,092,259.23), most likely ($7,599,909.99) and maximum values ($11,107,560.76).

3.2.2.4 Federal costs

Federal agencies monitor and control foodborne related outbreaks. The tasks include investigating the cause of the outbreak including collection of data from hospitals, laboratories, epidemiological investigations, making food safety related recalls and setting quality standards. Annual operating costs for all federal agencies involved with *Salmonella* outbreaks are divided into four components a) Health Canada, b) Public Health Agency of Canada: National Microbiology Laboratory (NML) c) Public Health Agency of Canada: other and d) Canadian Food Security Agency(CFIA). The costs for Health Canada are derived from the costs given by (Thomas et al. 2015b). Costs for PHAC: NML are divided into two parts a) consumable costs and b) staff costs. The costs are estimated for two scenarios for NML: 1) the current technology of Pulsed-field gel electrophoresis (PFGE) and 2) new technology of WGS. The consumable cost and time requirement for wet lab and analysis per isolate for PFGE is estimated to be $219.99- $297.88 per isolate by PulseNet Canada (Reimer et al. 2016). A uniform distribution is used to estimate the mean cost of consumables. The consumable costs and time requirement for wet lab and analysis per isolate for WGS are collected from expert opinion (Bekal 2017). The cost of staff (wet lab and analysis) per hour is calculated using Thomas et al. (2015b) estimates of staff costs at NML. Staff costs are assumed to remain the same for PFGE and WGS as no data is available. PHAC also runs other departments such as Outbreak Management Division, Enteric Surveillance and Population Studies Division and Center for Emergency Preparedness and Response Division which help in outbreak investigation. The costs for these are clubbed under PHAC: Other and the costs for these divisions are based on estimates provided by Thomas et al. (2015b).

The estimated cost for CFIA is based on the annual expenditure reported for food safety program for fresh fruits and vegetables, poultry and egg in CFIA Departmental Performance Report (2014-15) (Canadian Food Inspection Agency 2015). The mandate of the programs is to verify that products meet all the health and food safety requirements. The cost for the food safety program for poultry and meat is summed together. The costs pertaining to poultry are assumed to be half of that of the subprogram for poultry and meat. It also checks for unfair market practices in labelling and quantity requirements of pre-packaged fruit and vegetable products.

Costs for Health Canada and CFIA are assumed to remain the same after the technology change. It is assumed that with improvement in technology the implicated food vehicle will be detected earlier and there will be a lot more recalls, implying that the decrease in time required to recall food items from the market is offset by the increase in work due to more recalls and identification of outbreaks.

3.2.2.5 Producer costs

Producer costs are incurred to detect *Salmonella* in fresh produce before being sold in the market. Tests are conducted during pre-harvest and harvest periods to check for presence of *Salmonella* in the produce. Randomized sample testing is done for this purpose. One of the major salad producers in Quebec was contacted to get estimates of the costs annually for 2015. The producer conducts tests in its own laboratory and some samples are sent to external laboratory. Samples are sent to external laboratory when they are tested positive in the company laboratory.

At the external laboratory, there are several tests that are conducted like Bax test, MFLP-49 test, Rapid test and Detection test. The cost of testing at the company laboratory is $8 per sample. The cost of testing at the external laboratory ranges from $ 17.50 to $ 35.50. The cost of sending the samples (postal costs) to the external laboratory is $110. The high transportation cost is due to the fact the sample needs to be sent to the external laboratory the same day. The costs for poultry and egg producers is not available at this time.

3.2.3. Health Adjusted Life Years

Health Adjusted Life Years (HALY) is a broad term used for metrics which measure the decline in full health due to morbidity and total life years lost due to mortality from a disease (Buzby and Roberts 2009).

Disability Adjusted Life Years. Disability Adjusted Life Years (DALY) is a metric which adds number of life years lost due to mortality (YLL) and number of life years lost due to morbidity (YLD) (World Health Organization 2015). It is a metric which is internationally accepted by World Health Organization (WHO).

DALY= YLL + YLD, where YLL $= \sum_l d_l \times e_l$, Years of Life Lost (YLL) equals summation of deaths *(d)* due to health outcome *(l)* of a disease multiplied by expected years of life remaining at death *(e).* The expected life expectancy is calculated using average life expectancy in Canada and YLD $= \sum_l n_l \times t_l \times w_l$,Years Lost due to Disability (YLD) equals summation of number of cases *(n)*, duration of illness *(t)* multiplied by the applicable disability weights *(w)*. The disability weights are based on a WHO report on DALYs estimates from all around the world for *Salmonella* (World Health Organization 2015).

Quality Adjusted Life Years. Quality Adjusted Life Years (QALY) losses are calculated based on disease outcome trees which specify the probability of different health states of a disease and duration of illness for each of the health state and Health Related Quality Loss weights (HRQL). QALY loss is basically the difference between the baseline HRQL weight and HRQL for the specified health state (Batz et al. 2014). The QALY loss from premature death is calculated differently from other health states because the HRQL for premature deaths is zero. QALY weights per case are derived from Hoffmann et al. (2012).

3.2.4. Uncertainty analysis

There is uncertainty associated with the number of cases of *Salmonella* and valuation of resource. This uncertainty arises due to various assumptions made about structural relations and parametric evaluations of different resources. PERT distribution is used to define various cost inputs in the model and obtain a mean estimate and 90 percent confidence interval. @Risk add-in software from Palisade corporation for MS-Excel is used to run Monte Carlo simulations.

3.2.5. Reduction in number of illness due to WGS

WGS is an effective tool in detection of *Salmonella* in food products. Introduction of WGS there will lead to early detection of *Salmonella.* This in turn will lead to reduction in number of illnesses. The change in number of cases from *Salmonella* is accounted by taking into consideration two outbreaks a) the 2013-2014 sprouted chia seed outbreak in BC, ON and QC and b) poultry related outbreak in 2016. In the first case if the recall would have taken place three months prior to the actual recall then 52 less illnesses (82 percent of total illnesses) would have occurred (Public Health Agency of Canada). In the second case, if the recall would have taken three months after the start of the outbreak then the number of illnesses would have reduced by 97 (89 percent of total illnesses) (Public Health Agency of Canada). After considering the above two estimates, a modest estimate of 70 percent reduction in number of illnesses due to implementation of WGS is assumed.

3.3. Methodology: Input- Output Model

3.3.1. Introduction

An input-output model is built from data pertaining to an economic region- a nation, a region or a state (Miller and Blair 2009). For the current analysis, inter-industry flow of goods and services is tabulated for Canada. Canada follows a rectangular input-output model. These are known as the Supply-Use tables and are divided into industries and commodities. The latest Supply Use tables by Statistics Canada were released in November 2016 for the reference year 2013. The study uses these tables to analyze the impact of benefits from WGS at a macro level (Statistics Canada 2017a).

The Supply table consists of 488 commodities, 236 industries, international imports, total supply at basic prices, trade margins, transportation, gas and storage margins, total supply at purchasers' price. The Use table consists of 236 industries and 488 commodities at the basic prices which make up the intermediate input demand and 98 categories of final demand by consumer, final demand by non-profit institutions serving households' final consumption expenditure,8 categories of final demand by the government, 162 categories of gross capital formation, change in inventories of finished goods and goods in process, changes in inventories of raw material and goods purchased for resale, international export, international re-exports. The Supply table traces the production of commodities by domestic industries and the Use table traces their use as intermediate inputs in production of other goods or as final demand for consumption, investment and exports (Statistics Canada 2016a). Supply-Use table help in detailed analysis of impact of exogenous change in final output demand, change in output of one or more industries, change in one or more product output etc. (Statistics Canada 2016b).

3.3.2. Accounting framework for Canadian Supply- Use Tables

The following equations describe the mathematical manipulations required for measuring the impact of changes in the economy due to WGS on industrial output, GDP and employment (Miller and Blair 2009).

$V = v_{ij}$ is a matrix of the values of commodity outputs. Each row in the matrix represents the different commodities produced by an industry domestically. Each column j represents the different industries that produce a commodity i domestically. This is known as the supply matrix. This matrix is transposed for coherent matrix algebra: $V' = v_{ji}$

$U = u_{ij}$ is a matrix of the values of intermediate commodity inputs used in further production. Each row shows the distribution of different industries that use a commodity as input. Each column shows the distribution of i commodities used as input by an industry j.

$F = f_{ij}$ is a matrix of values of commodity which form the final demand by households, government and non-profit organizations serving households and gross capital formation of businesses. Each column shows i commodities purchased by category j.

The rectangular model is based on the following accounting equations (Miller and Blair 2009, Mukhopadhyay and Thomassin 2011):

$q = Bg + e$ (1)

where $g_j = \sum_j v_{ji}$ and $q_i = \sum_j v_{ji}$

$q = m \times 1$ vector, where q is total commodity output; m is the number of commodities.

$B = m \times n$ matrix, where B is the value of commodity inputs per $1 of industry output also known as industry technology coefficient; m is the number of commodities; n is the number of industries.

$g = n \times 1$ vector, where g is the value of total industry output.

$e = m \times 1$ vector, where e is the vector of final demand (without imports).

Equation 1 shows that the total output is the sum of intermediate and final demand, where B relates the level of industrial output to intermediate demand for commodities for production.

$g = Dq$ (2)

$D = n \times m$ vector, where D is the market share coefficients; m is the number of commodities; n is the number of industries.

$q = m \times 1$ vector, where q is total commodity output.

$g = n \times 1$ vector, where g is the value of total industry output.

multiplying D both sides and solving for g provides equation for the model of domestic gross output by industry

$g = (I - DB)^{-1}\, De \quad (3)$

Equation 3 shows the dependence of output on final expenditure. $(I - DB)^{-1}\, D$ is the impact matrix which estimates the direct and indirect effects of a change in commodity production or demand on the economy.

Equation 3 can be modified into following equation to account for leakages such as imports, withdrawals from inventories and scrap metals.

$$g = (I - D\,(I - \hat{u} - \hat{a} - \hat{e})B)^{-1}\, D\,[(I - \hat{u} - \hat{a} - \hat{e})f + (I - \hat{u})E + (I - \hat{a} - \hat{e})\,X\,] \quad (4)$$

$\hat{u}$ is a diagonal matrix of imports to commodity use.

$\hat{a}$ is a diagonal matrix of inventory withdrawals to commodity use.

$\hat{e}$ is a diagonal matrix of government production to commodity use.

E is a vector of re-exports.

f is a a vector of final demand excluding exports, re-exports, imports, government production and withdrawals from inventory.

X is a vector of commodity exports.

From equation 4 $(I - D\,(I - \hat{u} - \hat{a} - \hat{e})B)^{-1}$ is an inverse matrix and is called the Leontief inverse. Exogenous shocks can be applied using the above inverse to either an industry specific output or to final domestic expenditure.

3.3.3. Aggregation

Originally the model contains 488 commodities, 236 industries. For the convenience of the analysis 236 industries have been aggregated into 28 industries. Similarly, 488 commodities were aggregated into 120 commodities for both supply and use tables. The aggregated supply and use tables have 120 commodities and 28 industries. The 98 categories of final consumer demand and non-government profit organizations that work for households are combined into a single final consumer demand. The 8 categories of final demand by the government are aggregated into a single final demand by government. The 162 categories of gross capital formation are aggregated into one. Hence, the final demand matrix consists of 120 commodities and final consumer demand, exports, final government demand, gross capital formation and inventory additions.

3.3.4. Direct and indirect effects

The direct effect is change in output of an industry due to a dollar's worth of change in final demand. This will lead to a change in GDP, employment and imports. The indirect effect is the change in the inter-industry purchases due to change in industrial output. This effect shows the chain effect of change in output of all the industries that provide input to other industries. The coefficients for estimation of GDP and employment are provided by Statistics Canada and are used in an aggregated form with 28 industries.

3.3.5. Simulation exercises

CBA estimates the micro level net benefits of WGS for the economy. It is important to measure the impact of these benefits on the economy at a macro level. The net benefits estimated at the micro level will be used to carry out macro level analysis using input-output framework. The input-output analysis describes the interindustry flows and measures how the change in demand/supply of one industry impacts sectoral output, GDP and employment. This will provide economy wide impact of the benefits from WGS. With the introduction of WGS, there will be changes in the direct healthcare cost, indirect costs and federal costs. The input-output framework estimates the impact of these changes on the industrial output, Gross Domestic Product (GDP) and employment. Also, the direct and indirect impact on different industries of the economy is measured, along with the sectoral changes. Four different simulation exercises are carried out and these are described as below.

Scenario 1: This scenario captures the decrease in the total number of days of illnesses. As seen in CBA, introduction of WGS will lead to earlier detection of outbreaks which will lead to less number of cases of *Salmonella*. This leads to increase in productivity. This increase in the total income leads to increase in consumer expenditure. The total final consumer demand will increase which should rise the industrial output, GDP and employment due to the interindustry effect.

Scenario 2: This scenario captures the impact of decrease in direct healthcare costs. As less number of people become ill the direct healthcare costs, i.e. the costs associated with medical intervention, decreases. This leads to a decrease in government expenditure on healthcare services. The impact of the decrease is estimated by changing aggregated final government demand. This scenario will provide the impact of decrease in government expenditure on hospitalization services on industrial output, GDP and employment. It is expected that with the decrease in public spending the industrial output, GDP and employment will contract. It should be noted that the decrease in employment is because of the interdependence of the macro variables[8]. Though, in practice the demand for health care services exceeds the supply. Hence, decrease in employment should not be expected. In the framework, changes in a

[8] Accounting framework shows the linkages between final demand, output and employment.

variable of an industry will affect other industries as well. In reality however, if the number of illnesses reduce the healthcare expenditure is not expected to change, in the short-run.

Scenario 3: This scenario captures the decrease in federal expenditure due to the introduction of WGS. As WGS is introduced it is estimated that the operational costs for National Microbiological Laboratory (NML) will be reduced. The impact of the reduction in federal expenditure is addressed by changing the final government demand. This should lead to decrease in output, GDP and employment. Similar to scenario 2, there should be no reduction in employment, in practice, as labour will be shifted from projects concerning Salmonella to other projects.

Scenario 4: To estimate the impact of all the above changes the three scenarios are combined. This scenario provides a comprehensive measure of impact of WGS on the economy.

Chapter 4: Results and Discussion

4.1. Introduction

The primary results of this study are the annual COI estimates for *Salmonella* from various food vehicles, the net benefits from changing the current outbreak detection technology to WGS and macro-economic impact using input-output framework. Intermediate results show the various components of direct healthcare cost, indirect costs, federal costs and producer costs according to the severity of illness (no doctor visit, doctor visit, hospitalized and recovered and premature death). The Intermediate results also include the impact on industrial output, GDP and employment in Canada due to adoption of WGS are measured using input-output analysis. The industries affected the most according to the input-output analysis are also identified in the study. The chapter is divided into two sections. The first section discusses the results from the CBA and in the next section the results from the input-output analysis are discussed.

All the results are in Canadian dollars 2013 prices.

4.2. Cost and Benefit Analysis

This section measures the microeconomic impact from adoption of WGS. The results for estimated number of illnesses and the costs arising from them are discussed in the following section. The COI for PFGE and WGS is calculated to estimate the net benefits from them. Since, the clinical symptoms of typhoidal *Salmonella* are different from nontyphoidal *Salmonella* only costs for nontyphoidal *Salmonella* are accounted for.

4.2.1. Estimated number of illnesses and COI

The estimated number of *Salmonella* illnesses from fresh produce, poultry and eggs in Canada are 27,865, 14,413, 4,804. Table 4.2.1 shows the estimated number of *Salmonella* illnesses in Canada from 2000-2015.

Table 4.2.1: Number of *Salmonella* illnesses in Canada 2000-2015

Year	Number of reported *Salmonella* illnesses	Domestically acquired Ratio	Number of Domestically acquired illness	Foodborne acquired ratio	Illnesses domestically and food related
2000	5,691	0.74	4,211.34	0.8	3,369.07
2001	6,074	0.74	4,494.76	0.8	3,595.80
2002	5,968	0.74	4,416.32	0.8	3,533.05
2003	5,065	0.74	3,748.10	0.8	2,998.48
2004	5,098	0.74	3,772.52	0.8	3,018.01
2005	6,007	0.74	4,445.18	0.8	3,556.14
2006	5,478	0.74	4,053.72	0.8	3,242.97
2007	6,146	0.74	4,548.04	0.8	3,638.43
2008	6,076	0.74	4,496.24	0.8	3,596.99
2009	5,866	0.74	4,340.84	0.8	3,472.67
2010	7,020	0.74	5,194.80	0.8	4,155.84
2011	6,622	0.74	4,900.28	0.8	3,920.22
2012	6,832	0.74	5,055.68	0.8	4,044.54
2013	6,190	0.74	4,580.60	0.8	3,664.48
2014	7,635	0.74	5,649.90	0.8	4,519.92
2015	7,731	0.74	5,720.94	0.8	4,576.75
TOTAL	99,499		73,629.26		58,903.40
Average annual number of domestically acquired foodborne *Salmonella* infections per year (3681.46)					
× Multiplier for under-reporting and under-diagnosis (26.1)					
× attributable to fresh produce (0.29)					
× attributable to poultry (0.15)					
× attributable to egg (0.05)					

Notes: a) Thomas et al. (2013) estimates that 26 percent of Salmonella cases reported in Canada are travel related and 20% of the total Salmonella are from sources other than food. b) Thomas et al. (2013) estimates the under-reporting and under-diagnosis multiplier to be 26.1 for Salmonella in Canada. c) Ravel et al. (2009) estimates that found that in Canada, from 1976 to 2005, there were 6,908 foodborne outbreaks out of which only in 2107 (40 percent) outbreaks the causative agent food vehicle was recognized. Out of these 79 outbreaks has recognized Salmonella as the causative agent and the food vehicle.

These estimates are based on the annual number of illnesses adjusted for under-reporting and under-diagnosis multiplier and are attributed to fresh produce, poultry and eggs for Canada. It is important to classify the number of illnesses according to the severity of illnesses so that the resources used can be classified accordingly.

Table 4.2.2 shows the illnesses from various food sources, the probability distribution and number of illnesses divided according to the severity (no doctor visit, doctor visit, hospitalized and recovered, and premature death). 90 percent of individuals who get sick from *Salmonella* recover without visiting a doctor and only 0.018 percent of individuals die from it. This shows that *Salmonella* is generally a mild disease but it affects a large number of individuals.

Table 4.2.2: Distribution of total illnesses into different categories

Branch	Health state	Probability	Duration of Illness assumed (Days)	Cases		
				Fresh Produce	Poultry	Eggs
Total				27,865	14,413	4,804
1	No doctor visit	90.92	3	25,334	13,104	4,368
2	Visit doctor	7.20	5	2,006	1,037	345
3	Hospitalized, severe	1.88		523	270	90
3.a	Hospitalized, recovered	1.862	7	514	268	89
3.b	Hospitalized, premature death	0.018	21	10	2	1

Note: The values have been rounded up in the table. Hence, might not add up the total.

4.2.2. Direct healthcare Costs

The direct healthcare costs measure the costs associated with the medical intervention. This forms a significant component of COI estimates. The direct healthcare costs are divided into hospitalization costs, physician costs, medication costs and laboratory costs. Table 4.2.3 shows the hospitalization costs for patients who were hospitalized and recovered and those who died prematurely. It shows the length of stay at the hospital, cost for each patient and PERT distribution for each category. The costs per day for patients who die prematurely is 25 times of those who recover after hospitalization. This is because it has been assumed that premature deaths are a result of severe enteritis and different resources, like ventilator, IV fluids etc., are used to treat severe cases making the costs higher than that of non-severe cases. Table 4.2.4 shows the physician cost for each category of illness, number of visits for each category and PERT distribution. The physician cost increases with the severity of illness as the specialized consultants required for the treatment increase with the severity[9].

Table 4.2.3: Hospitalization costs from PFGE

Category	Cost per day ($)	LOS (days)	Cost per patient ($)	PERT	
Hospitalized, Recovered	838.75	7	5,871	minimum	3,839,738.06
				most likely	5,119,650.75
				maximum	6,399,563.44
Hospitalized, Premature death	7,232	21	22,667.4	minimum	223,720.22
				most likely	298,293.62
				maximum	372,867.03

[9] For details see section 3.2.2.

Table 4.2.4: Physician costs from PFGE

Category	Number of Consultations	Cost per patient ($)	PERT	
Doctor Visit	2	129.08	minimum	328,179.3
			most likely	437,572.4
			maximum	546,965.5
Hospitalized, Recovered	7	289.73	minimum	189,480.5
			most likely	252,640.6
			maximum	315,800.8
Hospitalized, Premature death	21	4460.22	minimum	44,020.9
			most likely	58,694.5
			maximum	73,368.1

Notes: a) Repeat consultations are valued differently in some of the provinces distinction is made between first consultation and repeat consultation. b) First consultation and a repeat consultation. c) First consultation by a physician and six times repeat consultations. d) General physician visit (first visit and thirteen repeat consultations) fourteen times, seven days of physician visit in the Intensive Care Unit (ICU) seven times.

Table 4.2.5 shows the cost of laboratory tests for different categories of illness and the PERT distribution for the same. The test costs for those who visit the doctor is $32.67 per patient. The total test costs for the same category is $110,748. The test costs for those who were hospitalized are included in the hospitalization costs. Table 4.2.6 shows the medication costs per patient, the number of days of dosage and PERT distribution. The medication costs rise as the severity increases because it is assumed that patients with high severity of illness will be provided higher dosage of medication. For individuals who have been hospitalized and die prematurely, the medication costs are already included in the hospitalization costs. The costs for those who consult a doctor is 4 times of those who don't visit a doctor. The PERT distribution for all types of direct healthcare costs takes into account the uncertainty associated with cost estimates.

Table 4.2.5: Laboratory test costs from PFGE

Category	Number of tests	Cost per patient ($)		PERT
Doctor Visit	1	32.67	Minimum	83,061.5
			Most likely	110,748.7
			Maximum	138,435.9

Table 4.2.6: Medication costs

Category	Number of days of dosage (thrice every day)	Cost per patient ($)		PERT
No Doctor Visit	3	2.95	Minimum	94,760.63
			Most likely	126,347.50
			Maximum	157,934.38
Doctor Visit	5	8.23	Minimum	20,945.39
			Most likely	27,927.19
			Maximum	34,908.98

Table 4.2.7 shows the mean total costs and 90 percent confidence interval of direct healthcare costs such as medication, hospitalization, physician, laboratory tests according to severity of disease. The mean total direct healthcare costs are $6.43 million where hospitalization costs account for 83 percent of the mean total direct healthcare costs. Hoffmann et al. (2012) and Majowicz et al. (2006) also find that hospitalization costs make the largest component of medical costs in USA and Canada respectively. The direct healthcare costs calculated in this study are based on an average of costs from various provinces like Ontario, British Columbia, Alberta and Saskatchewan. To the researcher's knowledge, this is the first study to take into consideration different provinces. Most of the studies in previous literature only consider costs from Ontario (Majowicz et al. 2006, Henson et al. 2008, Ruzante et al. 2010). Though, the direct

healthcare costs are calculated taking an average of costs from four different provinces, still information from some of the provinces like Quebec and Newfoundland is missing. There is scope for improvement in the averages. Additionally, the costs associated with sequelae like reactive arthritis, irritable bowel syndrome and inflammatory bowel disease are not included in the analysis. Also, the travelling costs incurred for seeking medical care are not accounted for in the current study.

Table 4.2.7: Direct healthcare cost estimates of mean total and 90 percent interval, from PFGE

Type of cost	Category	Mean total cost ($)	5%	95%
Medication Costs	No Doctor Visit	126,347	106,716	145,978
	Doctor Visit	27,927	23,588	32,266
	Total	154,274		
Hospitalization Costs	Hospitalization, Recovered	5,119,650	4,324,172	5,915,069
	Hospitalized, Premature death	298,293	251,946	344,638
	Total	5,417,944		
Physician Costs	Doctor Visit	437,572	369,528	505,559
	Hospitalization, Recovered	252,640	213,387	291,893
	Hospitalized, Premature death	58,694	49,575	67,814
	Total	748,907		
Laboratory Costs	Doctor Visit	110,748	93,514	127,955
	Total	110,748		
Total		6,431,871		

4.2.3. Indirect Costs and VSL

Table 4.2.8 shows the mean total indirect cost and VSL. The indirect cost has been divided into two parts: productivity loss due to own illness and productivity loss due to caregiving. The daily wage loss is estimated to be $224.39 per day for all categories. The productivity loss is estimated to be $21.1 million (Table 4.2.8). The indirect cost is almost three times that of direct healthcare cost. The indirect costs might be an underestimate as the mean wage rate is used and actual wage rates can be higher than the mean wage rate. Patients who do not visit the doctor constitute the largest category of productivity loss. Productivity losses are a major component of COI. Majowicz et al. (2006) and Thomas et al. (2015b) find that productivity losses make up for 73 percent of total costs for foodborne illnesses.

Table 4.2.8: Indirect costs: Productivity loss due to own-illness and caregiving and VSL

Type of Cost	Category	Mean total costs ($)
Productivity loss:		
Own-illness	No Doctor Visit	12,624,341.73
	Doctor Visit	1,666,213.16
	Hospitalization, Recovered	857,190.79
	Total	15,147,745.68
Caregiver	No Doctor Visit	4,982,829.44
	Doctor Visit	657,654.57
	Hospitalization, Recovered	338,333.32
	Total	5,978,817.33
Total		21,113,836.16
Value of Statistical Life	Death	98,783,562.02

VSL associated with deaths is $98.78 million (Table 4.2.8). Some of the COI studies for foodborne illnesses in Canada do not account for loss from death (Majowicz et al. 2006, Henson et al. 2008). Hence, VSL is not accounted for in these studies. Thomas et al. (2013) and Hoffmann et al. (2012) also found that the estimates of costs from deaths are high, this is due to high VSL per death both in Canada and US. VSL is not based on the age at death hence the value could be overestimated if mostly older people die from it.

4.2.4. Federal Costs

Three federal agencies are involved with regulating and monitoring food safety in Canada. The cost for them are discussed as follows. Table 4.2.9 shows the cost estimates for NML from PFGE and WGS. Table 4.2.10 reports costs for three federal agencies which are divided into a) Health Canada, b) PHAC and c) CFIA. The time required for subtyping an isolate decrease from 7.1 hours to 1.3 hours for WGS along with the costs of consumables. The costs for PHAC are estimated to be $2.88 million out of which $2.22 million (77 percent) are spent on testing at NML and $652,661 make up the other operating costs at PHAC. The cost for Health Canada is estimated at $224,175. Costs for CFIA is estimated at $158.34 million which makes up for 98 percent of the total federal costs. The costs for CFIA poultry program are high for the year 2015. Though, for later years (2016 onwards) a decrease in expenditure on the program can be seen. The CFIA's costs might be overestimated as some portion of the budget for the food safety program's sub program for fresh fruits and vegetables, poultry and egg is dedicated to verification of labelling and quantity requirements (Canadian Food Inspection Agency 2015). Also, the food safety programs include other pathogens such as *E.Coli, Listeria* etc. Since, it is difficult to divide the costs according to different pathogens, the federal costs might be an overestimate given that CFIA contributes a big part to the costs. Cost estimates for Health Canada are not based on expert opinion (PHAC, Health Canada and INSPQ) but are estimates based on costs arising from one Listeriosis outbreak in Canada (Thomas et al. 2015b). The costs for provincial laboratories involved in testing of clusters and outbreak investigation of *Salmonella* are not included. Also, costs associated with local inspection agencies could not be included due to unavailability of the data.

PulseNet Canada estimates that it will cost approximately $302,837 (USD 250,000) to upgrade each laboratory with WGS (Reimer et al. 2016). PulseNet Canada plans to upgrade thirteen of its laboratories (Reimer et al. 2016). This will cost around $3.93 million for upgradation to WGS. Furthermore, the cost estimates for CFIA and Health Canada are assumed to remain the same after technological change as no data is available about the impact of change on the costs. The opinion on costs and time requirement of WGS for *Salmonella* detection is varied. Expert opinion report on WGS in the European Union states that the median cost is twice (€ 90) of that for PFGE and the median time required is approximately the same for WGS as for PFGE (European Centre for Disease Prevention and Control 2015). But the report also states that in the future both the cost and operating time are expected to decrease for *Salmonella* detection by WGS (European Centre for Disease Prevention and Control 2015). Expert opinion gathered by the researchers for Canada states that the cost for consumable for WGS ($135.6 per isolate) is less than PFGE ($258.49 per isolate) (Table 4.2.9). It is difficult to estimate the exact time requirement for analysis as technological advancement would decrease the time required.

Table 4.2.9: Cost estimates for National Microbiology Laboratory (NML) for PFGE and WGS

	PFGE		WGS	
Time required	7.167	hours per isolate	1.375	hours per isolate
Consumable	258.49	$ per isolate	135.6	$ per isolate
staff wage (a)	234.36	$ per isolate	46.035	$ per isolate
Total	492.85	$ per isolate	181.60	$ per isolate
Total cost	2,229,653.40	annually	821,535.78	annually

Table 4.2.10: Federal costs from current technology (PFGE)

Type of federal agency	Mean total costs ($)
Health Canada	224,175
PHAC: NML	2,229,653
PHAC: others	652,661
Total PHAC:	2,882,314
CFIA: Fresh Fruits and Vegetables	27,078,567
Poultry	120,602,010
Egg	10,660,299
Total CFIA:	158,340,876
Total	161,447,365

4.2.5. Producer costs

Table 4.2.11 shows the costs accruing to the vegetable and fruits producer for testing of *Salmonella* in the pre-harvest and harvest. The costs for testing for *Salmonella* by the producer with five farms of lettuce is estimated to be $14,492. The cost information for testing of *Salmonella* by the producers is only present for one producer in Quebec. If the early testing of *Salmonella* helps in preventing an outbreak, then the producer will be able to save $429,717.[10] Information from producers of different provinces would improve the knowledge about different pre-sale detection practices and the costs arising from them[11]. There will be added benefits to producers from the introduction of WGS as there will be a reduction in time required for

[10] The savings from pathogenic testing, which leads to prevention of an outbreak, is a rough estimate of one week of production and is limited in scope.

[11] These tests do not provide complete protection from pathogenic outbreaks in the food products. In case of an outbreak, the costs to the producer are expected to be higher due to recall expenses, loss of customer confidence resulting in loss of business, advertisement expenses to restore brand name etc. The expenditure incurred to prevent Salmonella is not uniform for all the producer e.g. Salad producer may not have similar washing and chlorination process as sprout producer. Further data is required on such expenditures for other producers.

detection of *Salmonella* and reduction in false positive from *Salmonella* testing. These could not be included in the current study due to lack of information. To the knowledge of the research, there are no published costs available for the egg and poultry producers.

Table 4.2.11: Vegetable and Fruits Producer costs

Type	Costs
Internal laboratory	1,066.67
External laboratory and transportation costs	13,426.00
Total	14,492.67

4.2.6. Health Adjusted Life Years

The non-monetary health related estimates for *Salmonella* are provided by DALY and QALY. DALY provides a non-monetary measure of morbidity and mortality from a disease. Table 4.2.12 shows that 529.20 years of DALYs are lost due to *Salmonella* from various food vehicles annually. Table 4.2.13 shows 289.90 years of QALYs are lost due to *Salmonella*. The estimates differ for DALY and QALY because of the different weights used for estimation[12].

Table 4.2.12: Disability Adjusted Life Years lost from *Salmonella* for Canada

Years of Life Lost (YLL)	Years of Life Lived with Disability (YLD)	Disability Adjusted Life Years Lost (DALY)
499	30.40	529.20

[12] For details see section 3.2.3.

Table 4.2.13: Quality Adjusted Life Years estimates for different categories of illness

Category	Number of illnesses	QALYs weights per Case	Total QALY
No doctor Visit	42807	0.0003	12.84
Doctor Visit	3389	0.0014	4.75
Hospitalized, Recovered	871	0.0077	6.71
Death	13	Based on age at death	265.6
Total	47082		289.90

4.2.7. Net Benefits from WGS

Introduction of WGS for *Salmonella* detection will bring changes in the number of illnesses and COI. Hence, reducing the direct and indirect costs. It is assumed that there is 70 percent reduction in illnesses due to introduction of WGS. Though, the reduction has been applied to total number of illnesses (reported and unreported in the surveillance system) it is assumed that due to the high discriminatory power of WGS implicated food products can be identified at a higher rate (den Bakker et al. 2014, Bell et al. 2016). WGS has also been identified as an effective tool in detecting anti-microbial resistance (Bell et al. 2016, McDermott et al. 2016). The comprehensive information, like geographical origin of isolate, made available by WGS will lead to a reduction in the number of unreported and reported illnesses. As the detection of number of implicated food products rises the producers will implement more stringent controls to reduce the harm to reputation and litigation (Scharff et al. 2016). Furthermore, Scharff et al. (2016) take into account the underestimation multiplier while calculated the reduction in number of illnesses from introduction of PulseNet in the US.

Table 4.2.14 shows that the decrease in direct healthcare costs is $4.502 million and indirect cost of $14.77 million from the new technology. Federal costs are also expected to decline for PHAC by $1.822 million due to decrease in costs of consumables and staff time for WGS. This leads to a total benefit of $90.25 million for the economy. The VSL forms the highest component of the net benefits, followed by productivity increases due to reduction in number of deaths and the number of illnesses. Ruzante et al. (2010) found that COI from *Salmonella* from Spinach at $0.14 million (direct and indirect medical costs, including VSL) and the DALY loss of 1 year for Canada. This estimate does not include costs to federal agencies or to the producer.

Table 4.2.14: Whole Genome Sequencing costs and benefit estimates

Category	**Cost in PFGE $**	**Cost for WGS $**	**Net Benefit in $**
Direct healthcare Costs			
Medication cost	154,274	46,282	107,991
Hospitalization cost	5,417,944	1,625,383	3,792,561
Physician fee	748,907	224,672	524,235
Laboratory test fee	110,748	33,224	77,524
Total	6,431,873	1,929,562	4,502,311
Federal Costs			
Health Canada	224,175	224,175	0
PHAC: NML	2,229,653	821,535	1,408,117
PHAC: others	652,661	238,245	414,415
Total PHAC:	2,882,314	1,059,781	1,822,533
CFIA	158,340,876	158,340,876	0
Total	161,447,365	159,624,832	1,822,533
Indirect cost: Productivity Loss	21,113,836	6,334,150	14,779,685
Value of Statistical Life	98,783,562	29,635,068	69,148,493
Final Total	287,776,636	197,523,613	90,253,023

Batz et al. (2012) attributed the COI and QALY from different food vehicles for the US. *Salmonella* from fresh produce ranks at the eighth position in fifty pathogen-food combinations, with COI of $581 million and QALY loss of 2,946 years. These estimates are higher than the estimates stated in the current study. This is because the number of illnesses are higher for US than that for Canada.

4.3. Results and Discussion Input-Output Model

Thus far, the direct benefits generated from the adoption of WGS have been discussed. The microanalysis does not capture the impact of the technological change on macroeconomic variables like total industrial output, GDP and employment. This section will discuss the macroeconomic benefits from WGS. The benefits from WGS will increase the demand not only for the industries involved in the food safety and medical intervention of the disease but will also change the demand for industries that provide intermediate goods to these industries. Hence, affecting the industrial output, GDP and employment. The microeconomic net benefits derived from WGS, discussed in the previous section, amount to $90.25 million with VSL and $21.10 million without VSL.

This section details the macroeconomic impact of the net benefits from WGS on the Canadian economy. Four scenarios have been created to check the impact of the benefits. Each scenario provides insights into the change in industrial output, GDP and employment due to the introduction of WGS. Modelling different scenarios helps to study the impact of different benefits of WGS like increased productivity, decrease in direct healthcare costs, change in the expenditure of federal agencies. This also helps in identifying those sectors of the economy which have been impacted due to the change. A fourth scenario has been modelled to measure the impact of all the changes collectively. The net benefits from WGS (microeconomic impact) have been modelled into four scenarios: 1) The reduction in the number of days of illnesses leads to less absenteeism from work due to own illness and caregiving. Less absenteeism leads to increase in income for individuals by $14.77 million. This increase in income is modelled as an increase in consumer final demand. 2) The reduction in the number of illnesses leads to decrease in the direct healthcare cost. This is due to the decrease in hospitalization costs, physician costs, medication costs and laboratory test costs for public agencies. There will be a reduction in expenditure on medical intervention by $4.50 million. 3) Shifting the technology from PFGE to WGS at NML will decrease the operational costs. This will lead to savings of $1.82 million for the federal government. 4) The impact of all of the above three scenarios can be measured by combining the increase in final demand and the decrease in federal expenditure (direct healthcare costs and operating costs) due to shifting from PFGE to WGS. This provides a comprehensive measure of the changes in industrial output, GDP and employment due to shift in the technology. Equation 3 is used to calculate the impact on the industrial output, using input-output model. The GDP and employment coefficients provided by Statistics Canada are used to calculate the impact of different scenarios (Statistics Canada 2017a). Various sectors of the economy will be impacted by the adoption of WGS in distinct ways. Hence, the sectoral impact of each scenario is also measured.

4.3.1. Impact on output

The impact of the four scenarios on the industrial output can be seen from Table 4.3.1. The total industrial output in 2013 for Canada was $3,428,653 million. In scenario 1, there is an increase in final consumer demand by $14.8 million which is 0.0008 percent of the original final demand. This increase in consumer demand leads to increase in industrial output by $27.7 million. The industrial output is more than the initial increase in consumer demand. When the consumer demand increases for certain industries the demand of intermediate goods increases, which in turn increases the production. In scenario 2, there is a decrease in the direct expenditure by \$4.50 million. This is 0.00585 percent of the total expenditure by the government on healthcare in 2013 (\$78,064 million). This leads to a decrease in industrial output by \$7.441 million. In scenario 3, the reduction in operational costs for NML leads to the decrease in federal expenditure by \$1.8 million. This is 0.0083 percent of the federal expenditure in 2013 (\$44,162 million). This leads to a reduction of \$3.043 million in industrial output. This is almost double the reduction in direct healthcare costs. In scenario 4, the final demand expenditure changes by \$8.45 million taking into account the increase in consumer final demand in scenario 1 and decrease in expenditure in scenario 2 and scenario 3. This leads to an increase of \$15.88 million in industrial output. As the demand is not sensitive to the price change these scenarios do not capture price sensitivity of the demand. The increase in industrial output is based on the assumption that the sectoral increase in demand will be proportional to the ratio of original demand for each sector to that of total final demand. Though the changes in output are not very high but it is important to consider that *Salmonella* impacts a small part of the whole economy but it will have multiplicative impact as the sectors other than food and healthcare will be impacted.

Table 4.3.1: Change in output of the Canadian economy due to various scenarios

Scenario	Change in output (in millions)	Percentage change in output
1: Increase in productivity leading to increase in final demand	27.765	0.00083
2: Decrease in direct healthcare costs	7.441	0.00022
3: Decrease in federal expenditure	3.043	0.00009
4: Total final impact	15.88	0.00047

Different sectors of the economy respond in a distinct way for each of the scenarios. In scenario 1, the consumer expenditure increases which will lead to increase in output for different industries. Table 4.3.2 shows that the amusement and recreational services industry has the highest percentage change in an output. This could be due to high income elasticity for such services. As the income increases the expenditure on such services increases substantially leading to increased industrial output for the sector. This is followed by tobacco and food and drinks processing industry as increased income leads to increased expenditure on processed food and tobacco. Table 4.3.3 shows ten industries with the highest percentage change in industrial output in scenario 2. As the expenditure on health care changes due to decrease in number of illnesses, the output of hospital services industry also decreases by 0.00509 percent of the original hospital output in 2013. This impacts the output of other health services industries such as physician services, dentist services, miscellaneous ambulatory health care services, nursing and residential care facilities and social assistance.

Table 4.3.2: Highest percentage change (increase) in industrial output in Scenario1

Rank	Industry	% change in industrial output
1.	Amusement and recreational services	0.00150
2.	Tobacco	0.00150
3.	Food and Drinks Processing industry	0.00145
4.	Non-profit	0.00142
5.	Textile and clothing	0.00137
6.	Financial and Insurance Services	0.00130
7.	Stores	0.00127
8.	Agriculture	0.00123
9.	Personal Services	0.00120
10.	Electricity and Natural gas	0.00113

Table 4.3.3: Highest percentage change (decrease) in industrial output in Scenario 2

Rank	Industry	% change in industrial output
1.	Hospital services	0.00509
2.	Health services (other)	0.00069
3.	Paper and printing	0.00019
4.	Personal Services	0.00017
5.	Petroleum and chemical industry	0.00016
6.	Postal and Storage	0.00014
7.	Water, sewage and other systems	0.00013
8.	Legal, Accounting, Architect, engineering, computer and other services	0.00013
9.	Whole-sale distributors	0.00013
10.	Electricity and Natural gas	0.00012

For scenario 3, the decrease in operational costs for NML leads to maximum decrease in industrial output for hospitals services and federal expenditure (Table 4.3.4). The results for scenario 4 are similar to that of scenario 1 because both the scenarios impact the final demand matrix of the economy (Table 4.3.5).

Table 4.3.4: Highest percentage change (decrease) in industrial output in Scenario 3

Rank	Industry	% change in industrial output
1.	Hospital services	0.00043
2.	Other federal government services (except defense)	0.00039
3.	Governmental Services	0.00039
4.	Health services	0.00026
5.	Legal, Accounting, Architect, engineering, computer and other services	0.00007
6.	Water, sewage and other systems	0.00007
7.	Paper and printing	0.00006
8.	Petroleum and chemical industry	0.00006
9.	Postal and Storage	0.00006
10.	Transportation	0.00005

Table 4.3.5: Highest percentage change (increase) in industrial output in Scenario 4

Rank	Industry	% change in industrial output
1.	Amusement and recreational services	0.00086
2.	Tobacco	0.00086
3.	Food and Drinks Processing industry	0.00083
4.	Textile and clothing	0.00078
5.	Financial and Insurance Services	0.00076
6.	Stores	0.00073
7.	Agriculture	0.00070
8.	Personal Services	0.00068
9.	Electricity and Natural gas	0.00065
10.	Communications	0.00064

4.3.2. Impact on GDP

The GDP at base prices in 2013 for Canada was $1,599,575 million. Table 4.3.6 shows that impact on the GDP for the different scenarios. The change is highest for Scenario 1. The GDP increases by 0.0016 percent for scenario 1 because of increase in final consumer expenditure.

The GDP decreases by 0.00042 and 0.00018 percentage for scenarios 2 and 3 due to reduction in direct healthcare costs and federal expenditure respectively. In scenario 4, the GDP increases by 0.00094 which measures the impact of final net benefits on the GDP.

Table 4.3.6: Impact on GDP for different scenarios

Scenario	Change in GDP (in millions)	Percentage change in GDP
1: Increase in productivity leading to increase in final demand	23.21	0.00161
2: Decrease in direct healthcare costs	6.21	0.00042
3: Decrease in federal expenditure	2.57	0.00018
4: Total final impact	13.38	0.00094

4.3.3. Impact on employment

As the industrial output changes the demand for labour also changes. Table 4.3.7 shows the change in employment due to change in technology for the different scenarios. Table 4.3.8 shows the change in employment for the different sectors of the economy for the four scenarios. These sectors have been selected due to major industrial changes expected within the sectors. In scenario 1, as the consumer expenditure increases due to increase in productivity it is expected that the employment in the economy will increase. The number of labor employed increases by 201 (0.00113 percent). The sector that generates the most amount of employment is information, culture, recreation, accommodation followed by healthcare sector, food services, agriculture and public administration. This is due to increase in demand for goods and services in the economy which leads to industries employing more workers to fulfill the demand. In scenario 2, the direct healthcare expenditure decreases this leads to decrease in number of labour employed by 54 (0.00030 percent). The healthcare services industry is impacted the most as demand for healthcare decreases, the employment in the sector will also decrease.

Table 4.3.7: Impact on employment in different scenarios

Scenario	Change in employment	Percentage change in employment
1: Increase in productivity leading to increase in final demand	201.00	0.00113
2: Decrease in direct healthcare costs	53.78	0.00030
3: Decrease in federal expenditure	22.25	0.00013
4: Total final impact	115.87	0.00065

Table 4.3.8: Impact on employment of different sectors for four scenarios

Sector	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Agriculture	4.51	0.21	0.75	2.74
Manufacturing	16.32	1.46	0.52	9.89
Healthcare Services	16.40	17.16	8.22	9.94
Information, Culture, Recreation, accommodation and food services	45.17	4.90	2.30	26.70
Public Administration Services (except healthcare)	15.38	2.74	5.39	14.37

In scenario 3, there is a decrease in federal expenditure as the operational costs for NML decrease. The number of labour employed decreases by 22.25 (0.00013 percent). The reduction scenario 2 & 3 is a result of interdependence of the macro variables but a similar reduction might not take place in practice. As, the people employed might have to work on other projects as the work load from Salmonella reduces. In scenario 4, similar to scenario 1 there is an increase in employment due to increase in final expenditure in the economy. The number of labour employed increases by 116 (0.00065 percent) (Table 4.3.7). The industries impacted the most are information, culture, recreation, accommodation and food services followed by healthcare services, manufacturing and agriculture (Table 4.3.8).

4.4. Conclusion

The results show a net benefit from adoption of WGS which has a multiplicative effect on the economy. The microeconomic analysis shows that the net benefits of WGS are $21.10 million without VSL and $90.25 million with VSL. The net benefit from WGS per case is $2,738[13]. The COI for *Salmonella* from PFGE is $287.78 million. The cost per case from PFGE is $6,112 in Canada[14]. The highest cost component for PFGE and WGS is the federal cost (PFGE: $161.44 million, WGS: $159,62 million) followed by VSL (PFGE: $98.78 million, WGS: $29.63 million). The federal costs are high due to large expenditure on food safety programs undertaken by CFIA. The cost of VSL is high because loss from one death is $7.59 million. The non-monetary estimates are 529.20 years (DALY) and 289.90 years (QALY). The cost per QALY from PFGE is approximately $1 million.

These microeconomic benefits are then used to calculate the impact on industrial output, GDP and employment. The change in GDP for the four scenarios ranges from $2.57million to $23.21 million. The change in employment is the highest for scenario 1 (201) as the increase in consumer expenditure is highest in this scenario. The employment decreases in the healthcare industry due to the reduction in direct healthcare costs (scenario 2). The industrial output

[13] Net benefits divided by the reduction in number of illnesses.
[14] This will vary according to the categories of illness.

increases in scenario 1 by $27.765 million because of increase in consumer expenditure as the income rises due to fewer work days missed. In scenario 4, there is an increase in industrial output by $15.88 million due to the comprehensive net benefits from WGS. Similarly, the industrial output decreases in scenario 2 by $7.441 million because of a decrease in direct healthcare costs due to the reduction in the number of illnesses. In scenario 3, the industrial output decreases by $3.043 million due to a decrease in operational costs for NML. To the knowledge of the researcher, there is no study which measures the impact of the change in technology for outbreak detection and models the net benefits to find the impact on macroeconomic variables. Andersen and Christensen (2008) measure the cost and benefits for *Salmonella* control policy in Denmark and then use a CGE model to find the impact on GDP. They find a negative effect on GDP for first seven years of the policy implementation and a positive effect afterwards. The positive effect is due to improved labour productivity in the economy. The difference in results of Andersen and Christensen (2008) and current study may be due to the fact that the Danish economy is smaller and increasing regulations on producer impacts the economy negatively. Smith et al. (2009) calculate economy-wide impact for H1N1 epidemic on the British economy. They find that the impact on GDP and industrial output of the epidemic is higher than that of the current study. The final impact on macroeconomic variables depends on the extent of the outbreak, type of prevention policies, the severity of disease, type of medical resource use, type of disease and economic burden of the disease. It is important to study micro and macroeconomic impacts of the diseases for implementing cost-effective policies.

Chapter 5: Conclusion

Salmonella is one of the major foodborne illness agents in Canada. Every year in Canada around 88,000 people get sick from eating food products contaminated with *Salmonella* and around 925 of them are hospitalized (Thomas et al. 2013, Thomas et al. 2015a). Almost, 50 percent of *Salmonella* illnesses are caused by fresh produce, poultry and eggs in Canada (Ravel et al. 2009). Canada follows a systematic evidence-based method of investigating *Salmonella* outbreaks. Three federal agencies (Health Canada, PHAC and CFIA) along with the provincial and local agencies are involved in monitoring and containment of the outbreaks. Currently, PulseNet Canada is in the process of upgrading thirteen laboratories to WGS (Reimer et al. 2016). PHAC laboratories are also being upgraded to WGS[15]. Though the technology has been termed as a gold standard for *Salmonella* testing it still has many caveats. A new sequencing tool, WGS, is being developed which will detect *Salmonella* quicker and with more precision. Economic analysis of diseases is important for measuring the burden of diseases and finding cost-effective methods for improving food safety.

COI and HALY are two widely used methods of estimating the monetary and non-monetary costs of *Salmonella* illnesses. Economic estimates of foodborne diseases have been calculated for various countries like the USA (Buzby et al. 1996, Frenzen et al. 1999, Hoffmann et al. 2012, Scharff 2012), Canada (Todd 1989, Majowicz et al. 2006, Henson et al. 2008) and the Netherlands (Kemmeren et al. 2006). Henson et al. (2008), Majowicz et al. (2006) estimate the annual cost of foodborne diseases for a single province in Canada. Most of the studies that

[15]According to PHAC expert, WGS is being introduced in PHAC laboratories.

estimate the monetary and non-monetary losses from foodborne diseases also include the losses from *Salmonella*, implying the importance of the disease. None of the above-mentioned studies attributes the incidence of illness or the COI from a pathogen to specific food vehicles. Batz et al. (2012) and Ruzante et al. (2010) are the two known studies that attribute the COI and non-monetary estimates to various food vehicles for US and Canada respectively. Ravel et al. (2009) provide estimates of *Salmonella* illnesses that can be attributed to different food groups for Canada but the article does not provide any economic analysis of the same. Some of the studies in Europe have analyzed the costs and benefits of *Salmonella* control programs. Andersen and Christensen (2008) conduct a CBA for *Salmonella* control strategy in Denmark. Sundström et al. (2014) perform a CBA for hypothetical implementation of Danish and Dutch *Salmonella* control strategies in Sweden. Unlike previous studies, this study focuses on one pathogen along with a specific food vehicle at a national level. To the best of the researcher's knowledge, none of the studies calculates the costs for *Salmonella* from fresh produce, poultry and eggs in Canada or conducts a CBA of technological improvement in outbreak detection. This study bridges the gap in the current literature by estimating the annual monetary and non-monetary burden from *Salmonella* from fresh produce, poultry and egg. The study translated the microeconomic net benefits from WGS to macroeconomic impact of the same using input-output modelling. The study measures the impact of all the changes brought on by the introduction of WGS on each sector of the economy.

To achieve the objective of the study the following methodology is used. First, the total number of *Salmonella* illnesses from fresh produce, poultry and eggs in Canada is calculated. Then monetary (COI) and non-monetary (DALY and QALY) costs are estimated, given the current technology of PFGE used for *Salmonella* detection. Costs from WGS are also estimated and these are further used to calculate the net benefits from WGS. The COI includes direct healthcare costs (hospitalization, physician, laboratory and medication costs), indirect costs, VSL and federal costs. The costs for producers who test for the presence of *Salmonella*, pre-harvest and harvest, have also been calculated[16]. Since, the clinical symptoms of typhoidal *Salmonella* are different from nontyphoidal *Salmonella* only costs for nontyphoidal *Salmonella* are accounted for. DALY and QALY have been estimated to take into consideration non-monetary burden of the disease. Monte Carlo simulations are used to incorporate uncertainty into the model. PERT distribution is used to define various cost inputs in the model and to obtain a mean estimate and 90 percent confidence interval. The Supply-Use tables from Statistics Canada have been used to calculate the impact on industrial output, GDP and employment (Statistics Canada 2016a, Statistics Canada 2017a). Four scenarios have been modelled to estimate the impact of the change in technology on the macroeconomic variables. The first scenario estimates the impact of the increase in productivity as the number of illnesses decrease and fewer individuals take sick days off from work. The second scenario estimates the decrease in direct healthcare costs due to the reduction in the number of *Salmonella* illnesses. The third scenario measures the impact of the decrease in federal expenditure due to the reduction in operational costs for NML. The fourth scenario measures the comprehensive impact of total net benefits for the economy.

The CBA shows that the net benefits of WGS are \$21.10 million without VSL and \$90.13 million with VSL. The net benefit from WGS per case is \$2,738. VSL forms the largest component

[16] Though, these have not been included in the net benefits as the benefits from testing are tentative and testing does not provide complete protection against the outbreak.

of the net benefits followed by indirect costs. This shows that WGS will lead to increased productivity of workers in the economy. Hence, the consumer welfare will increase due to increase in income. These benefits have a multiplicative impact at the macro level. Four scenarios have been created to measure the impact of adoption of WGS on industrial output, GDP and employment. These scenarios take into consideration in the impact of an increase in productivity (scenario 1), a decrease in direct healthcare costs (scenario 2), a decrease in federal expenditure (scenario 3) and a comprehensive impact of net benefits from WGS (scenario 4). The comprehensive impact of net benefits from WGS on industrial output is $15.88 million (scenario 4). The change in industrial output ranges from $3.043 million to $27.765 million. The change in GDP in scenario 4 is 0.00094 percent. Though, the impact on GDP is not very high it should be noted that the change depends on the intensity of the outbreak, effective implementation of food-safety strategies and behavioral changes in consumer and producer behavior. The employment increases by 116 when the comprehensive impact of WGS is measured (scenario 4). The highest labour generation is in information, culture, recreation, accommodation and food services industry followed by healthcare (scenario 4).

Strengths and limitations of the study

There are not many studies that attributed COI and DALY to food vehicles. Most of the studies that calculate the direct healthcare costs and indirect costs from *Salmonella* do not take into consideration federal costs and producer costs. This study calculates the costs from *Salmonella* in food products at the national level. This is the first study to take into account average costs from different provinces in Canada. The microeconomic estimates from CBA are then used to calculate the macroeconomic impact on Canada. Four scenarios have been developed to measure the impact of the change in productivity, direct expenditure, federal expenditure and comprehensive final impact on industrial output, GDP and employment. Industries with the highest impact have also been identified. Such a framework helps in measuring the net benefits from technological change and identifying the key industries impacted by such a change. This helps in informed policy-making not just for the industries that are directly affected but those indirectly affected by the changes.

The current study faces some shortcomings due to lack of data. It could not be determined if the attribution of number of illness from fresh produce, poultry and eggs, by Ravel et al. (2009), is mutually exclusive. The estimate of net benefits is a conservative one as all the benefits incurred by producer and federal agencies could not be included. The federal expenditure on controlling and monitoring *Salmonella*, specifically, is an approximation as no information was available for the same. Willingness to pay by consumers for food safety could not be included in the model. Hence, the net benefits are underestimated. The producer costs are an approximation as data was not available for every type of producer. The costs for the producers will vary according to the type of product and the processing methods used. For example, the prevention and control methods used by sprout producers are not the same as those used by salad processing industry. The net benefits depend on the assumptions made and the unit costs available from various sources. The macroeconomic impact does not take into consideration the change in producer and consumer behavior as the food-safety regulations change. The net benefits are also dependent on the effectiveness of the technology and the recall procedure used to remove contaminated product from the market. As the adoption of WGS is relatively new and still under process. So, the estimated benefits from it are an approximation. Nevertheless, the analysis shows that the adoption of technology will lead to benefits for the economy with the reduction in direct and indirect costs from *Salmonella*. Even though there are some limitations to the study it is still important to analyze the economic implications of using WGS for outbreak detection. Economic analysis of foodborne diseases is important to inform policymakers about the resource burden from the diseases and encourage adequate food safety control and intervention programs.

Policy Analysis

It is important to analyze technological advancements in food safety sector which impact the public welfare. This helps in efficient policymaking and advocating for further research and development. As the net benefits from WGS are positive, the technological advancement will lead to increased industrial output and employment for the economy.

There will be savings for the federal and provincial agencies as the costs are decreased due to the reduction in the number of illnesses.

The public healthcare costs are shared by federal and provincial governments in Canada. As the direct healthcare costs decrease there will be a reduction in public sector expenditure. It is important that the savings from direct healthcare costs be invested. If the savings are not invested there will be a decrease in industrial output by $7.441 million. To prevent this, these savings should be used to promote further research in the genomics of different pathogens. The decrease in the number of illnesses and federal expenditure, ceteris paribus, impact the employment in the healthcare industry the most. To mitigate the impact on the public healthcare industry there should be appropriate policy changes.

The costs from WGS are expected to decline over the years (Callejón et al. 2015, Reimer et al. 2016). So, introducing WGS in provincial and local testing agencies could improve the benefits in the long run. This will also save transportation costs associated with sending the samples for pathogenic testing to national laboratories. Further, it is important to train the staff for such technological advancements.

It is also important to improve data collection and transparency for federal and provincial agencies as this will lead to improvement in research and policy analysis. Operational and fixed expenditures undertaken by the agencies should be made available in the public domain.

It is expected that improved pathogen detection will encourage producers to adopt stringent food safety practices. To this end, use of bacteriophages in pre-harvest and processing stages should be encouraged to reduce the chances of contamination. Use of bacteriophage will reduce the probability of contamination of the food products and can be economically beneficial if the cost from the intervention is less than the cost of recalling the product from the market. It is also important that the costs of recalling and throwing away contaminated food products be recorded. Processing and packaging facilities should be made liable for compensating damages due to contamination and stringent rules should be enforced.

As the productivity increases leading to increase in consumer expenditure, the growth in the industrial output for amusement and recreational industries along with tobacco industry is the highest (Tables 4.3.2 and 4.3.5). On one hand, this shows the increase in the welfare of the consumers, on the other hand, the increased consumption of tobacco can lead to more public health issues.

The improvement in the technology should be complemented with improvement in procedures undertaken before and after the testing. There should be an efficient and fast transportation of samples from markets to laboratories. The recall procedure for contaminated products should be improved and necessary steps should be taken to prevent delay in recalls. The coordination among laboratory personnel, inspection officers, producers, provincial and federal agencies should be improved. Active intervention by the local, provincial and federal agencies will reduce the health and economic burden of foodborne diseases. Food and Agriculture Organization states that technological improvements need to be accompanied with good surveillance systems, multidisciplinary investigations along with good agricultural and manufacturing food safety and hygiene practices (FAO 2016).

Academicians from different disciplines like epidemiology, microbiology and other food safety sciences should be brought together to conduct multidisciplinary research. Economic analysis of foodborne diseases will benefit from the expertise of multidisciplinary research teams.

A holistic approach to food safety will improve the benefits from WGS in outbreak containment.

Future Research

Given the current study, some areas of further research have been identified that could not be included due to the limitation of scope and time. These are recommended as potential research areas.

1) The comprehensive estimates for provincial costs from outbreak investigations are not available. Provincial laboratories are involved with outbreak investigation and local agencies are tasked with monitoring and implementation of food safety

regulations. Hence, it is important to study the costs to these agencies and how they are impacted by the change of the technology.

2) Further, research is also required on the impact of technological changes on federal agencies like Health Canada and CFIA.
3) There is a need for data and research on economic losses from positive pathogen detection in the food product. No information is currently available in the literature regarding the same. Also, additional information is required about the costs to producers from other measures undertaken for pathogen detection and recall from the market. Impact of changes in food safety technology and regulations on the producers remain to be studied.
4) Similarly, behavioral change in consumers due to these food safety regulations and technological advancement also needs to be studied.
5) The results from this study can be used to estimate the impact of technological change in Canada on the international trade using Computable General Equilibrium model. Dynamic general equilibrium modelling can be used to study the long run impact of WGS on the economy.

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Appendix

Table 2.2: Types of studies undertaken in the Literature

Reference	Type of Disease	Methodology	Food vehicle specified	Outbreak costs or Annual costs	Cost Estimates
Majowicz et al (2004) Canada	Gastroenteritis	COI[1] using phone survey	No	Annual	CAD 3.7 million (2005)
Hoffmann et al (2012) USA	14 Food borne Pathogens	COI and QALYs[2];	No	Annual	$14.0 billion & 61,000 QALYs
Batz et al (2012) USA	14 Pathogens with 12 categories of food	COI and QALYs	Pathogens-food combinations	Annual	The top 10 pairs were responsible for losses of over $8 billion and 36,000 QALYs
Henson et al (2008) Canada	Gastrointestinal	COI using Phone survey	NO	Single year	CAN$514.2 million (2004)
Todd (1989) USA and Canada	Foodborne Illness	COI divided into two groups: food processing industry and food services	NO	67 outbreaks	$ 1,334.6 million (1985)
Sundstro¨m et al (2014) Sweden	*Salmonella* control	CBA[3]	No	Annual	€- 5 to -105 million (losses)
Buzby et al (1996) USA	6 pathogens	COI	No	Annual	
Suijkerbuijk et al (2016) Netherlands	*Salmonella*	COI	Smoked Salmon	Single outbreak	7.5 million (Euro) (2012)

Scharff et al (2012) USA	Foodborne Illness (31 identified pathogens and 4 unspecified agents)	Basic COI and Enhanced COI	No	Annual	Basic: \$51.0 billion Enhanced: \$77.7 billion (2010)
Gadiel et al (2010) New Zealand	6 pathogens	COI	No	Annual	\$ 161.90 million (2009)
Adhikari (unpublished) (2004) USA	*Salmonella*	COI	No	Annual	\$2.8 billion (2004)
Andersen et al. (2008) Denmark	*Salmonella* control	CBA and General Equilibrium Analysis	Different industries are identified: Pork, Poultry and Egg	Annual	Direct Cost- US\$64–119 million
Ruzante et al (2010) Canada	6 pathogen-food combinations	Multi-criteria Risk Analysis	Yes	Annual	Top rated food- pathogen combination: Campylobacter spp.- chicken, *Salmonella* spp.- chicken
Frenzen et al (1999) USA	*Salmonella*	COI	No	Annual	HCA: \$464 million and LMA: \$2,329 million (1998)
Lake et al (2010) New Zealand	6 foodborne illnesses	COI and DALY[4]	No	Annual	\$86 million DALY- 1,510
Buzby et al (1996) USA	7 foodborne pathogens	COI	No	Annual	US\$ 6.5-34.9 billion
Kozak et al (2012) Canada	Foodborne illnesses	N/A	No	Annual	N/A
Kemmeren et al (2006) Netherlands	Foodborne illnesses	COI and DALY	No	Annual	77.8 million (Euro) (2004) and DALY- 5670 years

Notes: 1. COI: Cost of illness, 2. QALY: Quality Adjusted Life Years, 3.CBA: Cost- Benefit Analysis, 4. DALY: Disability Adjusted Life Years