Exploring Food Insecurity as a Risk Factor for Eight Enteric Infections in Ontario, Canada, 2019-2022: Multilevel Ecological Study

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Food insecurity and foodborne illness are significant public health issues in Canada, associated with poor health, direct healthcare costs, and lost productivity. While previous ecological studies in higher-resource countries have explored the relationship between broad socioeconomic determinants and foodborne infections, none have explored food insecurity as a risk factor for enteric infections. Food insecurity is recognized as a potential intermediary determinant that can influence an individual's vulnerability and exposure to foodborne illness. This study aimed to identify the magnitude, distribution, and spatial patterns of reported *Campylobacter* spp., *Salmonella* spp., Shiga toxin-producing *E. coli* (STEC), *Listeria monocytogenes*., *Shigella* spp., *Cyclospora cayetanensis*, *Giardia duodenalis* spp., and hepatitis A virus infections across Ontario, Canada, from January 2019 to December 2022. Additionally, it explored whether age- and sex-adjusted annual pathogen-specific incidence rates were associated with the prevalence of household food insecurity at the Public Health Unit (PHU) level during 2021.

Public Health Ontario's publicly available surveillance tools were used to collect data on household food insecurity and reported case counts of eight enteric infections for 34 Ontario PHUs. Annual age- and sex-adjusted pathogen-specific incidence rates were calculated for each PHU using direct standardization and were visualized using choropleth maps. Purely spatial, temporal, and space-time high infection rate clusters were identified using retrospective scan statistics, with a Poisson model. Global and local spatial autocorrelation patterns of annual pathogen-specific incidence rates were examined using the Moran's I spatial statistical method. Fixed and random effects Poisson and Negative Binomial regression analyses were conducted to estimate incidence rate ratios (IRR) for each enteric pathogen and the prevalence of household food insecurity, while controlling for demographic and socioeconomic covariates. A

geographically weighted Poisson regression analysis was used to explore whether the association between pathogen-specific incidence rates and household food insecurity differed spatially across PHUs.

Reported cases of all enteric pathogens, except for *Listeria monocytogenes*, had a noticeable decline after 2019. *Campylobacter* spp., *Salmonella* spp., and *Giardia duodenalis* consistently had the highest incidence rates across PHUs from 2019-2022. Spatial and space-time analyses showed that *Salmonella* spp. and STEC high-infection rates mainly clustered in Central- and South-West regions of Ontario. *Campylobacter* spp., *Listeria monocytogenes*, *Shigella* spp., *Cyclospora cayetanensis*, *Giardia duodenalis*, and hepatitis A infections were widely distributed across the province. *Campylobacter* spp., STEC, *Listeria monocytogenes,* and *Cyclospora cayetanensis* were the only pathogens to exhibit a temporal pattern, with infections clustering in the warmer months. Two significant space-time clusters of *Salmonella* spp. and hepatitis A were associated with confirmed outbreaks in Lambton Public Health and Middlesex-London Health Unit. In 2021, the prevalence household food insecurity had an inverse association with the incidence rates of *Campylobacter* spp., STEC, and *Giardia duodenalis*, with minimal spatial variability of the IRRs across PHUs. No significant associations were observed between household food insecurity and the other enteric pathogens.

Food insecurity may influence the incidence of foodborne illness at an aggregate level. Spatial and temporal clustering of enteric pathogens suggests local and seasonal risk factors could be associated with foodborne illness. Future research should investigate whether the incidence rates of foodborne illness differ among populations experiencing marginal, moderate, and severe levels of food insecurity. The findings from this study could help PHUs develop public health interventions that simultaneously address food insecurity and food safety.

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List of Abbreviations

CCHS	Canadian Community Health Survey
CI	Confidence Interval
CIS	Canadian Income Survey
GGWR	Generalized Geographically Weighted Regression
HAV	Hepatitis A Virus
HFSSM	Household Food Security Survey Module
HUS	Hemolytic Uremic Syndrome
iPHIS	Integrated Public Health Information System
IRRs	Incidence Rate Ratios
MAUP	Modifiable Areal Unit Problem
NTS	Non-Typhoidal Salmonellosis
PHU	Public Health Unit
PHUs	Public Health Units
RR	Relative Risk
r_s	Spearman's Rank Correlation Coefficient
SES	Socioeconomic status
spp.	Multiple species within a genus
STEC	Shiga toxin-producing *Escherichia coli*
VIF	Variance Inflation Factor

1.0 Background

1.1 Overview of Foodborne Illness

Foodborne illness is an "illness that occurs when an individual gets sick from consuming food contaminated with a harmful microorganism" (1; p. 5). These harmful pathogens include bacteria, toxins, fungi, parasites, or viruses, which are commonly transmitted through the consumption of contaminated food or water and are collectively known to cause enteric disease (1,2,3). Humans are primarily exposed to enteric pathogens through the fecal-oral route or person-to-person transmission (3). Other well-known sources responsible for the transmission of enteric pathogens include direct contact with animals and indirect contact with fomites (3). Once, these pathogens are inside the human body, they can replicate by breaching and evading the host's cellular and humoral defense systems, potentially spreading to other hosts (3).

Enteric pathogens are classified into three distinct groups based on their transmission patterns: zoonotic, geonotic, or human origin (3). Many common foodborne pathogens such as *Campylobacter* spp. *and Salmonella* spp. are zoonotic pathogens, meaning they can be transmitted from animals to humans (3,4). These pathogens can cause cellular damage by establishing in human tissue, leading to various mild enteric symptoms such as diarrhea, abdominal pain, nausea, vomiting, and fever (3,5). In severe cases, foodborne illness can result in different long-term health complications depending on the specific pathogen that causes an infection. For example, STEC infections can progress into hemolytic-uremic syndrome (HUS) and kidney disease, *Campylobacter jejuni* can cause a rare autoimmune disorder Guillain-Barré syndrome, and hepatitis A virus can cause liver inflammation and jaundice, which can lead to hospitalization or death (3,5).

1.2 Health and Economic Burden of Foodborne Illness in Canada

Foodborne illness has been recognized as a significant public health issue in Canada, posing a considerable health and economic burden (6,7). Each year, approximately 12.5% of Canadians are affected by a foodborne illness, resulting in 11,600 hospitalizations and 238 deaths (8,9). The annual economic cost of foodborne illness in Canada is approximately $2.8 billion, primarily due to increased medical care costs, lost productivity, and loss of life (10-12). At an individual level, the median annual cost per case of foodborne illness in Canada is approximately $834 (13).

In 2020, the overall health burden associated with enteric infections declined. During the COVID-19 pandemic, FoodNET Canada reported 28% fewer reported cases of enteric illness compared to previous years (14). This decrease is likely due to the implementation of strict public health measures, changes in healthcare-seeking behaviours, improved hygiene practices, and the reallocation of resources to control the COVID-19 pandemic (15).

1.3 Prevention and Surveillance of Foodborne Pathogens

Most foodborne infections and outbreaks are preventable. Effective disease prevention requires a coordinated effort across epidemiological, food safety, and laboratory investigations (16). Rapid laboratory detection methods with high sensitivity, such as nucleic acid-based methods, are essential for timely and coordinated investigations (16,17). Managing foodborne outbreaks requires strong collaboration and communication between various stakeholders across different sectors (16). Despite a collaborative structure in Canada, further advancements in prevention, control practices, surveillance systems, and multi-jurisdictional communication are required to reduce the health and economic burden of foodborne illness (18). Surveillance systems are essential for public health; they help assess the magnitude of disease or risk of different

exposures, identify high-risk populations, and inform the design and implementation of targeted prevention strategies (19).

Canada lacks a coordinated public health surveillance system where surveillance is performed across numerous independent data systems under the leadership of various organizations (20). The lack of uniformity introduces multiple barriers, including outdated technology, fractured data systems, challenges in recruiting and retaining qualified workers, and a lack of a standardized approach for collecting data (20). These issues can delay decision-making in health responses (20). The development of effective surveillance systems requires interdisciplinary collaboration between experts and an integration of their expertise in epidemiology, microbiology, diagnostics, virulence, and pathogenicity, coupled with specific technologies to create a surveillance system that is capable of efficiently addressing public health emergencies (18,20).

1.4 Impact of Foodborne Pathogens on the Food Industry

Foodborne outbreaks are responsible for significant economic losses in the food industry. The number of foodborne outbreaks has increased over time due to the reliance on globalized food trade, which involves different production sites and complex supply chains (21). These factors drive food production and distribution companies to prioritize their financial competitiveness in a global market, leading to companies being less compliant with food safety standards (21). If food processing companies do not have adequate preventative control measures in place, system failures and Class 1 recalls are more probable (22). A Class 1 recall involves cases who consume a food product that will likely cause serious adverse health consequences or death (23). Class 1 recalls pose a serious threat to customers' health and, on average, reduce a company's economic value by 1.5-3% (23).

1.5 Common Enteric Pathogens in Canada

In Ontario, data from the integrated Public Health Surveillance System (iPHIS) indicate *Campylobacter* spp., *Salmonella* spp., Shiga toxin-producing *Escherichia coli* (STEC), *Listeria monocytogenes*, *Shigella* spp., *Cyclospora cayetanensis*, *Giardia duodenalis*, and hepatitis A virus are commonly reported enteric pathogens responsible for the majority of foodborne illness cases (24-27).

1.5.1 Campylobacter

Campylobacter jejuni is a major foodborne pathogen that causes campylobacteriosis (28). Campylobacteriosis is a major source of gastrointestinal illness worldwide (28,29). Globally, *Campylobacter* affects approximately 400-500 million people each year (30,31). However, in North America, the reported number of *Campylobacter* infections is severely underreported in surveillance systems because most campylobacteriosis cases have mild symptoms, and few require treatment or hospitalization (30,32). It is estimated that only 2.6% of *Campylobacter* cases are reported in the United States (33). *Campylobacter* infections are believed to be mainly foodborne (33). The main transmission source is the consumption of raw or undercooked poultry products; it can also be contracted by consuming other meat products, contaminated dairy products, contaminated water or ice, traveling, and direct contact with infected animals (30,34-37).

Campylobacter infections usually manifest as asymptomatic or mild symptoms (29,36). When mild symptoms are present, they can present as a fever, abdominal pain, vomiting, and acute watery or bloody diarrhea (29,36). *Campylobacter* infections can also lead to severe complications such as meningitis, colon inflammation, gallbladder inflammation, irritable bowel syndrome, septicemia, and Guillain-Barre Syndrome (29,36,38,39). Younger children, older

adults, individuals who are immunocompromised, and travelers are at the highest risk of developing severe complications (34-37). *Campylobacter* infections are estimated to be the most common cause of gastroenteritis in Canada due to numerous risk factors that contribute to increased susceptibility (38,39). Campylobacteriosis is responsible for approximately $80 million in healthcare costs annually, in Canada (40).

1.5.2 Salmonella

Non-typhoidal *Salmonella* spp. are gram-negative bacteria that cause salmonellosis (41). Globally, non-typhoidal salmonellosis (NTS) is estimated to be the second most common reported foodborne illness after campylobacteriosis, affecting 93.8 million people and resulting in 155,000 deaths annually (41,42). *Salmonella enterica* serotype Enteritidis was the most reported serotype associated with NTS in Canada, followed by serotypes Typhimurium, and ssp I 4,[5],12:i:- (32). Exposure sources for NTS are serotype dependent. Humans are commonly exposed to *Salmonella* Enteritidis by consuming contaminated poultry and eggs (43,44). *Salmonella* Typhimurium and I ssp I 4,[5],12:i:- can be contracted by consuming contaminated pork products (45,46). Other common exposure sources that have been linked to *Salmonella* outbreaks include eating contaminated meat products, dairy products, and seeded vegetables, and contact with animals (41,47,48).

NTS commonly manifests as acute clinical symptoms such as diarrhea, nausea, vomiting, fever, and abdominal cramps (41,49,50). However, approximately 5% of individuals develop invasive NTS, which can manifest into severe complications such as bacteremia, meningitis, and other infections (41,50-52). Children < 5 years of age, older adults, and immunocompromised individuals are particularly vulnerable to invasive NTS (41,53). In Canada, NTS poses a substantial annual economic burden of $148.5 million (54).

1.5.3 Escherichia coli

Escherichia coli (*E. coli*) is a gram-negative proteobacterium that causes gastrointestinal illness (55,56). *E. coli* infections can be transmitted by consuming raw or uncooked beef, unpasteurized dairy products, contaminated raw fruits and vegetables, contaminated water, unpasteurized juices, human-animal contact, human-human contact, and direct contact with manure (57,58). A common *E. coli* pathotype frequently associated with human foodborne illness is Shiga toxin-producing *E. coli* (STEC) (56). STEC is responsible for causing many foodborne infections in Canada, with an estimated 22,344 cases per year, costing $26.7 million (59).

Acute symptoms range from watery or bloody diarrhea, abdominal pain, vomiting, and fever (59,60). STEC can manifest into severe long-term complications such as hemorrhagic colitis, hemolytic uremic syndrome (HUS), neurologic complications, and death (59,60). STEC-HUS induces vascular damage by damaging red blood cells and reducing the number of platelets in the human body, causing kidney damage (61). Children, the elderly, and immunocompromised populations are at a greater risk of developing acute and severe complications (59,60). Sockett et al. (59) estimate that 37,867 long-term outcomes are associated with STEC infections in the Canadian population annually, costing Canadians $377.2 million each year.

1.5.4 Listeria monocytogenes

Listeria monocytogenes is the only *Listeria* species identified as a human pathogen because of its ability to cause listeriosis (62-64). In contrast to most foodborne pathogens, *Listeria monocytogenes* has a unique ability to grow at refrigerated temperatures, low pH environments, and foods with high salt concentrations, allowing the pathogen to grow in many different food types and environments (65,66). *Listeria monocytogenes* is often isolated from raw and processed meats, dairy products, fish, seafood, vegetables, ready-to-eat foods, and fruit (66-69).

Infections usually affect pregnant women, older adults, newborns, and immunocompromised people; these at-risk populations should be extremely cautious and avoid any high-risk foods (64,66,68). Moreover, in high-risk populations, listeriosis can lead to severe outcomes such as bacteremia or septicemia, central nervous system damage, miscarriage, stillbirth, and spontaneous abortion. (62,70-72). However, in low-risk populations, listeriosis can range from subclinical to mild non-invasive symptoms, including abdominal pain, muscle pain, fever, vomiting, and diarrhea (62,73,74). Globally, there are an estimated 23,150 cases of listeriosis annually, resulting in approximately 5,463 deaths (65). In Canada, listeriosis is one of the least frequently reported foodborne pathogens, although it has a 20-30% case-fatality rate in vulnerable populations and a higher case-fatality rate than any other foodborne pathogen in Canada (32,75). *Listeria monocytogenes* is a severe foodborne pathogen that poses a large economic burden. For example, a 2008 outbreak in Canada, involving 57 cases of listeriosis, was estimated to cost $242 million (76).

1.5.5 Shigella

Shigellosis is an enteric disease caused by *Shigella*, a non-motile gram-negative rod bacterium (77). *Shigella* has four species: *Shigella dysenteriae, Shigella flexneri, Shigella boydii*, and *Shigella sonnei* (77). Humans are the only natural reservoirs for these species of bacteria (78). *Shigella flexneri* is the most common species associated with shigellosis in low-and middle-resource countries, whereas *Shigella sonnei* is the predominant species associated with shigellosis in high-resource countries (77). Globally, an estimated 163.2 million cases of shigellosis occur annually in low- and middle-resource countries, largely attributed to factors including poor sanitation and hygiene conditions, untreated water, and overcrowding (79).

High-resource countries experience significantly lower prevalence rates of shigellosis, with an estimated 1.5 million cases reported each year (79). However, there are specific populations within these countries with an increased risk of infection, including children under five years old, the elderly, travelling to endemic regions, and homosexual men (77,80,81). *Shigella* spp. are transmitted via the fecal-oral route, primarily through person-to-person contact or the consumption of contaminated food or water (82). Shigellosis symptoms usually present as watery or bloody diarrhea, abdominal pain, nausea and fever. In severe cases dehydration, arthritis and bacteremia can occur (83).

1.5.6 Cyclospora cayetanensis

Cyclospora cayetanensis is a coccidian protozoan parasite that causes cyclosporiasis (84). Humans are the only known host where *Cyclospora cayetanensis* can reproduce (85). Infections occur when individuals ingest active oocysts. These oocysts are excreted in human feces and require 7-15 days to sporulate at 15-25℃ to become infectious (86). Due to a long sporulation process, person-to-person transmission is unlikely (87). It is estimated that 90% of *Cyclospora cayetanensis* infections are transmitted through the consumption of contaminated food or water (33,86). Most outbreaks have been linked to raw produce, including raspberries, blackberries, cilantro, basil, and leafy greens (86). Contamination of raw produce can occur if contaminated water is used in agricultural practices or through poor handling of food by infected food workers (86).

Infected individuals usually experience asymptomatic or mild symptoms, including watery diarrhea, nausea, abdominal pain (85). In rare cases, symptoms can persist into more severe consequences such as weight loss and severe dehydration, which can be fatal (88). In low- and middle-resource countries, children, the elderly, and immunocompromised individuals have

increased susceptibility of developing cyclosporiasis. Although in high-resource countries where the parasite is not endemic, individuals who travel to endemic countries are at a greater risk of infection (89).

The global prevalence of cyclosporiasis is relatively low, with only 3.4% of humans worldwide developing gastrointestinal illness from *Cyclospora cayetanensis* infections (90). However, the prevalence rates are significantly higher in low- and middle-resource countries (7.6 and 4.8%) compared to high-resource countries (0.4%) (90). Despite, a low prevalence of *Cyclospora cayetanensis* in high-resource countries, the number outbreaks have increased over time in high-resource countries due to the globalization of the food supply and the reliance of fresh fruits and produce from endemic countries (89).

1.5.7 Giardia duodenalis

Giardiasis is a gastrointestinal illness caused by the protozoan parasite *Giardia lamblia* (87). Giardiasis is the most prevalent parasitic disease worldwide, affecting an estimated 184 million people each year (91). *Giardia duodenalis* has been identified as a high-priority pathogen due to a steady increase in the annual number of reported cases of giardiasis globally (91,92). The parasite is transmitted by the fecal-oral route through the ingestion of *Giardia duodenalis* cysts (93). Individuals can develop an infection by consuming contaminated water or food, contact with contaminated surfaces, person-to-person or person-animal contact (87,93). Natural reservoirs of *Giardia duodenalis* include humans, dogs, cats, cows, sheep, goats, pigs, and beavers (94,95).

The prevalence of giardiasis is significantly higher in low- and lower-middle-resource countries ranging from 20-30% of the population (87). Low- and lower-middle-resource countries are disproportionately affected by giardiasis due to poor sanitation, hygiene practices,

and limited access to potable water (96,97). In contrast, the annual prevalence of giardiasis is significantly lower in high-resource countries, ranging from 2-7% of the population (87). Despite, greater access to safe and readily available water and better hygiene and sanitation practices, 75% of giardiasis outbreaks in the United States are linked to waterborne transmission (98). Risk factors for waterborne infection include drinking water from a river, lake, or stream, swimming in a natural body of water or public swimming pools, and camping (93,98). Foodborne transmission of *Giardia duodenalis* is less common, accounting for only 15% of giardiasis outbreaks reported in the United States (98). Produce, ice, and fruit are the most common vehicles associated with foodborne outbreaks (98,99).

Giardiasis often presents as acute clinical symptoms such as diarrhea, dehydration, nausea and abdominal pain (100). Long-term complications are rare but have been reported, including symptoms of muscular deficiencies, arthritis, and allergies (100,101). Populations with an elevated risk of developing an infection include children in daycare or school settings, campers, individuals who travel internationally, and homosexual men (87,100,101).

1.5.8 Hepatitis A

Hepatitis A virus is a positive-strand RNA virus that causes infectious hepatitis in humans (87). Humans are the only natural hosts for hepatitis A virus, and transmission occurs by the fecal-oral route, usually from person-to-person contact or from the ingestion of contaminated food or water (102). Foodborne transmission only accounts for a small proportion of hepatitis A cases; specific food items, including frozen strawberries, shellfish, and ready-to-eat foods, have been frequently associated with outbreaks (103-106). However, many reported hepatitis A cases have an unknown source of infection (106).

An estimated 100 million hepatitis A infections occur each year worldwide (107). The burden of hepatitis A infections is significantly higher in low- and middle-resource countries due to poor sanitation, inadequate housing conditions, and a higher proportion of the population living in poverty (107). Hepatitis A infections are quite rare in high-resource countries although there are specific groups with an elevated risk of contracting hepatitis A virus. This includes travellers, homosexual men, individuals who inject drugs, the homeless, prisoners, and immunocompromised individuals (107). The clinical symptoms of acute hepatitis A infection include nausea, vomiting, abdominal pain, diarrhea, dark-coloured urine, and jaundice (107). Children under the age of five are usually asymptomatic (107). Although, hepatitis A primarily manifests as acute symptoms, in rare cases liver failure can occur, especially in older adults and individuals with pre-existing liver conditions (108).

1.6 Spatial and Temporal Patterns of Enteric Pathogens in Canada

Recent advances in spatial and spatio-temporal epidemiology have provided a greater understanding of the spatial and temporal patterns of enteric infections, indicating potential etiological factors (109). In Canada, geographic information systems and geo-statistical methods, such as spatial autocorrelation analysis and space-time scan statistics have been applied to investigate spatial, temporal, and space-time patterns and clusters of multiple enteric pathogens, including *Campylobacter*, *Salmonella* spp., *E. coli*, *Listeria monocytogenes*, *Shigella* spp., and *Giardia duodenalis* (110-117).

Spatial analyses have revealed that *Campylobacter*, *Salmonella* spp., and *E. coli* high-infection rate clusters are present in rural regions with greater cattle, swine, and poultry density (113,118). *Giardia duodenalis* infections show high-rate clusters in areas near freshwater bodies, which can be attributed to increased camping activities, increased prevalence of wildlife, and use

of untreated drinking water in these regions (117). Temporal analyses have revealed different seasonal trends amongst enteric pathogens; most *Campylobacter, E. coli,* and *Listeria monocytogenes* infections occur in the late spring and summer months, while *Salmonella* spp. infections predominantly arise in the summer and early fall months (110-115). *Giardia duodenalis* infections peaked during the spring and summer months, whereas *Shigella* spp. had no identifiable seasonal pattern (110,117). Space-time analyses have been used to identify localized high-infection rate clusters during specific periods, aiding researchers in finding outbreaks that may have been undetected by public health units (114,116). Spatio-temporal epidemiology has revealed that environmental and seasonal factors can influence the incidence of infectious diseases and should be considered when designing targeted intervention strategies to reduce the burden of enteric disease.

1.7 Determinants of Foodborne Illness

1.7.1 Social Determinants of Health

Despite advancements in hygiene, surveillance, and control practices in high-resource countries, the burden of communicable diseases is not equally or fairly distributed across the population (119). These health inequities are largely influenced by a range of social determinants of health that shape both individual- and population-level exposure and vulnerability to unsafe food (120).

These determinants have been categorized into three different levels: proximal, intermediate and distal. Proximal determinants are individual level characteristics such as health behaviours, living conditions, income, employment, education, and food insecurity that directly affect an individual's exposure, vulnerability, and physical health (119,121). These proximal determinants are heavily influenced by intermediate determinants including physical, social and political access to health care systems, the status of the community in which an individual lives

in, and cultural continuity (120,121). Distal determinants such as racism, social exclusion and self-determination are the macro-level conditions that shape the proximal and intermediate determinants (120).

All three levels of determinants play critical roles in shaping health outcomes. However, proximal determinants have an immediate and direct influence on an individual's lifestyle, behaviours, preferences, and environment (119). Understanding these factors is essential for identifying broad social, economic, or political factors that contribute towards poor health outcomes in different population groups (119,121).

1.7.2 Proximal Level Determinants and Foodborne Illness

Several individual-level risk factors have been associated with the transmission of foodborne pathogens in human populations, beyond the consumption of contaminated food and water. These include frequent dining at restaurants, poor hygiene and sanitation practices, contact with an infected person or animal, international travel, inadequate food safety knowledge, and poor food safety behaviors (122-127). Demographic factors such as age, sex, and ethnicity have also been associated with specific foodborne outbreaks, due to specific food preferences and consumption patterns (128-130). Differences in food consumption patterns can be influenced further by structural economic determinants. Socioeconomic status (SES) has been recognized as a key predictor of chronic and communicable diseases. Individuals with lower SES are at a greater risk of developing diabetes, cardiovascular disease, and various infectious diseases (131-135). However, the relationship between SES and enteric infections is poorly understood, mainly due to the complex nature of each pathogen, being biologically unique, and possessing unique transmission pathways, influenced by many different behavioural risk factors and social determinants of health (131).

Low income and marginalized populations often face unique food safety barriers due to limited social or economic access to essential food safety equipment such as cutting boards, food thermometers, dishwashers, and refrigerators operating at adequate temperatures (125,131, 136,137). Furthermore, families with lower incomes are more likely to use food banks and emergency food assistance providers compared to families with higher incomes (78). Food banks and emergency food assistance programs present additional unique exposure pathways for foodborne illness, since donations to these organizations can include unsafe food products, potentially unsafe or unsuitable for consumers (138). Additionally, these programs can have poor management and heavily rely on volunteers who lack adequate food safety knowledge and training, increasing the risk of contamination (139). Interestingly, individuals and families with higher SES characteristics also frequently engage in behaviours that increase their risk of developing foodborne illnesses, such as consuming undercooked or raw meat, owning pets, eating at restaurants, and international travel (125,131,140).

1.7.3 Proximal Determinants of Foodborne Illness Aggregated to the Population-Level

Most research on foodborne illness has focused on individual- and household-level risk factors. However, it is also important to consider how enteric infection rates are distributed across populations geographically. Emerging evidence suggests that aggregate-level social, demographic, and economic characteristics are associated with the incidence of enteric infections in different regions, as follows.

At the aggregate-level, socioeconomically advantaged regions, measured by higher income and higher education levels have been associated with a higher incidence of *Campylobacter* infections (118,141,142). The associations between *Salmonella* spp. infections and aggregate-level SES measures are complex and conflicting. Certain studies have reported that populations

living in census tracts with lower unemployment rates, higher income, and education levels were associated with a higher incidence of *Salmonella enteritidis* infections (142-145). However, high-infection-rate spatial clusters of *Salmonella* spp. in Toronto, Canada, were found in geographical areas with both higher and lower average median family income and households with a greater number of children (146).

Similarly, the incidence of *E. coli* infections has shown a complex non-linear relationship with aggregate-level SES measures. Populations residing in lower poverty census tracts were found to have a higher incidence of *E. coli* infections (145,147,148). While other research reported cases included in high-infection rate clusters of STEC in Ontario, Canada, had increased odds of living in areas of low income, and a low proportion of lone-parent families (149).

In the case of listeriosis, the highest incidence rates have been observed in the most socioeconomically disadvantaged areas of England (150). In the United States, higher poverty rates at the census tract level were associated with increased incidence rates of shigellosis (130,151). More advantaged regions in Canada and Australia, considered to have a higher quality of life, were found to be significantly associated with a lower incidence of *Giardia duodenalis* infections (152,153). Currently, the association between the incidence of *Cyclospora cayetanensis* and hepatitis A infections and aggregate-level SES characteristics has not been explored, despite outbreaks occurring in high-resource countries (154,155).

While broad aggregate-level socioeconomic indicators are important predictors of communicable diseases, they do not fully capture the relationship with foodborne illness. Since these indicators do not directly measure an individual's or a household's experience with food access and food safety. One key determinant that has not been considered in this relationship is

food insecurity, which serves as an intermediary determinant that could help to establish links between different structural determinants of health and the risk of foodborne illness (119).

1.8 Food Insecurity and Foodborne Illness

1.8.1 Food Insecurity in Canada

According to the Food and Agriculture Organization of the United Nations, food security is "when all people, at all times, have physical, social, and economic access to sufficient, safe, and nutritious food that meets their dietary needs and food preferences for an active and healthy life" (156,157; p.56). To achieve food security there are four pillars that must be satisfied: availability, accessibility, utilization, and stability (158). Food insecurity exists when one or more of these pillars is disrupted, which can compromise food safety and ultimately human health (158). However, this framework of food security is outdated, since it does not consider the broad and complex dynamics that are associated with hunger and malnutrition (159).

Recently, Clapp et al. (159) have proposed a six-dimension framework for food security policy formulation, adding two additional pillars: agency and sustainability. Agency involves the redistribution of power within food systems, that allows individuals and vulnerable groups to be involved in the governance process, to minimize any food system inequities (159). Sustainability focuses on whether food systems can provide longer-term food security and nutrition for future generations, without compromising economic and environmental resources (159). Canada's federal sustainable development strategy aligns with these new dimensions of food security. The second goal of the strategy, for example, emphasizes the need for a more sustainable food system (160). However, the current industrial and technological model of food production is not sustainable for future generations (159). To respond to these challenges Canada's agriculture sector has adopted new technologies and climate-resilient practices to create a more sustainable

food system that generates and supports long-term food security nationally (159,160). Although, Canada is taking appropriate next steps towards creating a more sustainable food system, food insecurity is still a significant public health issue (161).

As of 2023, an estimated 8.7 million Canadians were food insecure (161). The proportion of households experiencing food insecurity was the highest in Nova Scotia (28.9%), Prince Edward Island (28.6 %) and the lowest was in British Colombia (21.8%) and Quebec (15.7%) (161,162). In Ontario, 24.5% of households experienced food insecurity, this is slightly higher than the national average of 22.9% across the ten provinces (161,162). Food insecurity poses another serious social public health issue because of its negative health impact and the economic burden it places on healthcare resources and spending (163,64). Individuals living in chronically food-insecure households are at a greater risk of injury, infectious disease, and chronic disease, especially if they are living in severely food-insecure households. (163,165-167). From 2022 onward, there has been a significant increase in the proportion of Canadians living in marginally, moderately, and especially severely food-insecure households. Likely leading to increases in annual healthcare expenditures, disrupted household and family dynamics, and exacerbate social and economic inequities (163,164,168).

1.8.2 Food Insecurity and Food Safety

Historically, food insecurity and foodborne illness have been identified as separate issues in public health practice (169). However, food security and food safety are interrelated concepts that share proximal, intermediate, and distal social determinants including ethnicity, gender, income, education, living and working conditions (119,170,171). Household food insecurity, measured by any household-reported experiences of food deprivation over the last 12 months, is more common in lower-income households and marginalized populations in Canada

(161,172,173). Quinlan (125) concluded that lower-income and marginalized populations are at a greater risk of foodborne illness due to often inadequate food safety knowledge and behaviours. Within lower-income settings there may be inaccurate beliefs that exist, for example that freezing food kills bacteria, or that foods that always smells or tastes bad will make people sick, along with perhaps a lack adequate knowledge of proper cooling and storage methods (174,175).

Moreover, since the COVID-19 lockdowns, there has been an increase in unsafe food behaviours, such as consuming food past the use-by date (156). The use-by-date indicates the last day a food-item is safe to eat; consuming a food item after the use-by date significantly increased the risk of a consumer developing a foodborne illness (176). These unsafe behaviours are more common among food-insecure populations due to limited financial resources and poor access to quality foods (177). However, other research has reported that lower-income individuals frequently performed food safety practices (e.g., proper storage, cooking, and reheating) that exceeded their food safety knowledge (125,178).

1.8.3 Small Retailers and Food Safety Challenges

Lower-income populations are more likely to live in 'food deserts', which are "low-income geographic areas that lack access to a supermarket or large grocery store" (172,179; p.2). In these areas, food-insecure populations heavily rely on small markets and convenience stores that may offer some more nutritious fresh produce, meat, and dairy products (179-181). However, these products are often sold at higher prices than large grocery stores, further reinforcing circumstances that contribute to worsening levels of household food insecurity (182). Smaller and medium independently owned food stores are more likely to experience food safety barriers due to a lack of resources, limited knowledge, poor infrastructure, and refrigeration (181,183).

For example, non-supermarket owners and managers were found to purchase products from other supermarkets and transport these products in an unrefrigerated personal vehicle (184).

Food products from smaller markets located in food deserts, including ready-to-eat greens, strawberries, cucumbers, and milk, had higher microbial loads and higher internal egg temperatures (180,181). Populations that live in food deserts could be more likely to consume foods with poor microbial quality, which could increase an individual's risk of developing a foodborne illness.

1.8.4 Chronic Disease and Vulnerability to Enteric Infections

Food deserts are also known to have a higher density of fast-food outlets and increased access to highly processed foods (185). A Canadian study found that food-insecure populations have greater fast-food consumption patterns which can result in health challenges (186). Individuals who frequently dine at fast-food restaurants are at a decreased risk of foodborne illness compared to individuals who frequently dine at sit-down restaurants, due to different food preparation methods, customer consumption patterns, and differences between cooking and supplier guidelines (187). However, food insecurity is associated with poorer nutrition status, limited dietary quality, and diversity due to a heavy reliance on fast and processed foods, which could lead to weight gain and increase an individual's chance of developing chronic disease conditions (189,190). Chronic diseases, such as type 2 diabetes, can increase an individual’s susceptibility to foodborne illness and negatively affect the body’s ability to fight off foodborne infections, leading to more severe health complications such as *Listeria* meningitis (190-192).

1.9 Rationale

The existing findings demonstrate that the associations between different socioeconomic status (SES) variables and the incidence of enteric infections are complex and differ depending on the specific foodborne pathogen (118,130,141-151). These studies rely on broad economic determinants such as education or median income as area-level risk factors for enteric infections, which may not completely explain food consumption, food handling, and food production behaviours (119). Although these economic determinants are strong predictors of food insecurity at a population level, they may not capture an individual or family's experience with food consumption, food safety, accessibility, and availability (172,193). Food insecurity may serve as a direct intermediary determinant between SES and foodborne illness (131). Emerging evidence supports that food-insecure populations experience differential vulnerability to enteric infections due to increased susceptibility to various food safety exposures (119,158). Despite this link, no studies have explored whether area-level food insecurity is a risk factor for enteric infections. This study is the first to examine the relationship between the incidence of *Campylobacter* spp., *Salmonella* spp., STEC, *Listeria monocytogenes*, *Shigella* spp., *Cyclospora cayetanensis*, *Giardia duodenalis*, and hepatitis A infections and food insecurity at a population level in Ontario, Canada.

2.0 Specific Aims and Objectives

2.1 Overall Aim

This thesis aimed to investigate the area-level relationship between the incidence of *Campylobacter* spp., *Salmonella* spp., STEC, *Listeria monocytogenes*, *Shigella* spp., *Cyclospora cayetanensis*, *Giardia duodenalis*, and hepatitis A infections and household food insecurity in Ontario, Canada, 2019-2022.

2.2 Research Objectives

The specific objectives of this thesis were to:

1. Determine the annual age- and sex-adjusted incidence rates of reported *Campylobacter* spp., *Salmonella* spp., STEC, *Listeria monocytogenes*, *Shigella* spp., *Cyclospora cayetanensis*, *Giardia duodenalis*, and hepatitis A infections for each of Ontario's Public Health Units (PHUs) and identify purely spatial, purely temporal, and space-time high incidence rate clusters (2019-2022);
2. Explore the global and local spatial patterns of Public Health Unit (PHU) level annual pathogen-specific incidence rates; and
3. Examine the annual age- and sex-adjusted pathogen-specific incidence rates from (1) that are associated with household food insecurity rates, demographic, and socioeconomic factors at the PHU level (2021).

3.0 Methods

3.1 Study Population and Setting

This study was conducted in Ontario, Canada, from 2019-2022. Ontario is the most populous province in the country, with an estimated population of 14,573,565 in 2019, 14,761,811 in 2020, 14,842,488 in 2021, and 15,145,006 in 2022 (194). Moreover, Ontario contains 34 PHUs, each governed by a board of directors (Boards of Health), the legal bodies responsible for managing and administering public health programs and services provided within Ontario PHUs (195). The PHU operations are led by a Medical Officer of Health, Chief Executive Officer, Chief Administrative Officer, or Commissioner, depending on the typology of the PHU organizational structure (Autonomous, Autonomous-Integrated, Regional, Municipal Single-Tier, or Municipal Semi-Autonomous; 195). Each PHU serves a unique geographical area and provides a wide range of services such as health promotion and disease prevention programs (Figure 1) (196). PHUs are also grouped into different administrative health regions (i.e., Northeast, Northwest, East, Toronto, Central, and West) for government reports (196).

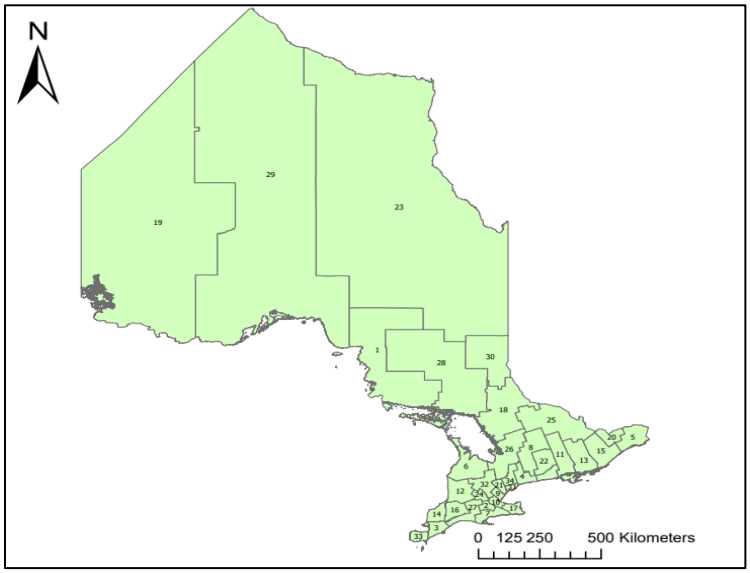


Figure 1. 34 Public Health Units in Ontario, Canada. The names of each PHU and their administrative health region is listed in Table A1 (Appendix A).

3.2 Data Sources

3.2.1 Enteric Infection Surveillance Data

Campylobacteriosis, salmonellosis, Verotoxin-producing *E. coli,* commonly referred to as Shiga toxin-producing *E. coli* (STEC), listeriosis, shigellosis, cyclosporiasis, giardiasis, and hepatitis A virus have all been classified as diseases of public health significance under Ontario Regulation 135/18: Designation of Diseases (197). Health care providers, laboratories, or other individuals are required to report diseases of public health significance to the Medical Officer of Health representing the local PHU (197,198). The PHUs subsequently report case data to the province using the integrated Public Health Information System (iPHIS) (198). The iPHIS is the main surveillance system used by all 34 PHUs to report cases of diseases of public health significance and serves as the primary source for the Infectious Disease Trends in Ontario tool (198).

This study used the Infectious Disease Trends in Ontario tool to collect aggregate surveillance data on reported *Campylobacter* enteritis, salmonellosis, STEC, listeriosis, shigellosis, cyclosporiasis, giardiasis, and hepatitis A cases that occurred at the PHU level from 2019-2022. The tool allows users to filter a specific PHU's case counts by five- and ten-year age groups (0-4, 5-9, 10-19, 20-29, 30-39, 40-49, 50-59, 60+), sex (male or female), month, and year (194). The tool also stratifies annual PHU-specific population counts by age group and sex (194).

PHU level case counts stratified by age group, sex, month, and year, and annual age- and sex-population counts were manually imported from the tool into Microsoft Excel, where multiple data sets were created to calculate unadjusted, adjusted incidence rates and conduct other statistical analyses. The data used in this study were from the most recent update of the Infectious Disease Trends in Ontario tool that occurred on December 13th, 2024. Ethics approval was not required for this study since the data is publicly available and anonymous.

3.2.2 Household Food Insecurity Data

PHU level household food insecurity data were obtained from a downloadable CSV file provided in the Household Food Insecurity Snapshot tool, created by Public Health Ontario (PHO) (199). The food insecurity tool captures geographic and temporal trends of the weighted percent of food insecure households experiencing marginal, moderate, and severe household food insecurity at the PHU level, PHU region, and snapshot peer groups (200). The interactive food insecurity snapshot map displays the prevalence of annual household food insecurity within Ontario PHUs from 2019-2022.

The publicly available food insecurity prevalence estimates used in this study ranged from 10.4%-23.4% and were measured previously by PHO, drawing on household data collected from the Canadian Income Survey (CIS) (201). The CIS is a cross-sectional survey that collects information on many economic indicators such as personal income, food security, and cost of housing (201). These indicators are supplemented with various demographic variables (201). Since 2018, the CIS has included the Household Food Security Survey Module (HFSSM) to measure food insecurity rates (201). The HFSSM is a validated measurement tool that measures inadequate or insecure access to food due to limited financial resources, availability, utilization, and compromised food consumption patterns (202-204).

The food insecurity estimates used in this study are based on data from the CIS because it has been recommended to monitor food insecurity over the Canadian Community Health Survey (CCHS) for several reasons, as follows (204). First, the CIS has a consistently higher response rate (70.1%). Second, the CIS is designed to produce annual-prevalence estimates. Third, the food insecurity prevalence rates provided by the CIS are updated regularly. Lastly, it measures various economic and labour indicators that can help inform the development of effective

interventions that address food insecurity. These features allow the CIS to capture a more accurate aggregate measure of food insecurity across Ontario (204).

3.3.3 Public Health Unit Demographic and Economic Profile Data - 2021 Canadian Census

Demographic and socioeconomic data for Ontario PHUs were collected from the 2021 Canadian Census of Population. The Census of Population is conducted every five years and is the primary source for providing publicly available data on Canada's population, demographic, and socioeconomic profiles (205).

The selection of certain demographic and socioeconomic predictor variables included in this study was aided by Statistics Canada Health Region Peer Groups-Working Paper, 2018 (206). In this paper, a stepwise discriminant analysis was conducted to identify which variables played a key role in defining PHUs based on their socioeconomic characteristics (206). The five strongest predictors identified in the stepwise analysis were: population density, proportion of the population that is a visible minority, proportion of the population under 20 years old, long-term unemployment rate, and internal migrant mobility (five years) (206). Out of these variables, visible minority proportion, long-term unemployment rate, and five-year internal migrant mobility were included as covariates in this study. In addition to these three variables, other aggregate-level socioeconomic variables such as median household income, average household size, total one-parent family households, education, and household spending characteristics were also included as covariates due to their potential influence on the relationship between food insecurity and foodborne illness.

3.3.4 Description of all Variables Included in the Study

Below is a summary of all the variables included in this study, along with their definitions, the source which they were retrieved, and measurement types (Table 1). All variables were aggregated to the PHU level. The administrative health region was not included as a predictor variable in the fixed regression models. However, it was included as a random effect in the multi-level models.

Table 1. Definition, data source, and measurement type of variables aggregated to the Public Health Unit level for analysis.

Variables	Definition	Source	Measurement Type
Annual age- and sex-adjusted pathogen-specific incidence rates (Outcome)	The total number of pathogen-specific cases. Divided by the population at risk at the start of the study period, subtracted by half the number of people developing the disease, multiplied by one year (2021), and then multiplied by 100,000 person years. Rates accounted for the age and sex structures of a PHU's population.	Infectious Disease Trends in Ontario tool (194).	Count/Rate
Age (Predictor)	Age category of the aggregate case counts.	Infectious Disease Trends in Ontario tool (194).	Categorical (0-4, 5-9, 10-19, 20-29, 30-39, 40-49, 50-59, 60+)
Sex (Predictor)	Sex of the aggregate case counts.	Infectious Disease Trends in Ontario tool (194).	Categorical (Male, Female)
Health Region (Random Intercept)	Administrative areas or regions of interest defined by the provincial Ministry of Health.	Infectious Disease Trends in Ontario tool (194).	Categorical (Central West, East, Central East, Southwest, Northeast, Northwest, Toronto).
Annual household food insecurity (2019-2022) (Predictor)	Proportion of households experiencing marginal, moderate, and severe inadequate access to food due to financial constraints, within a PHU.	Food Insecurity Snapshot Tool (199).	Continuous (%)
Visible minority (Predictor)	Proportion of the total population that is not Caucasian.	2021 Canadian Census (205).	Continuous (%)
Long-term unemployment rate (Predictor)	Proportion of the population aged 15 and over who did not have a job for a year or longer.	2021 Canadian Census (205).	Continuous (%)

Internal migrant mobility (Predictor)	Proportion of the population aged 5 years and over who have moved within Canada in the last five years.	2021 Canadian Census (205).	Continuous (%)
Median household income (Predictor)	The median after-tax income of all households within a PHU.	2021 Canadian Census (205).	Continuous
Average Household Size (Predictor)	Average number of people living in a private dwelling.	2021 Canadian Census (205).	Categorical (2.2, 2.3, 2.4, 2.5, 2.6, 2.8, 3.0, 3.2)
Total one-parent family households (Predictor)	The proportion of census family households that are one-parent families.	2021 Canadian Census (205).	Continuous (%)
Education (Predictor)	The proportion of the population aged 25-64 in private households with a postsecondary certificate, diploma, or degree.	2021 Canadian Census (205).	Continuous (%)
Household Spending Characteristics (Predictor)	The proportion of the total households that spend 30% or more of their income on shelter costs.	2021 Canadian Census (205).	Continuous (%)

3.4 Data Analysis

3.4.1 Descriptive Analysis

Annual unadjusted incidence rates for each pathogen were manually calculated in Microsoft Excel. The numerator was the total number of pathogen-specific cases aggregated to the PHU level. The denominator was the population at risk at the start of the study period, subtracted by half the number of people developing the disease during the time period (one year), and then multiplied by 100,000 person years (207). Annual age- and sex-adjusted incidence rates were computed for each PHU using direct standardization, with the 2021 Ontario population as the standard reference population (207).

Summary statistics, including the mean, median, minimum, maximum values, and standard deviation, were computed for all socioeconomic covariates in Microsoft Excel.

3.4.2 Incidence Rate Mapping

Both unadjusted and adjusted incidence rates were uploaded into ArcGIS Pro 3.4 (208), spatially joined to a PHU boundary file that was downloaded from Ontario GeoHub, and visualized using choropleth maps (209). A combination of geometric and manual classification methods was used to visualize pathogen-specific incidence rates over time (2019-2022) (210). The geometric interval data classification method was applied to a pathogen's 2019 incidence rates to establish five baseline class breaks. The baseline class breaks were then applied to the subsequent years (2020-2022), with the upper-class break for a pathogen left open and manually adjusted to account for annual differences in a specific pathogen's incidence rate. The geometric classification method was used to account for any growth or decline in pathogen-specific incidence rates over the study period (210).

3.4.3 Spatial, Temporal, and Space-time Cluster Analysis

A single dataset was created in Microsoft Excel that included three components: a case file that identified the number of cases stratified by the location ID (i.e., PHU) and the time of infection (month and year); a population file that contained the annual population size of each PHU; and a coordinates file that provided the x and y centroid coordinates for each PHU. The x and y centroids of each PHU were calculated in ArcGIS Pro 3.4 (208) using the Calculate Geometry Tool.

The dataset was uploaded into SaTScan v10.1 (211), where purely spatial, purely temporal, and space-time retrospective scan statistics were conducted using a discrete Poisson model to identify high infection rates of *Campylobacter* spp., *Salmonella* spp., STEC, *Listeria monocytogenes*, *Shigella* spp., *Cyclospora cayetanensis*, *Giardia duodenalis*, and hepatitis A. A circular scanning window with a maximum cluster size of 25% of the study population at risk was selected to identify any statistically significant purely spatial high-rate clusters. A maximum cluster size of 25% was chosen instead of the default (50%) to identify smaller clusters at the PHU level. A temporal scan statistic with a minimum temporal length of one month and a maximum temporal length of one year was specified in the temporal window tab to detect any statistically significant purely temporal high-rate clusters. A cylindrical space-time scan statistic with a circular geographic base was used to identify any statistically significant space-time high-rate clusters. The same maximum cluster size and temporal length settings were used in the space-time analysis.

The scanning window moves continuously across space and time and examines whether the number of observed cases in each location is Poisson-distributed, and if the expected number of cases in each PHU is proportional to the population size of that study region of interest (212,

213). High infection rate clusters were identified when the infection rate inside the scanning window was significantly greater than the expected infection rate outside the scanning window (213). The log-likelihood ratio test was used to identify high infection rate clusters that were the least likely to occur due to chance (212). Monte Carlo hypothesis testing with 999 replications was used to compute p-values for high infection-rate clusters (213). The relative risk (RR) was also computed for each statistically significant cluster by measuring the estimated risk inside a cluster compared to the estimated risk outside a cluster (212).

Statistically significant spatial and space-time high-rate clusters were visualized in ArcGIS Pro 3.4 (208) by uploading the shapefiles produced in SaTScan v10.1 (211). Statistically significant spatial, temporal, and space-time high-rate cluster results were also tabulated in Microsoft Excel.

3.4.4 Global and Local Spatial Autocorrelation Analysis

All analyses were conducted in ArcGIS Pro 3.4 (208).

Annual unadjusted pathogen-specific incidence rates were spatially joined to the PHU boundary files to create polygon features with the incidence rate data. Global spatial outliers were identified using the Spatial Outlier Detection tool with low detection sensitivity, where any point with a neighbour distance that exceeds a specific threshold is identified as a global outlier (214). Any PHUs that were identified as global outliers were excluded from both global and local autocorrelation analyses because of their potential to impact the accuracy of the spatial relationships between polygons.

Global spatial autocorrelation of the annual unadjusted pathogen-specific incidence rates was examined using the Incremental Spatial Autocorrelation (Global Moran's I) tool (208). The fixed distance band option and the Euclidian distance method were selected to determine an

appropriate threshold distance band. The Spatial Autocorrelation tool uses Global Moran's I statistics and compares the observed Moran's Index value and the expected index value to generate a z-score and p-value (215). A Moran's Index with a positive z-score with a value ≥ 1.96 and a p-value ≤ 0.05 indicates that high or low incidence rates across Ontario are more spatially clustered than expected under the assumption of complete spatial randomness (215). A Moran's Index with a negative z-score ≤ 1.96 and a p-value ≤ 0.05 indicates that high and low incidence rates are more spatially dispersed across Ontario than expected (215).

A beginning distance band of 214.96437 km was computed using the Incremental Spatial Autocorrelation (Global Moran's I) tool; this was the minimum distance required for each PHU to have at least one neighbour. This distance band was manually inputted into the Incremental Spatial Autocorrelation tool (208). The Incremental tool measures the Global Moran's I statistics at increasing distance increments (216). The number of distance increments was selected using a visual and iterative approach based on the spatial autocorrelation by assessing the distance line graphs. The distance band with the highest z-value ($p < 0.05$) in the incremental autocorrelation tool was selected for the local cluster and outlier analysis. If none of the distance bands produced a significant z-value, the default distance of 214.96437 km was used because it ensured each PHU had at least one neighbour.

Local spatial autocorrelation was examined using the Local Cluster and Outlier analysis tool (208). This tool computes a local Moran's I value, a z-score, a clustering type, and a p-value (217). A positive Moran's I with a p-value ≤ 0.05 indicates that a target PHU has a neighbouring PHU with similar incidence rates (217). This includes a target PHU with a high incidence rate surrounded by PHUs that have similarly high incidence rates or a target PHU with a low incidence rate surrounded by PHUs that have similarly low rates. A negative Moran's I with a p-

value ≤ 0.05 indicates that a target PHU has neighbouring PHUs with dissimilar incidence rates (217).

Spatial relationships were conceptualized using the zone of indifference method, Euclidean distance bands (centroid-centroid), and row standardization. This conceptualization method ensures that a target PHU and neighboring PHUs within a critical distance band receive a spatial weight of one (218). If any neighboring PHUs exceed this critical distance threshold, their respective spatial weights decrease as the distance to the target PHUs increases (218). The zone of indifference was chosen because it does not apply strict boundaries on neighbouring features, allowing more neighbouring features to be included in the analysis that could potentially influence the target feature (218). The results of the local spatial autocorrelation analysis were visualized via choropleth maps.

3.4.5 Regression Analysis

All regression analyses were conducted in RStudio (219).

Initially, Poisson regression models were used to examine the association between pathogen-specific incidence rates, household food insecurity, demographic, and socioeconomic variables. However, Poisson regression models often experience issues with overdispersion when modeling infectious disease data (220). Overdispersion violates the Poisson distribution assumption because the variance does not equal the mean (221). Each Poisson model was assessed for overdispersion with the goodness-of-fit-chi-squared test (219). *Campylobacter* spp., *Salmonella* spp., and *Giardia duodenalis* were the only pathogen-specific regression models that exhibited significant overdispersion, leading to the use of negative binomial regression models. All other pathogen-specific regression models did not have significant overdispersion thus a Poisson regression model was used.

Negative binomial regression models were conducted using the MASS package in to examine the associations between pathogen-specific incidence rates, household food insecurity, demographic and socioeconomic variables (222). Regression coefficients were exponentiated to obtain incidence rate ratios (IRRs) along with their 95% confidence intervals. These models were then compared with zero-inflated negative binomial models. The Vuong non-nested test was conducted using the pscl package to determine which model provided a superior fit with the dataset (223). The non-zero inflated models were deemed the superior models for each pathogen.

The dependent variable was the annual age- and sex-adjusted incidence rates of *Campylobacter* spp., *Salmonella* spp., STEC, *Listeria monocytogenes*, *Shigella* spp., *Cyclospora cayetanensis*, *Giardia duodenalis*, or hepatitis A infections at the PHU level in 2021. If the age or sex of a case was not specified, they were excluded from the analysis. The number of enteric infection cases missing age and sex data can be found in Table A2 (Appendix A). To account for differences in a PHU population structures, the estimated natural log of person-years (stratified by age, sex, PHU, and year) served as the offset variable in the model. The offset term is the denominator in the calculation of incidence rates.

The continuous predictor variables included in the regression analysis were the prevalence of household food insecurity rates in 2021, percentage of visible minorities, long-term unemployment rate, internal migrant mobility, median household income, total one-parent family households, education, and household spending characteristics. PHUs with missing household food insecurity estimates in 2021 were excluded from the regression analysis. The categorical variables included in the regression analysis were age, which was classified by 5- and 10-year intervals, and adults who were over the age of 60, sex, year, and health region. Except, the age groups for the *Listeria monocytogenes* regression analysis were stratified into broader

intervals since multiple age groups had zero case counts. The average household size was originally treated as a continuous variable. However, due to the variable's distribution in the scatter plot, average household size was transformed into a categorical variable. For each categorical variable, the category with the lowest regression coefficient was selected as the reference group.

Predictor variables were assessed for multicollinearity using Spearman's ranked correlation and the variance inflation test (224). Visible minority and average household size were highly correlated with various predictor variables (r_s >0.7 and a VIF>5). This led to the exclusion of visible minorities (%) and average household size from the multivariable models. A combination of manual backward elimination and stepwise backward elimination using the step() function was used to determine the optimal model (207,219). Predictor variables were manually removed from the model if their coefficients were not statistically significant (p>0.05), unless there was evidence of confounding. Confounding was assessed if an excluded covariate changed the sign, magnitude, and significance of a predictor variable's coefficient; if confounding was present, that covariate was included in the adjusted multivariable model (207).

To account for random variation across health regions, multilevel mixed-effects Negative Binomial regression models were constructed using the MASS package (222). The models retained the same dependent, predictor, and offset variables in the final multivariable model, except that the health region was included as a random intercept. However, since the predictor variables retrieved from the Canadian Census were only measured in 2021, the fixed and mixed-effect models only included data from that year. The likelihood ratio test was used to assess whether the fixed or mixed-effect model was superior. The quality of the fitted regression models was evaluated by inspecting residual vs fitted values, Q-Q residual plots, scale-location plots,

and residuals vs leverage plots. The plots were generated using the ggplot2 package in RStudio (225).

A Spatial Polygon Data Frame was created using projected coordinates from the UTM Zone 17N WGS84 coordinate system (219). A generalized geographically weighted regression (GGWR) was performed on the Spatial Polygon Data Frame using the spgwr package to explore whether the association between pathogen-specific incidence rates and household food insecurity was different across PHUs (226). The model settings specified a Poisson family, a Gaussian spatial weighting kernel function, and an adaptive bandwidth approach (227). An optimal spatial bandwidth was determined using the ggwr.sel function (227). This function performs cross-validation to assess model performance and selects the bandwidth that minimizes root mean square prediction error (227). The bandwidth that produced the lowest root mean square prediction error was included in the ggwr function to fit the model. To visualize spatial non-stationarity, the local coefficients were mapped in RStudio through the ggplot2 package (225). Additionally, the global model coefficients and the minimum, maximum, first quartile, third quartile, and median local IRRs were tabulated to summarize whether spatial non-stationarity was present.

4.0 Results

All Tables and Figures presented in the Results and Appendices are zoomable.

4.1 Case Counts and Incidence Rates for Eight Enteric Infections

4.1.1 The Annual and Cumulative Number of Reported Cases

Throughout the study period (2019-2022), a total of 23,869 cases of eight enteric infections were reported in Ontario, Canada. In 2019, before the COVID-19 pandemic, there were 8159 (34.19%) reported cases for the eight enteric pathogens (Table 2). The total annual number of reported cases significantly declined after 2019. *Campylobacter* spp. had the highest number of reported cases with 9594 (40.19%), while *Listeria monocytogenes* had the lowest number of reported cases with 290 (1.21%) (Table 2).

Table 2. Annual and cumulative reported case counts of eight enteric infections in Ontario, Canada (2019-2022).

No. (%)									
Year	***Campylobacter* spp.**	***Salmonella* spp.**	**STEC**	***Listeria monocytogenes***	***Shigella* spp.**	***Cyclospora cayetanensis***	***Giardia duodenalis***	**Hepatitis A**	**Total Annual**
2019	3232 (33.69)	2387 (34.76)	238 (31.99)	73 (25.17)	283 (34.51)	448 (32.35)	1298 (34.62)	200 (47.73)	8159 (34.19)
2020	1995 (20.79)	1511 (22.00)	131 (17.61)	69 (23.79)	165 (20.12)	351 (25.34)	853 (22.75)	77 (18.38)	5152 (21.58)
2021	2211 (23.05)	1194 (17.38)	169 (22.72)	73 (25.17)	125 (15.24)	98 (7.08)	786 (20.97)	52 (12.41)	4708 (19.72)
2022	2156 (22.47)	1776 (25.86)	206 (27.69)	75 (25.86)	247 (30.12)	488 (35.23)	812 (21.66)	90 (21.48)	5850 (24.51)
Total (2019-2022)	9594 (40.19)	6868 (28.77)	744 (3.12)	290 (1.21)	820 (3.44)	1385 (5.80)	3749 (15.71)	419 (1.76)	23,869 (100.00)

4.1.2 Demographic and Temporal Distribution of Enteric Pathogens' Incidence Rates

Throughout the study period (2019-2022), individuals aged 0-4 years consistently had the highest annual incidence rates of *Campylobacter* spp., *Salmonella* spp., and STEC infections, whereas individuals aged 60 years and older had the highest annual incidence rates of *Listeria monocytogenes* (Figure 2). The remaining pathogens did not have a single age group that consistently displayed the highest annual incidence rates of infections during the study period.

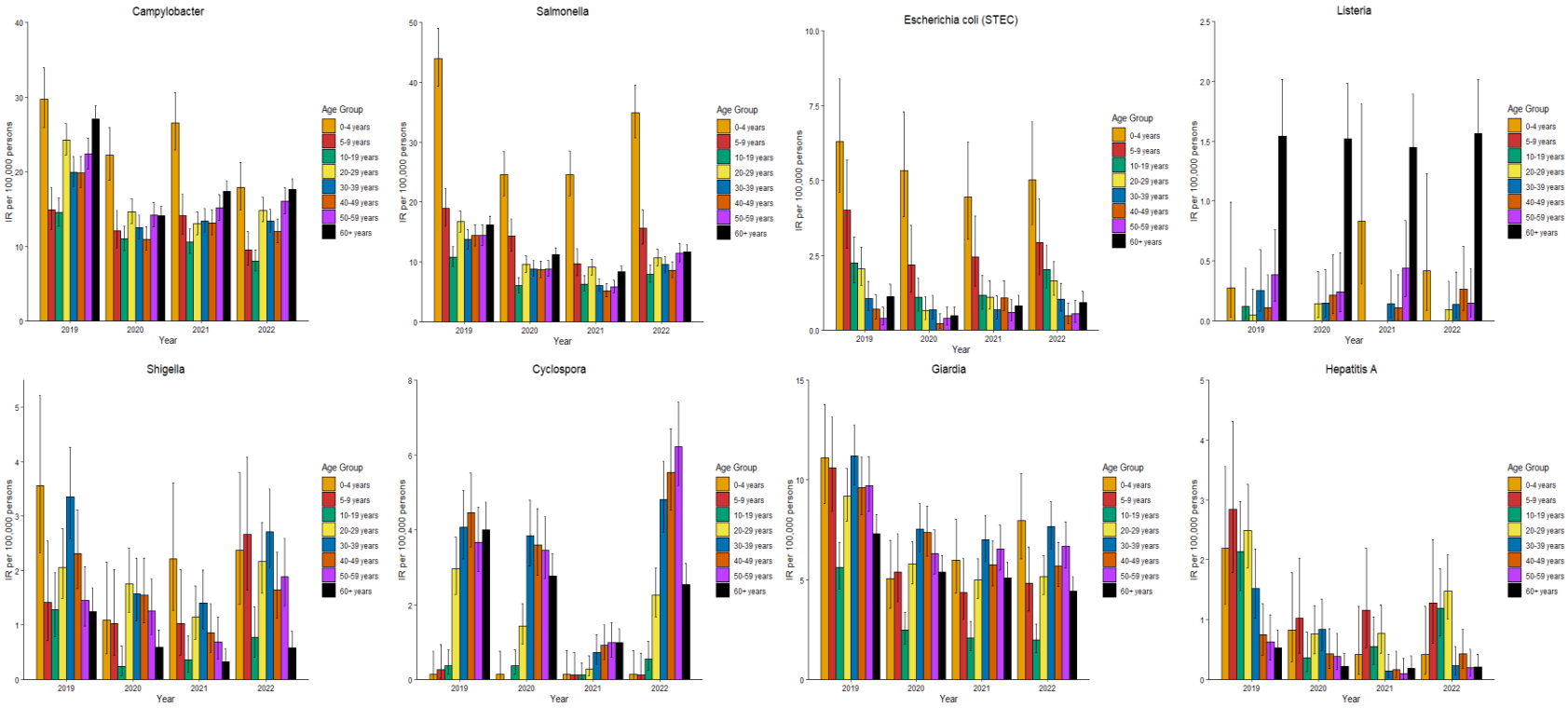


Figure 2. Annual incidence rates per 100,000 persons of eight reported enteric infections by age group in Ontario, Canada (2019-2022).

Males had higher annual incidence rates of *Campylobacter* spp., *Shigella* spp., *Giardia duodenalis,* and hepatitis A infections in each year of the study period compared to females (Figure 3). However, females consistently had higher annual incidence rates of STEC infections. The remaining pathogens' annual incidence rates varied by year, with higher rates in males during some years and higher in females during other years.

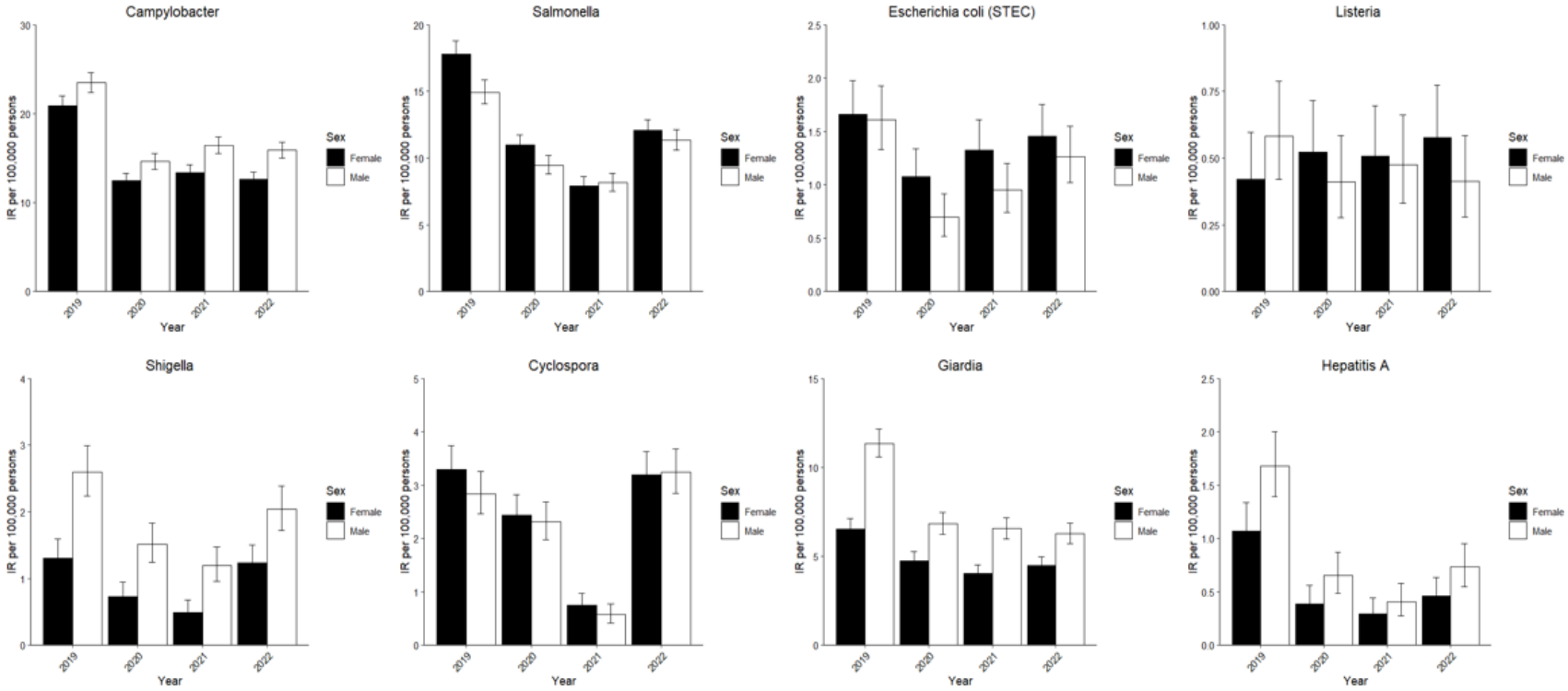


Figure 3. Annual incidence rates per 100,000 persons of eight reported enteric infections by sex in Ontario, Canada (2019-2022).

Campylobacter spp., STEC, and *Cyclospora cayetanensis* consistently had higher incidence rates during the summer months from 2019-2022 (Figure 4). The remaining pathogens did not display any distinct seasonal trends, as their incidence rates did not consistently peak in a specific season over the study period.

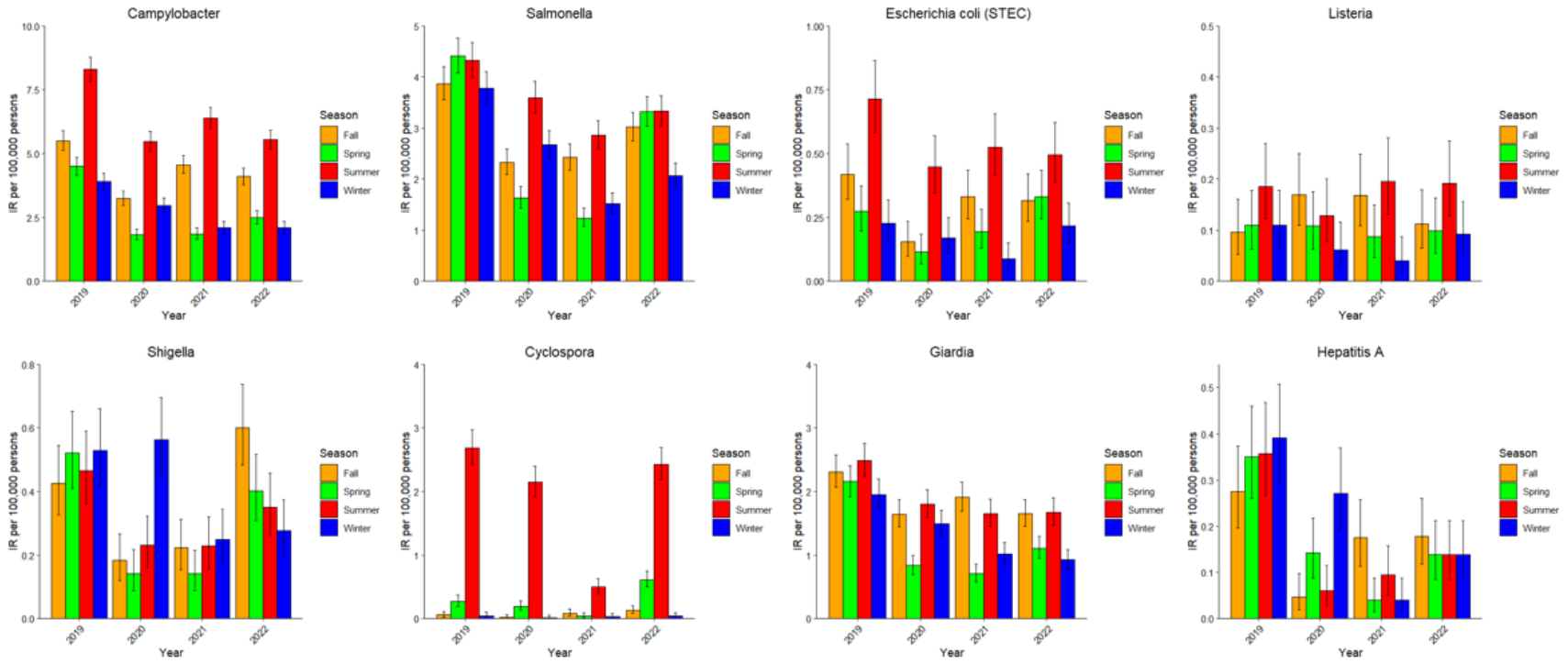


Figure 4. Annual incidence rates per 100,000 persons of eight reported enteric infections by season in Ontario, Canada (2019-2022).

Similar to the number of reported cases, the incidence rates of *Campylobacter* spp., *Salmonella* spp., STEC, *Shigella* spp., and hepatitis A infections significantly declined after 2019 (Figure 5). The incidence rates of *Listeria monocytogenes* remained consistent throughout the study period. Interestingly, the incidence rates of *Cyclospora cayetanensis* infections displayed the same declining trend after 2019, although *Cyclospora cayetanensis* experienced its highest annual incidence rate in 2022.

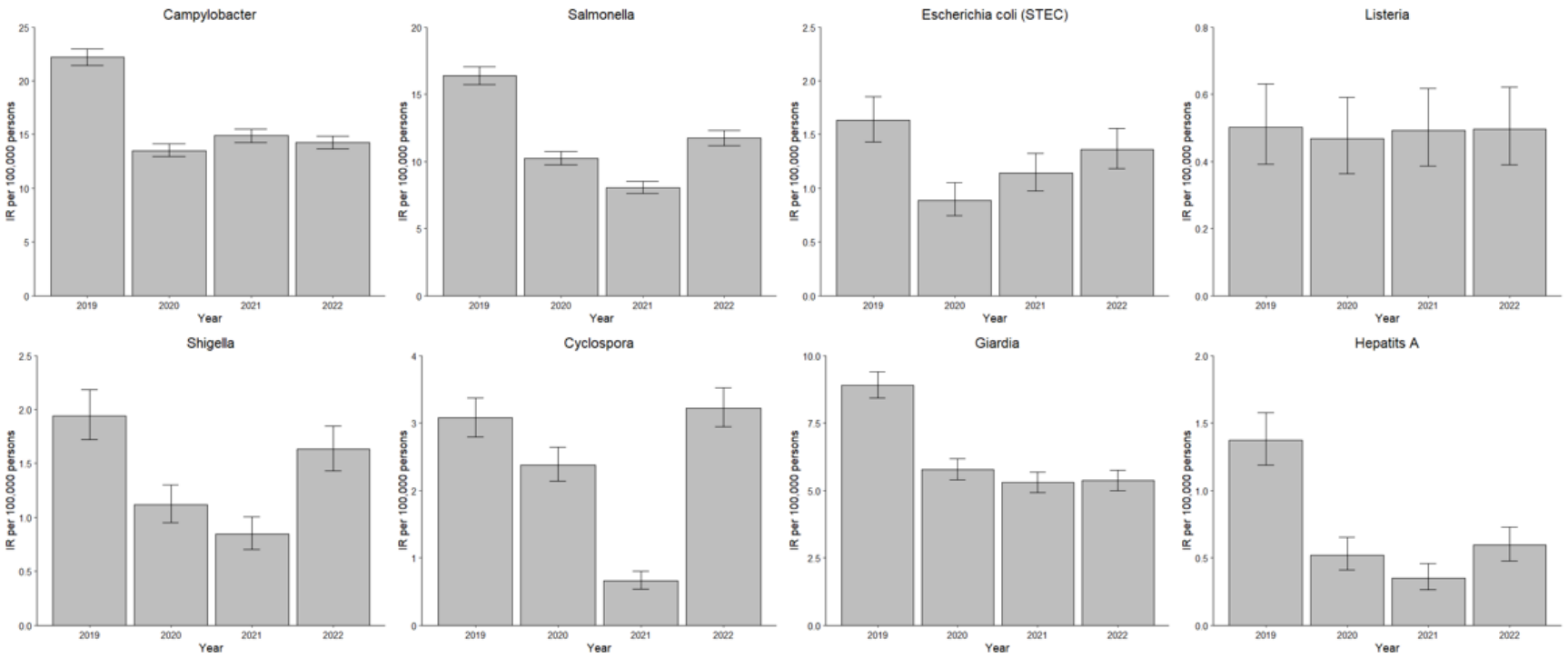


Figure 5. Annual incidence rates per 100,000 persons of eight reported enteric infections in Ontario, Canada (2019-2022).

4.1.3 The Distribution of Incidence Rates across Public Health Units Over Time (2019-2022)

Figures 6 and 7 show the changes in crude and adjusted incidence rates for each enteric pathogen at the PHU level over time from 2019-2022. Overall, the crude and adjusted incidence rates had similar values for each enteric pathogen across PHUs.

From 2019-2022, *Campylobacter* spp. *Salmonella* spp., and *Giardia duodenalis* had the highest incidence rates across PHUs compared to other enteric pathogens. *Listeria monocytogenes* and hepatitis A had the lowest annual incidence rates across PHUs throughout the study period. The highest annual incidence rates for *Campylobacter* spp. and STEC were found in Grey-Bruce, Huron-Perth, and Wellington-Dufferin-Guelph PHUs each year. *Giardia duodenalis* was the only pathogen that had some of its highest annual incidence rates in the Northern PHUs each year. In 2021, the annual incidence rates of *Salmonella* spp., *Shigella* spp., and *Cyclospora cayetanensis* significantly decreased in comparison to previous years. Across all years, the highest annual incidence rates for *Shigella* spp. were found in the City of Toronto.

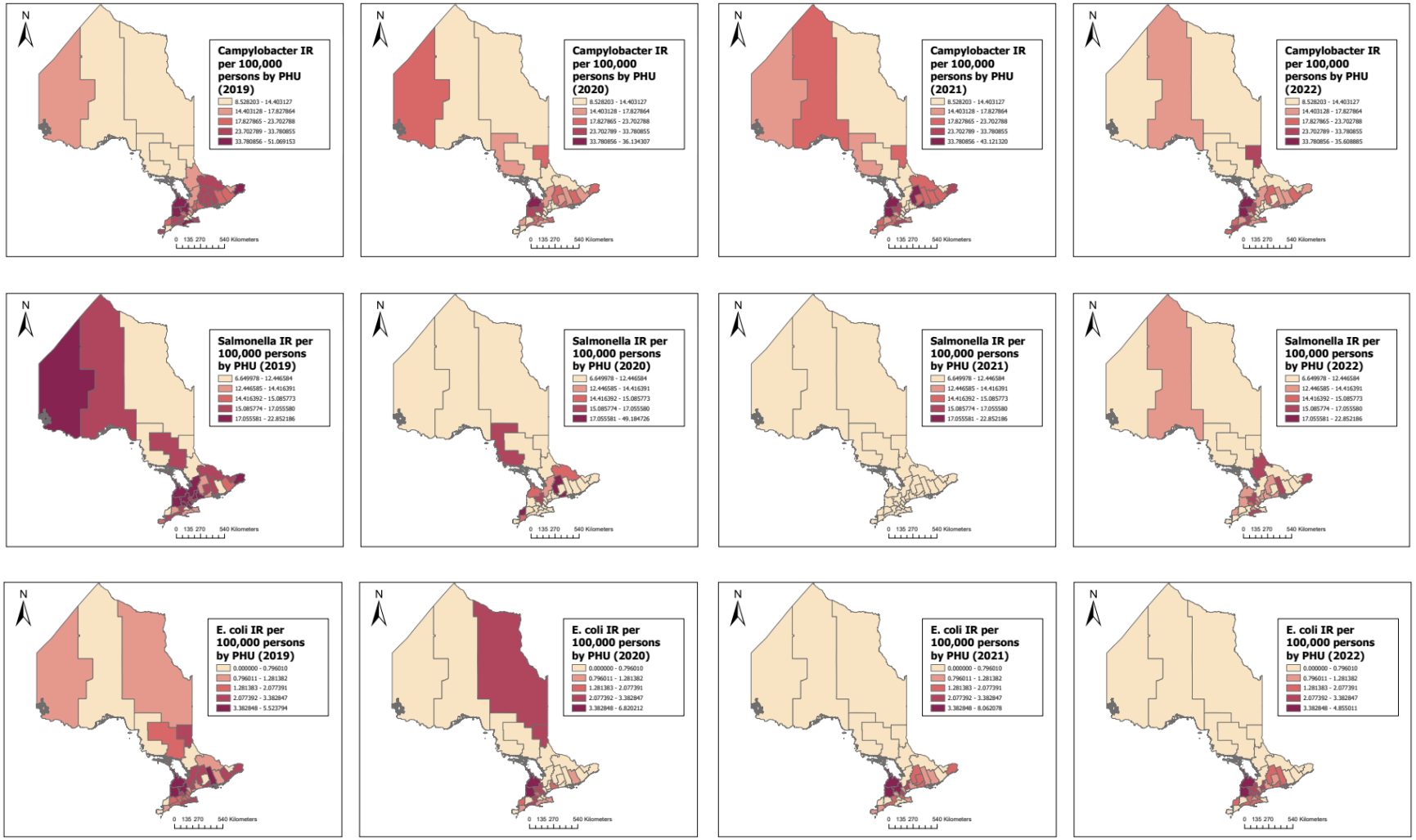


Figure 6. Crude incidence rates (IRs) of reported *Campylobacter* spp., *Salmonella* spp., STEC, *Listeria monocytogenes*, *Shigella* spp., *Cyclospora cayetanensis*, *Giardia duodenalis*, and hepatitis A infections at the Public Health Unit level in Ontario, Canada (2019-2022; continued on next pages).

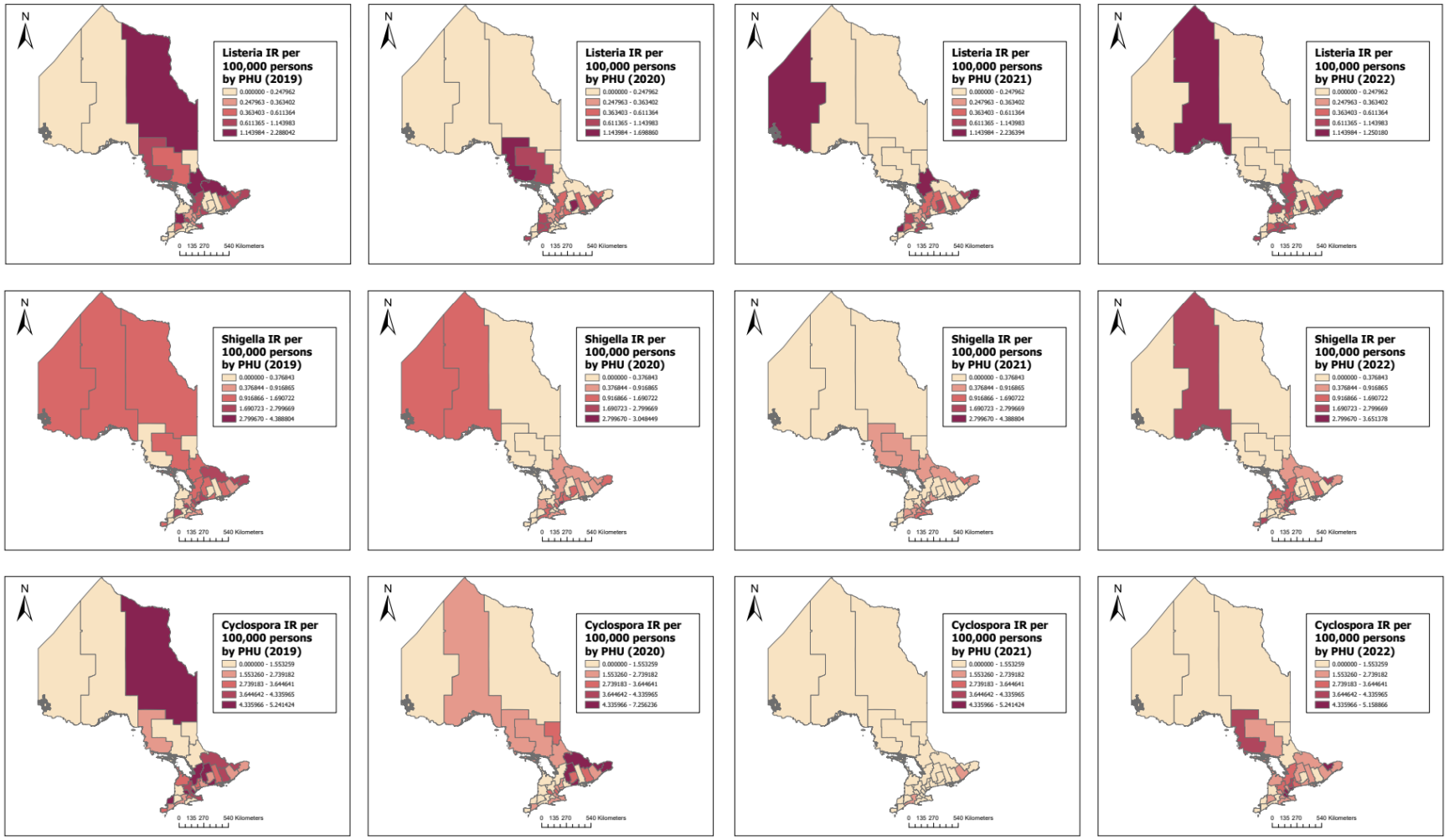


Figure 6. (Continued)

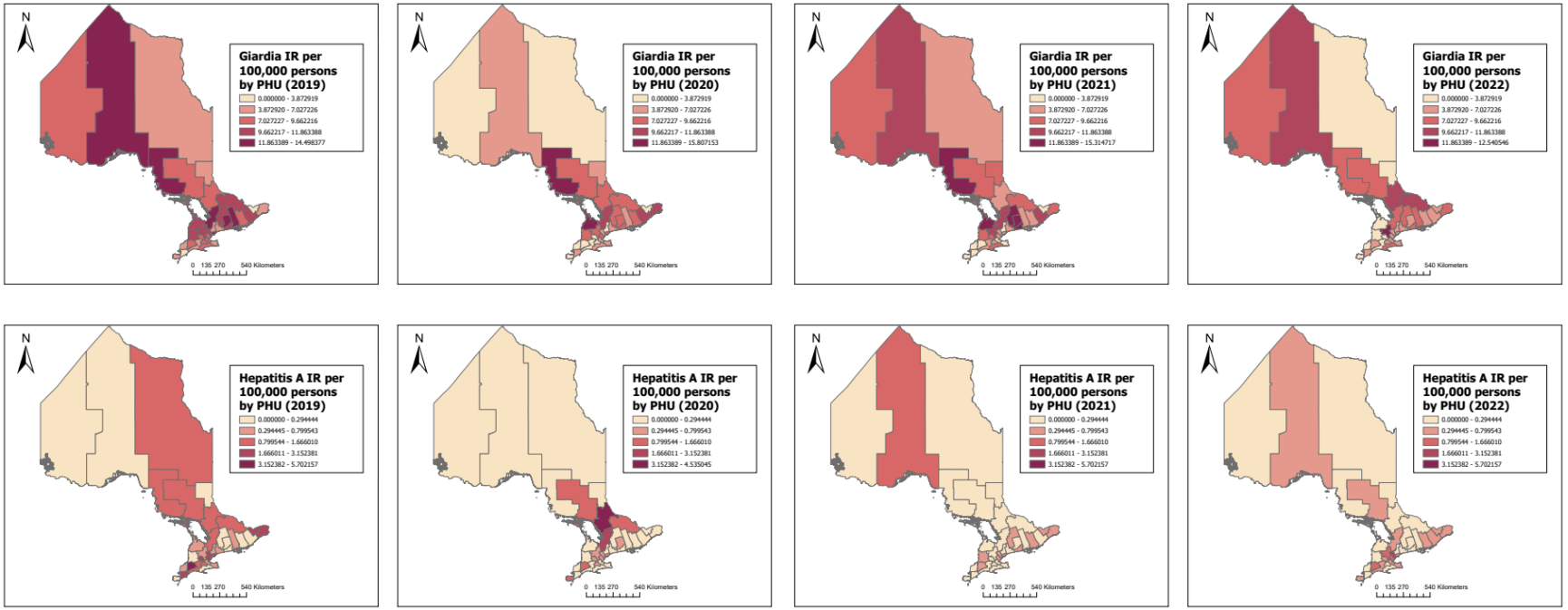


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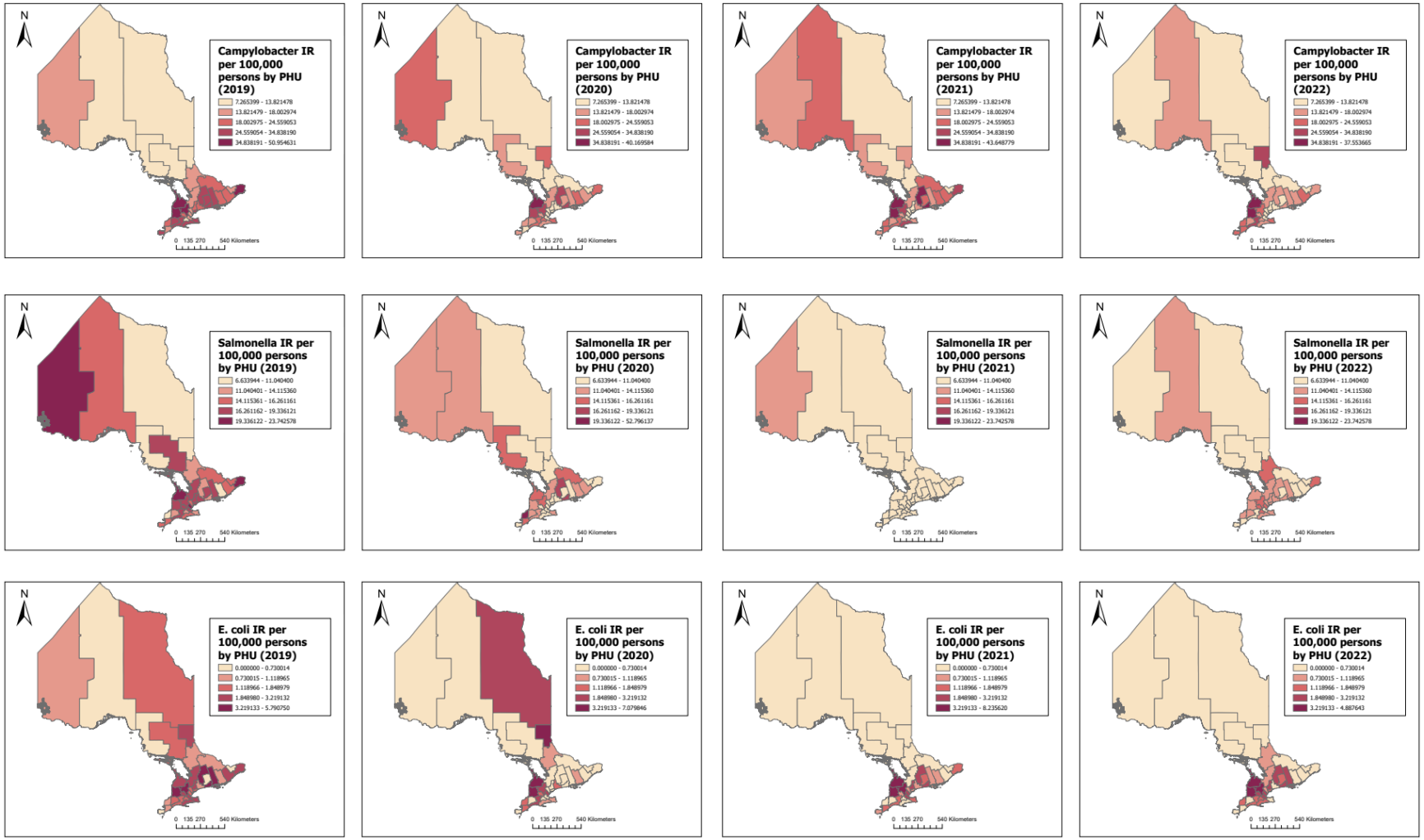


Figure 7. Age- and sex-adjusted incidence rates (IRs) of reported *Campylobacter* spp., *Salmonella* spp., STEC, *Listeria monocytogenes*, *Shigella* spp., *Cyclospora cayetanensis*, *Giardia duodenalis*, and hepatitis A infections at the Public Health Unit level in Ontario, Canada (2019-2022; continued on next two pages).

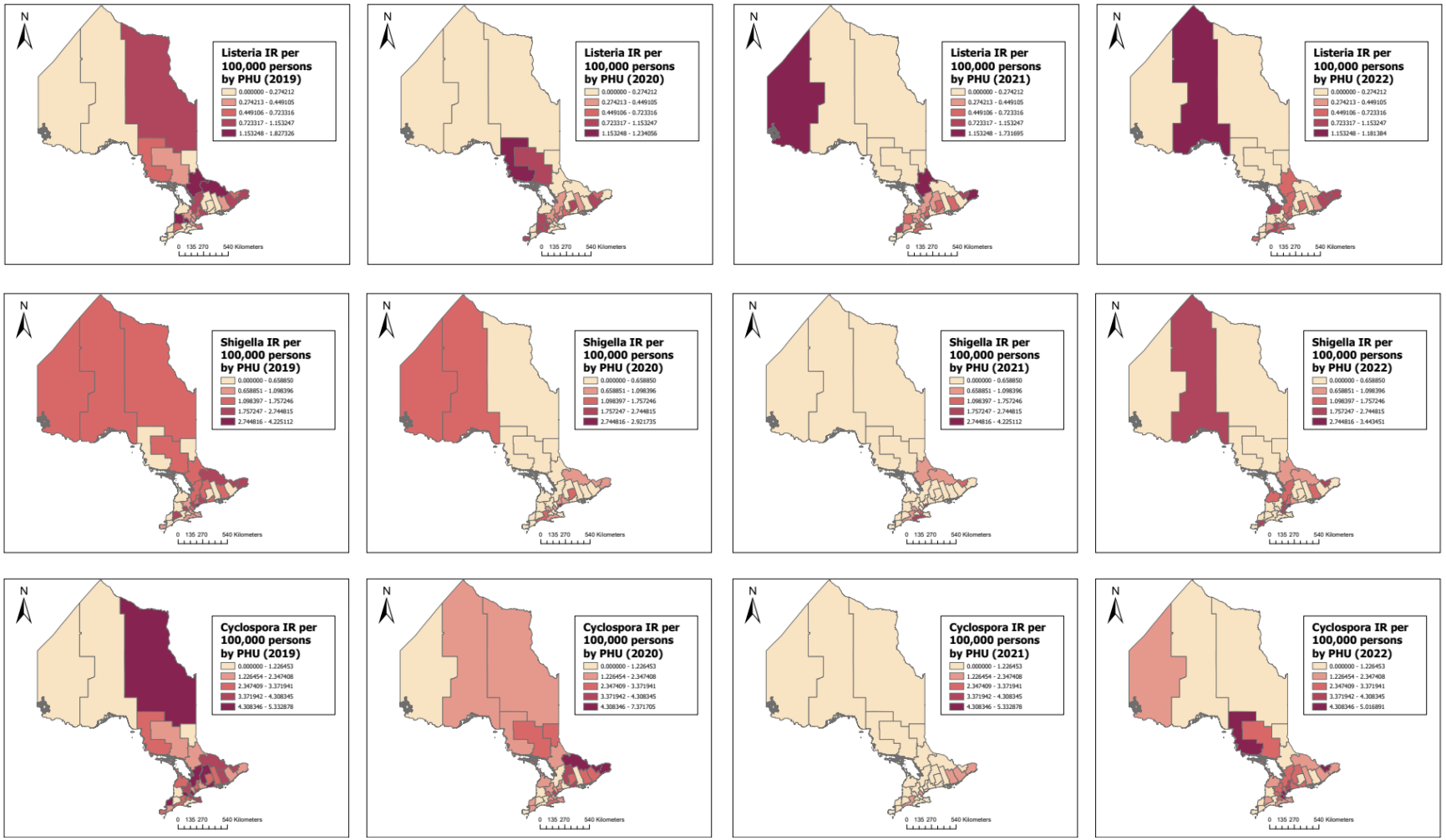


Figure 7. (Continued)

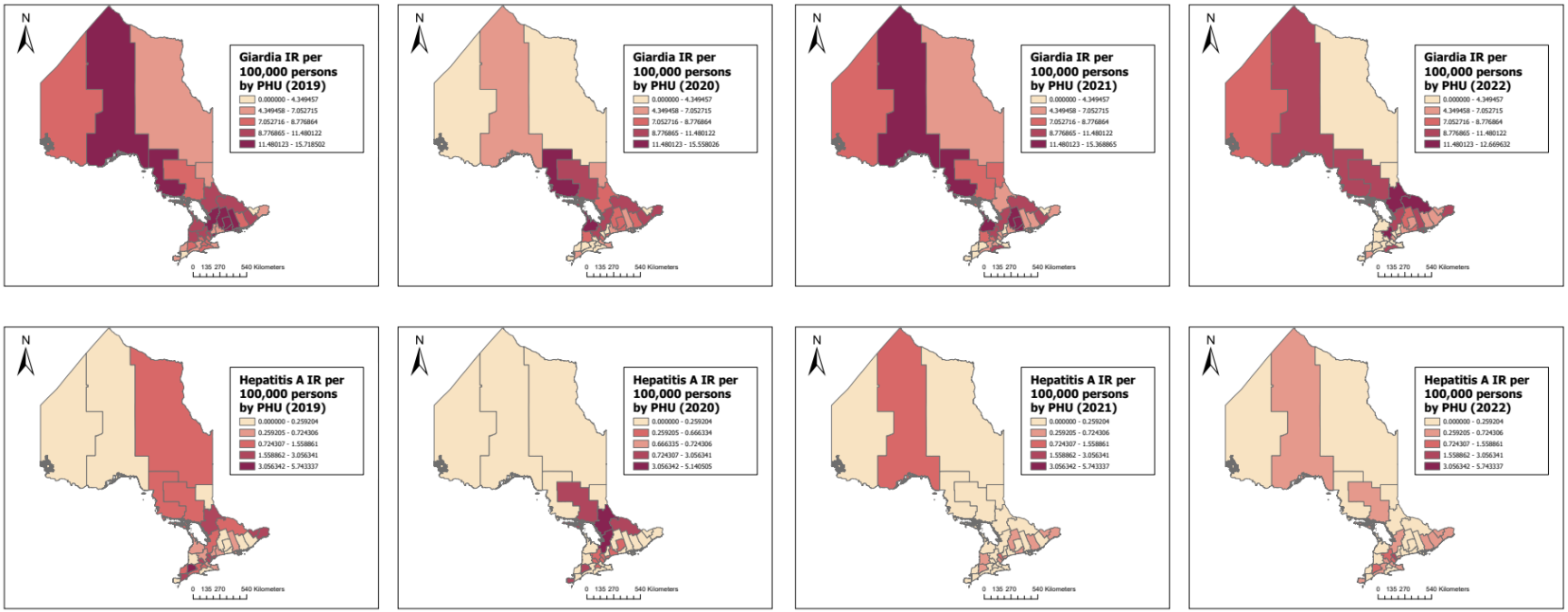


Figure 7. (Continued)

4.2 Spatial, Temporal and Space-Time Patterns of Enteric Infections

4.2.1 Purely Spatial High Infection Rate Clusters

A total of 20 significant ($p<0.05$) high infection rate purely spatial clusters were detected across Ontario for seven out of eight enteric pathogens (Figure 8, Appendix C: Table C1). *Listeria monocytogenes* was the only enteric pathogen that did not have any significant high-rate purely spatial clusters.

Three pathogens had high infection rate spatial clusters in both urban and rural PHUs. *Campylobacter* spp. (n= 6 clusters) had spatial clusters across the Southwest, Central West, Central East, and Eastern PHUs. Populations residing in Grey Bruce, Wellington-Dufferin-Guelph, and Huron-Perth were 2.29 times more likely to have a reported case of *Campylobacter* spp. than populations residing outside of these PHUs (Appendix C: Table C1). Additionally, *Giardia duodenalis* (n= 3 clusters) had high infection rate spatial clusters that were widely distributed across the province and was the only pathogen where populations living in the Northeast PHUs had a significantly elevated risk of infection (Figure 7). STEC (n = 3 clusters) high-infection rate clusters were not widely distributed across the province and were detected in the Central West and Southwest PHUs. Populations in Grey Bruce, Wellington-Dufferin-Guelph, and Huron-Perth were 3.93 times more likely to have a reported case of STEC than populations in other PHUs, similar to what was observed for *Campylobacter* spp. (Appendix C: Table C1).

Salmonella spp. was the only pathogen that had high infection rate spatial clusters detected solely in rural PHUs. *Salmonella* spp. (n= 2 clusters) clustered in the Southwest and Central West PHUs. The population of Lambton Public Health was 1.77 times more likely to have a reported case of *Salmonella* spp. compared to populations residing in other PHUs (Appendix C: Table C1).

Three pathogens had high infection rate spatial clusters that were only detected in urban PHUs. *Shigella* spp. (n= 1 cluster) was spatially clustered in Toronto Public Health, where the population was 3.69 times more likely to have a reported case (Figure 7). *Cyclospora cayetanensis* (n= 3 clusters) had high-infection rate clusters located in Ottawa, Halton Region, and Toronto. The population residing in Ottawa had the highest likelihood of a reported case of *Cyclospora cayetanensis*, being 1.96 times more likely to have a reported case compared to populations in other PHUs (Figure 7). Hepatitis A (n= 2 clusters) spatially clustered in Middlesex-London, Halton Region, and Peel Region. The population in Middlesex-London was the most likely to have a reported case of hepatitis A, being 3.04 times more likely to have a reported case of hepatitis A than populations in other PHUs (Figure 7).

An interesting observation was that populations who reside in Grey Bruce, Wellington-Dufferin-Guelph, and Huron-Perth were more likely to have reported cases for multiple enteric pathogens including *Campylobacter* spp., *Salmonella* spp., and STEC. Similarly, people who live in the City of Toronto were also at an increased risk of infection for multiple pathogens including *Shigella* spp., *Cyclospora cayetanensis*, and *Giardia duodenalis*.

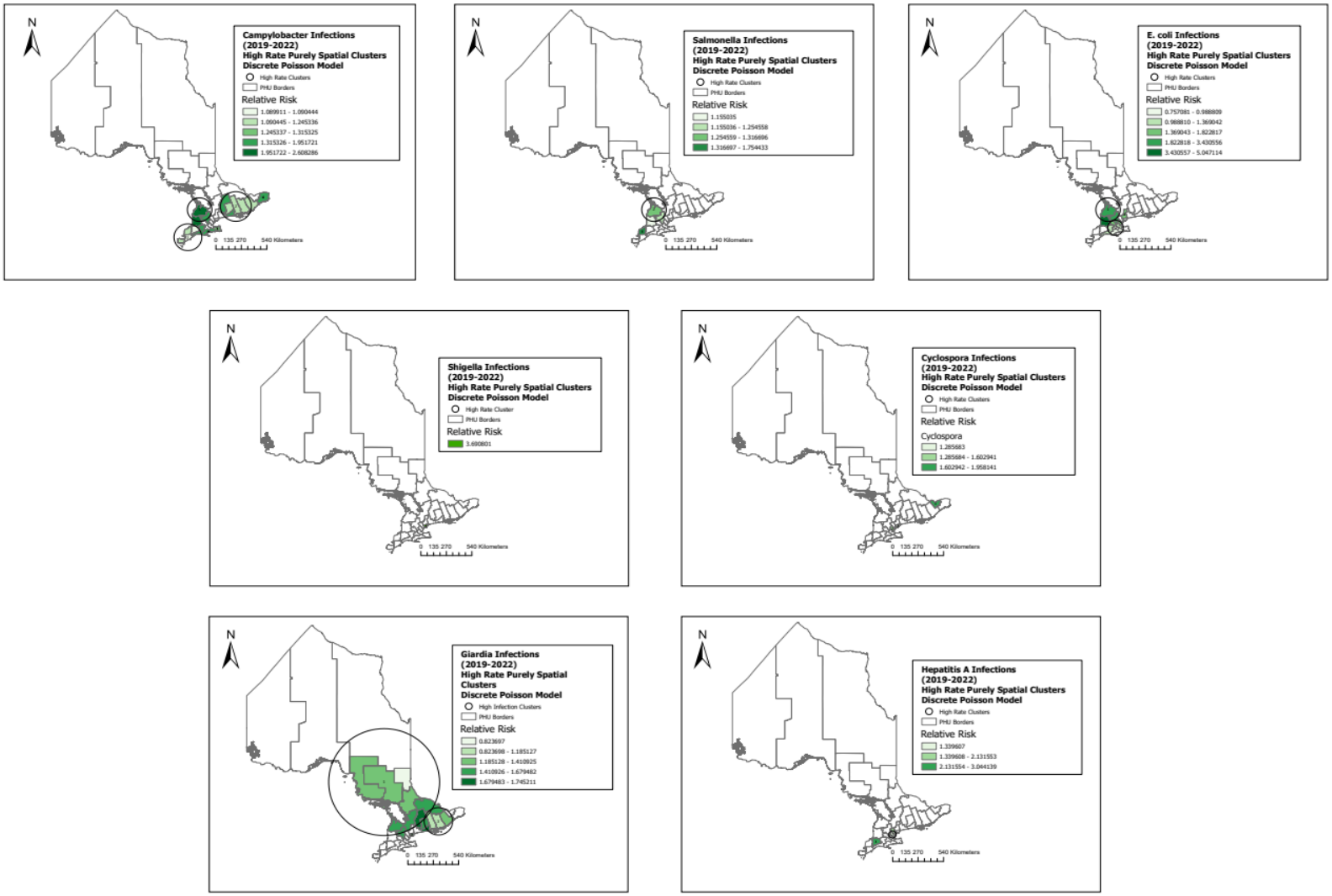


Figure 8. Significant spatial high infection rate clusters[1] of reported *Campylobacter* spp., *Salmonella* spp., STEC, *Shigella* spp., *Cyclospora cayetanensis, Giardia duodenalis*, and hepatitis A infections across Public Health Units in Ontario, Canada (2019-2022).

[1]High-rate clusters labelled numerically in maps, following the highest to lowest log-likelihood ratio order.

4.2.2 Purely Temporal High Infection Rate Clusters

Twelve significant ($p<0.05$) high-rate purely temporal clusters were detected for all eight enteric pathogens across Ontario (2019-2022) (Table 3).

Most clusters (59%) occurred in 2019, before the COVID-19 pandemic. Only one significant cluster was detected in 2020 (*Salmonella* spp.), and another in 2021 (*Listeria monocytogenes*). Two clusters were observed in 2022, and one cluster spanned across two years (2019/03-2020/02). *Campylobacter* spp., STEC, *Listeria monocytogenes,* and *Cyclospora cayetanensis* infections were primarily detected during the summer and fall months. *Salmonella* spp. and *Shigella* spp. each had two high-rate clusters: one cluster had a longer time frame, and another cluster with a shorter time frame. The shorter *Salmonella* cluster took place over the summer and fall months, while the shorter *Shigella* cluster occurred in the winter. *Giardia duodenalis* and hepatitis A did not display clear temporal patterns due to a long cluster time frame.

The relative risk for temporal clusters ranged from 1.14 to 8.55. The strongest seasonal peak was observed for *Cyclospora cayetanensis*, with a high-rate cluster from 2019/06 to 2019/07. During this temporal window, the population was 8.55 times more likely to have a reported case *Cyclospora cayetanensis* compared to other months in 2019.

Table 3. Significant temporal high-rate clusters of reported *Campylobacter* spp., *Salmonella* spp., STEC, *Listeria monocytogenes*, *Shigella* spp., *Cyclospora cayetanensis*, *Giardia duodenalis*, and hepatitis A infections in Ontario, Canada (2019-2022).

Pathogen	Clusters	Cluster Time Frame	Observed (n)	Expected (n)	Observed/ Expected	Relative Risk (RR)	P-value
Campylobacter spp.	C1	2019/06 to 2019/10	1816	987.25	1.84	2.04	0.001
	C2	2022/08 to 2022/11	922	818.09	1.13	1.14	0.016
Salmonella spp.	C1	2019/01 to 2019/11	2257	1542.82	1.46	1.69	0.001
	C2	2020/07 to 2020/10	667	575.5	1.16	1.18	0.013
STEC	C1	2019/06 to 2019/09	127	61.05	2.08	2.3	0.001
Listeria monocytogenes	C1	2021/06 to 2021/09	44	24.23	1.82	1.96	0.013
Shigella spp.	C2	2019/01 to 2019/01	36	17.1	2.11	2.16	0.004
	C1	2019/03 to 2020/02	298	202.29	1.47	1.74	0.001
Cyclospora cayetanensis	C1	2019/06 to 2019/07	371	56.82	6.53	8.55	0.001
	C2	2022/06 to 2022/11	388	177.15	2.19	2.65	0.001
Giardia duodenalis	C1	2019/01 to 2019/11	1215	842.17	1.44	1.65	0.001
Hepatitis A	C1	2019/01 to 2019/12	200	102.88	1.94	2.81	0.001

4.2.3 Space-Time High Infection Rate Clusters

Fifty significant ($p<0.05$) high infection rate space-time clusters for seven out of eight enteric pathogens were detected across Ontario from 2019-2022 (Figure 9 and Appendix C: Table C2). *Campylobacter* spp. and *Cyclospora cayetanensis* each had the highest number of space-time clusters (n=11), followed by *Giardia duodenalis* (n=7), *Salmonella* spp., STEC, and hepatitis A (each n=6), *Shigella* spp. (n=3), and *Listeria monocytogenes* was the only pathogen with zero space-time clusters.

Most of the space-time clusters occurred during 2019 (36%) before the COVID-19 pandemic, and 2021 had the fewest space-time clusters (8%). Additionally, four space-time clusters that had a time frame that spanned across two years, these clusters were not visualised in Figure 9 but are included in Appendix C: Table C2.

STEC mainly clustered in the rural Central and Southwest PHUs with multiple space-time clusters that took place in Grey Bruce, Wellington-Dufferin-Guelph, and Huron-Perth during the summer. In contrast, *Campylobacter* spp., *Salmonella* spp., *Cyclospora cayetanensis*, *Giardia duodenalis,* and hepatitis A space-time high-infection rate clusters were more geographically dispersed across the province, occurring in urban and rural PHUs. *Shigella* spp. was only observed in urban PHUs, specifically the City of Toronto.

Multiple large space-time clusters spanned into the Eastern, Northeastern, and Northern regions of Ontario such as *Campylobacter* spp. in 2021/06-2021/10, *Salmonella* spp. in 2019/01-2019/11 and 2020/07-2020/08, STEC in 2019/06-2019/12, and *Giardia duodenalis* in 2020/06-2020/11. These clusters often included PHUs with an RR <1, suggesting populations residing in these PHUs are less likely to have reported cases of these pathogens compared to populations residing outside of the cluster during these periods.

The populations residing in the rural Central West and Southwest PHUs were most likely to have reported cases of *Campylobacter* spp., *Salmonella* spp., and STEC during the summer and fall months. *Salmonella* spp., *Shigella* spp., *Cyclospora cayetanensis*, *Giardia duodenalis*, and hepatitis A all had significant space-time clusters that occurred in the City of Toronto.

Multiple small, high-infection-rate space-time clusters were associated with relatively high relative risk values. In October 2020, the population residing in Lambton Public Health was 32.04 times more likely to have a reported case of *Salmonella* spp. than those outside the cluster (Appendix C: Table C2). Another interesting small high-risk space-time cluster of hepatitis A was detected in Middlesex-London from January to April in 2019; people residing in this PHU were 23.42 times more likely to have a reported case, compared to people residing outside of this area (Appendix C: Table C2). *Cyclospora cayetanensis* space-time clusters consistently had the highest RR estimates, with populations in different PHUs being 4.5-12.98 times more likely to have a reported case, primarily during the summer months (Appendix C: Table C2).

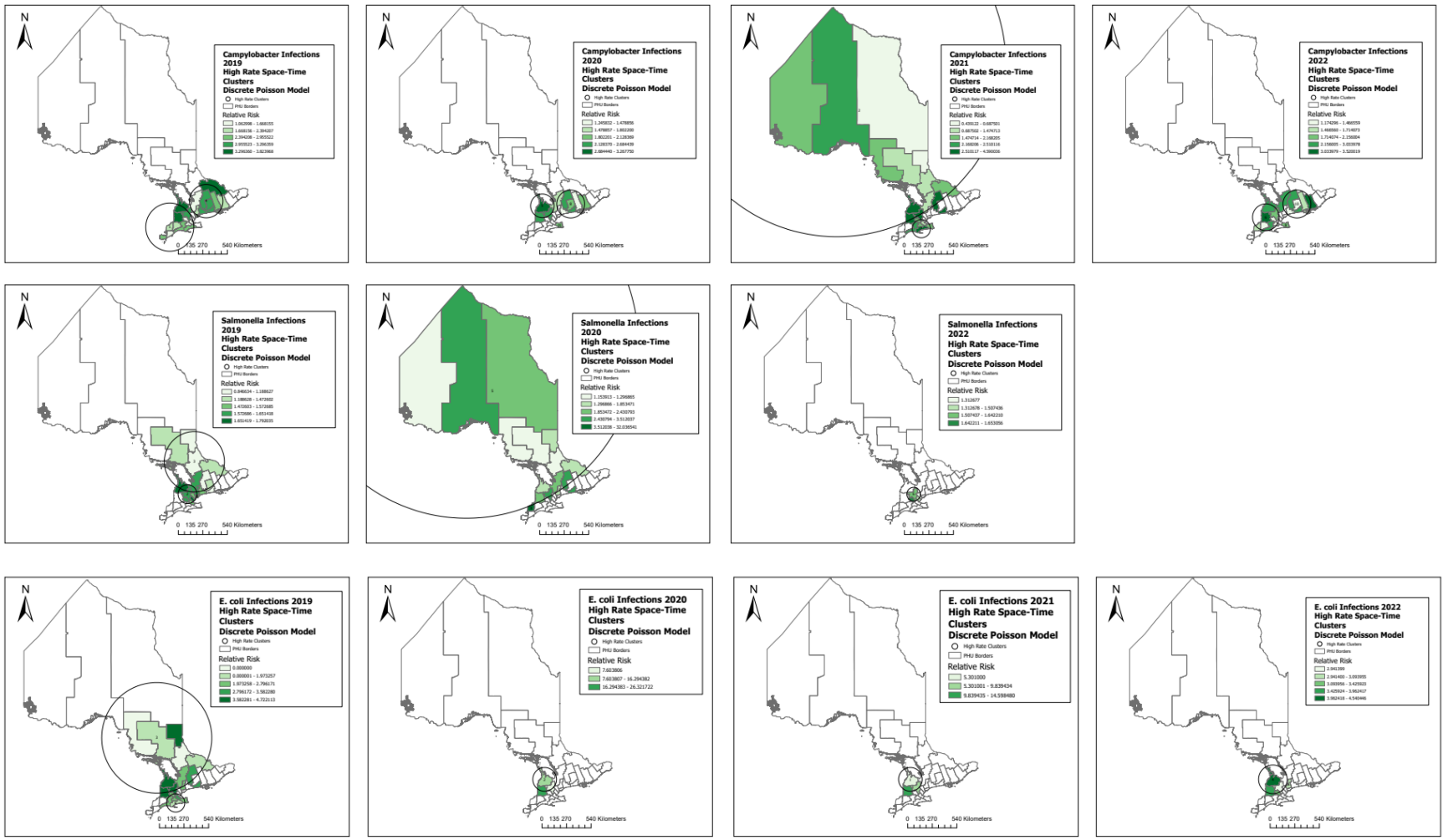
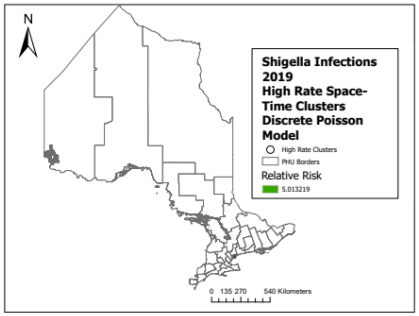
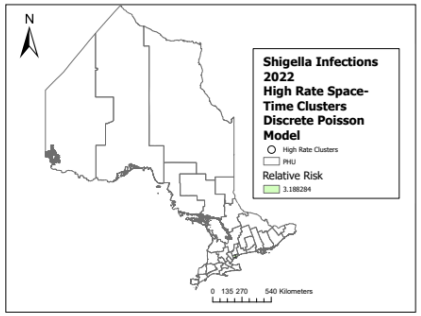
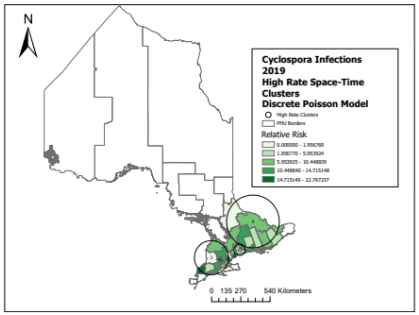


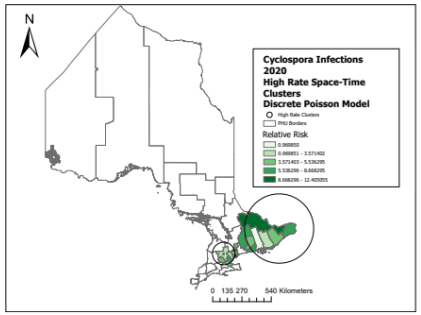
Figure 9. Significant space-time high-rate clusters[1] of reported *Campylobacter* spp., *Salmonella* spp., STEC, *Shigella* spp., *Cyclospora cayetanensis, Giardia duodenalis*, and hepatitis A infections across Public Health Units in Ontario, Canada (2019-2022; continued on next two pages).

[1]High-rate clusters labelled numerically in maps, identifying the time frame of the cluster by month and year (Appendix C: Table C2).









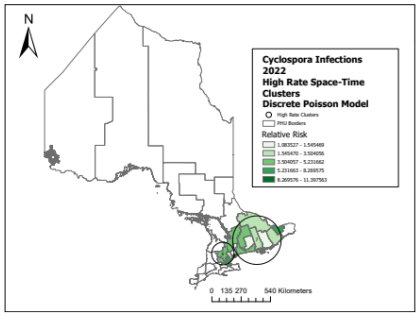


Figure 9. (Continued)

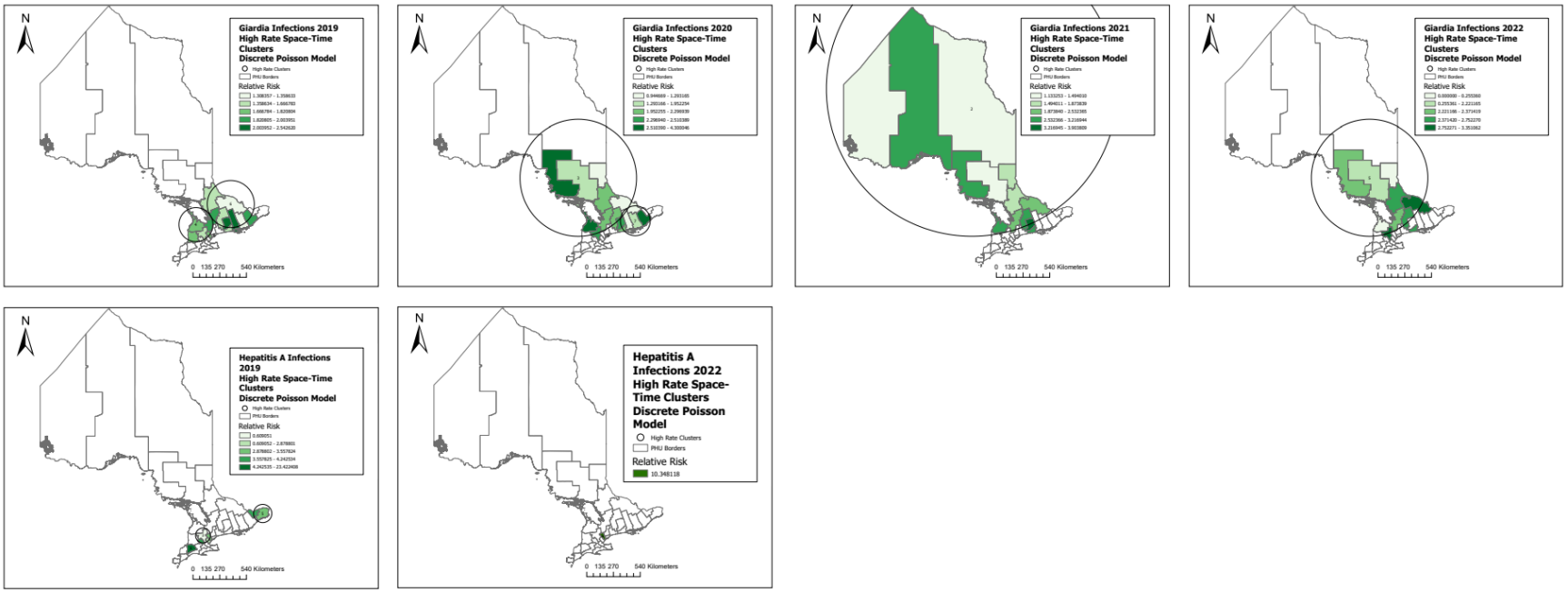


Figure 9. (Continued)

4.3 Spatial Patterns of Pathogen-Specific Incidence Rates across Ontario

4.3.1 Global Spatial Autocorrelation of Incidence Rates

The three Northernmost PHU's were global locational outliers due to their large geographic size relative to other PHUs in Ontario and were thus not included in the global and local autocorrelation analysis. Positive global spatial autocorrelation was detected for the annual incidence rates of several pathogens throughout the study period, including *Campylobacter* spp. (2019), *Salmonella* spp. (2021 and 2022), STEC (2020 and 2022), *Listeria monocytogenes* (2022), *Cyclospora cayetanensis* (2020 and 2021), *Giardia duodenalis* (2020 and 2021), and hepatitis A (2020 and 2021). This indicates that similar incidence rate values geographically cluster together, rather than being randomly distributed. Global spatial autocorrelation varied across pathogens and time, with significant clustering detected at different distance increments ranging from 214.96 km-688.52 km (Appendix B: Figure B1). *Shigella* spp. was the only pathogen that did not have significant global spatial autocorrelation at different distance increments from 2019-2022.

4.3.2 Local Spatial Clusters and Outliers of Incidence Rates

Statistically significant ($p<0.05$) local clusters and outliers of annual pathogen-specific incidence rates were detected across Ontario PHUs and are visualised in Figure 10. High-high incidence rate clusters of *Campylobacter* spp.*, Salmonella* spp.*,* and STEC were primarily observed in the Central and Southwest PHUs from 2019-2022. The majority of *Cyclospora cayetanensis* and *Giardia duodenalis* high-high clusters were detected in the Central Eastern, Eastern and Northeastern PHUs. *Cyclospora cayetanensis* and *Giardia duodenalis* were the only pathogens to have significant low-low incidence rate clusters in the Southwestern PHUs. In 2020 and 2021, *Campylobacter* spp. and *Listeria monocytogenes* had no significant local clusters or outliers.

High-low and low-high spatial outliers were less frequent and displayed more sporadic spatial patterns across the PHUs over time. STEC was the only pathogen that showed a consistent spatial pattern of clusters and outliers over time in Central and Southwestern Ontario. The location of spatial clusters and outliers for all other enteric pathogens had substantial variation each year. For example, in 2020 *Cyclospora cayetanensis* had high-high incidence rate clusters located in Eastern Ontario and low-low incidence rate clusters in Southwestern Ontario. However, in 2022 *Cyclospora cayetanensis* had high-high incidence rate clusters located in Southwestern Ontario. Additionally, *Campylobacter* spp. and *Listeria monocytogenes* incidence rates displayed spatial clustering in 2019 and 2022 whereas no significant spatial clusters or outliers were detected 2020 and 2021. *Salmonella* spp. had a high-low outlier in Northern Ontario in 2019 and high-low outlier in Eastern Ontario in 2022. No *Salmonella* spp. high-low outliers were detected in 2020 and 2021.



Figure 10. Local spatial clusters and outliers of *Campylobacter* spp., *Salmonella* spp., STEC, *Shigella* spp., *Cyclospora cayetanensis, Giardia duodenalis*, and hepatitis A infections, across Public Health Units in Ontario, Canada (2019-2022; continued on next page)

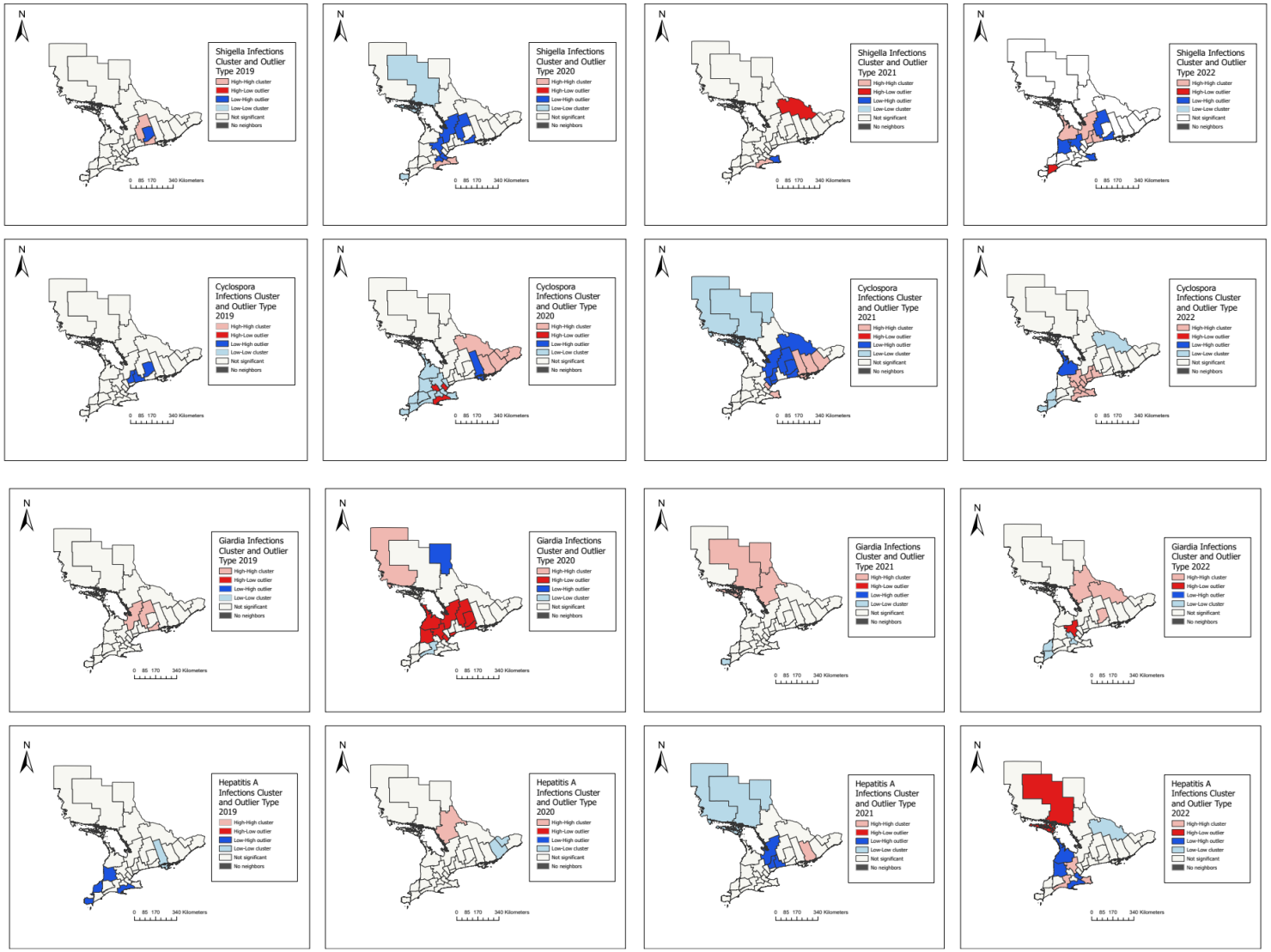


Figure 10. (Continued)

4.4 Predictors Associated with Pathogen-Specific Incidence Rates: Regression Results

A visual representation of the estimated age- and sex-adjusted incidence rates for eight enteric pathogens at different prevalence estimates of household food insecurity, holding all variables constant in the final multivariable model, is presented in Figure B2 (Appendix B).

4.4.1 Summary of Predictor Variables Characteristics

The mean annual prevalence of household food insecurity decreased from 2019-2021 (17.87%-16.13%) (Table 4). However, in 2022, it increased to 18.33% which was the highest observed value across PHUs during the study period (Table 4). The highest prevalence of household food insecurity occurred in Lambton Public Health in 2019 (23.8%), Algoma Public Health in 2020 (25.2%), Chatham-Kent Public Health in 2021 (24.2%), and Timiskaming Health Unit in 2022 (28.8%) (Figure 10). York Region had the lowest prevalence of household food insecurity in 2019 (11.1%), and Halton Region had the lowest prevalence of household food insecurity from 2020-2022 (9.9%, 11.2%, and 9.7%) (Figure 11).

The proportion of households experiencing food insecurity at the PHU level showed spatial variation over time. Several PHUs had missing food insecurity estimates during the study period including Haliburton, Kawartha, Pine Ridge District Health Unit (2019, 2021, 2022), Hastings Prince Edward Public Health (2019, 2020, 2022), Huron Perth Public Health (2020), Porcupine Health Unit (2020, 2021), and Timiskaming Health Unit (2020) (Figure 11).

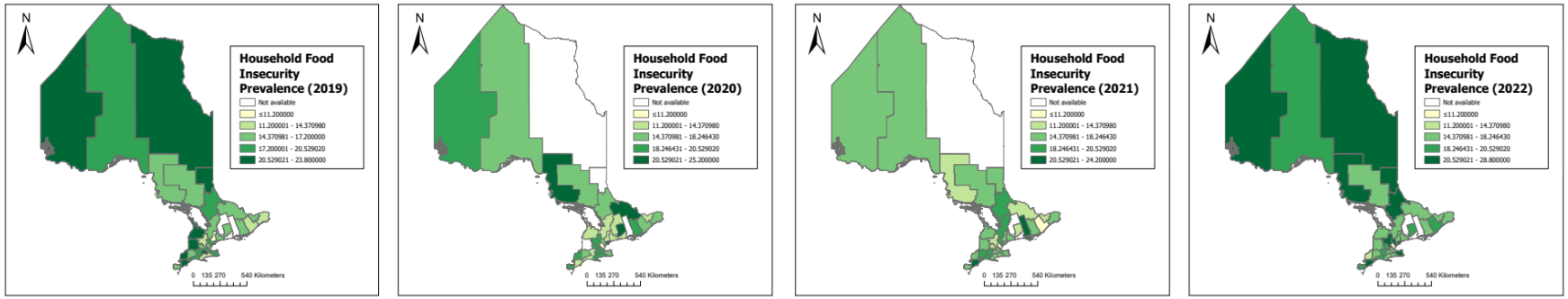


Figure 11. The proportion of households experiencing food insecurity at the Public Health Unit level in Ontario, Canada (2019-2022).

The demographic and socioeconomic characteristics of PHUs are shown in Table 4. Multiple variables such as visible minority, five-year internal migrant mobility rate, median household income, and education, also displayed considerable variability across PHUs.

Table 4. Summary statistics of demographic and socioeconomic characteristics for 34 Public Health Units in Ontario, Canada.

Predictor Variables	Minimum	Maximum	Mean	Standard Deviation	Median
Proportion of households experiencing food insecurity (2019).	11.1	23.8	17.87	3.45	17.05
Proportion of households experiencing food insecurity (2020).	9.9	25.2	16.90	3.94	17.2
Proportion of households experiencing food insecurity (2021).	11.2	24.2	16.13	3.08	16.2
Proportion of households experiencing food insecurity (2022).	9.7	28.8	18.33	3.77	18.2
Proportion of the population identified as a visible minority.	2.4	68.8	15.69	17.37	6.45
Proportion of the population aged 15 and over who did not have a job for a year or longer.	7.3	15.7	11.08	1.96	11.05
Proportion of the population aged 5 years and over who have moved within Canada in the last five years.	7.6	29.4	19.70	5.93	20.85
Average number of people living in a private dwelling	2.2	3.2	2.45	0.22	2.4
The median after-tax income of all households within a PHU.	62,800	103,000	75,735.29	9519.83	72,750
The proportion of census family households that are one-parent families.	12.4	20.8	16.35	2.23	16.05
The proportion of the population aged 25-64 in private households with a postsecondary certificate, diploma, or degree.	50.9	78.1	62.54	6.31	61.05
The proportion of the total households that spend 30% or more of their income on shelter costs.	22	45	27.35	5.00	26.2

4.4.1 Determinants of Campylobacter spp. Incidence across Public Health Units (2021)

The results of the univariable and multivariable models are shown in Tables 5-7. The univariable model revealed that the proportion of households experiencing food insecurity was not significantly associated with the age- and sex-adjusted *Campylobacter* spp. incidence rates (IRR=0.99777, 95% CI 0.97371-1.02226). However, in both the full and final multivariable models, a significant inverse association existed between age- and sex-adjusted *Campylobacter* spp. incidence rates and the proportion of households experiencing food insecurity. A one-unit increase in the prevalence of household food insecurity was associated with an approximate 3% decrease in the age- and sex-adjusted incidence rates of *Campylobacter* spp., while holding all other variables constant (IRR=0.97114, 95% CI 0.94849-0.99424). The proportion of the population that has moved within Canada in the last five years and median household income were the only variables not included in the final multivariable model.

The results from the multi-level mixed effects model (Table 8), were consistent with the fixed multivariable models. Household food insecurity still had a significant inverse association with the age- and sex-adjusted *Campylobacter* spp. incidence rates, while holding all other variables constant and accounting for clustering across administrative health regions (IRR=0.96803, 95% CI 0.94294-0.99379). Most of the demographic and socioeconomic predictor variables had significant negative associations. However, one difference in the mixed effect model was that the proportion of households spending >30% of their income on shelter costs was not statistically significant (IRR=1.00980, 95% CI 0.9908-1,02910).

The results from the GGWR (Table 9 and Figure 12) indicated that household food insecurity, long-term unemployment, median household income, one-parent families, and education had minimal spatial non-stationarity, suggesting the association between age- and sex-

adjusted *Campylobacter* spp. incidence rates have slightly different values across different PHUs. The direction of the associations observed in the global Poisson model was the same as those estimated and the GGWR model.

Table 5. Results of the univariable Negative Binomial model for reported *Campylobacter* spp. infections in 2021 (n=2133 from 32 Public Health Units).

Predictor Variables		**IRR[a)]**	**95% CI[b)]**	**p-value[c)]**
Household Food Insecurity (prevalence)		0.99777	0.97371, 1.02226	0.84802
Age Groups	0 to 4 years	2.87979	2.16102, 3.83872	<0.00001
	5 to 9 years	1.40923	1.02671, 1.92941	0.02923
	10 to 19 years	Ref.	Ref.	Ref.
	20 to 29 years	1.29150	0.97635, 1.71043	0.06798
	30 to 39 years	1.40558	1.06317, 1.86034	0.01407
	40 to 49 years	1.47890	1.11680, 1.96036	0.00490
	50 to 59 years	1.59868	1.21794, 2.10154	0.00055
	60 and older	1.69979	1.31921, 2.19553	0.00003
Male sex (referent: female)		1.25716	1.09550, 1.44283	0.00075
Long-term Unemployment (%)		0.87510	0.84855, 0.90255	<0.00001
Internal Migration (Five Years)		1.03980	1.02922, 1.05042	<0.00001
Median Household Income		0.99998	0.99997, 0.99998	<0.00001
Households with One-Parent Families (%)		0.89917	0.87301, 0.92631	<0.00001
Education (%)		0.95189	0.94336, 0.96053	<0.00001
Households Spending >30% on Shelter Costs (%)		0.95467	0.94567, 0.96387	<0.00001

[a)] IRR: Incidence Rate Ratio. [b)] CI: 95% Confidence Interval of the IRR. [c)] Statistically significant p-value ≤ 0.05.

Table 6. Results of the full multivariable Negative Binomial model for reported *Campylobacter* spp. infections in 2021 (n=2133 from 32 Public Health Units).

Predictor Variables		**IRR[a)]**	**95% CI[b)]**	**p-value[c)]**
Household Food Insecurity (prevalence)		0.97134	0.94836, 0.99479	0.01623
Age Groups	0 to 4 years	2.50157	2.00126, 3.12882	<0.00001
	5 to 9 years	1.34855	1.04429, 1.73501	0.02120
	10 to 19 years	Ref.	Ref.	Ref.
	20 to 29 years	1.24751	1.01151, 1.54194	0.04080
	30 to 39 years	1.24796	1.01105, 1.54361	0.04042
	40 to 49 years	1.30205	1.05261, 1.61357	0.01542
	50 to 59 years	1.42132	1.15868, 1.74822	0.00083
	60 and older	1.50774	1.25161, 1.82441	0.00002
Male sex (referent: female)		1.24197	1.12795, 1.36783	0.00001
Long-term Unemployment (%)		0.96493	0.93054, 1.00010	0.05314
Internal Migration (Five Years)		1.00065	0.98773, 1.01375	0.92111
Median Household Income		0.99998	0.99997, 0.99999	<0.00001
Households with One-Parent Families (%)		0.92657	0.88916, 0.96503	0.00029
Education (%)		0.96686	0.95017, 0.98384	0.00014
Households Spending >30% on Shelter Costs (%)		1.01386	0.99974, 1.02828	0.05636

[a)] IRR: Incidence Rate Ratio. [b)] CI: 95% Confidence Interval of the IRR. [c)] Statistically significant p-value ≤ 0.05.

Table 7. Results of the final multivariable Negative Binomial model for reported *Campylobacter* spp. infections in 2021 (n=2133 from 32 Public Health Units).

Predictor Variables		**IRR[a)]**	**95% CI[b)]**	**p-value[c)]**
Household Food Insecurity (prevalence)		0.97114	0.94849, 0.99424	0.01404
Age Groups	0 to 4 years	2.50191	2.00144, 3.12937	<0.00001
	5 to 9 years	1.34872	1.04439, 1.73529	0.02116
	10 to 19 years	Ref.	Ref.	Ref.
	20 to 29 years	1.24759	1.01153, 1.54212	0.04079
	30 to 39 years	1.24820	1.01122, 1.54397	0.04028
	40 to 49 years	1.30231	1.05279, 1.61396	0.01537
	50 to 59 years	1.42156	1.15884, 1.74858	0.00083
	60 and older	1.50797	1.25176, 1.82474	0.00002
Male sex (referent: female)		1.24199	1.12793, 1.36788	0.00001
Long-term Unemployment (%)		0.96533	0.93187, 0.99961	0.04940
Median Household Income		0.99998	0.99997, 0.99999	<0.00001
Households with One-Parent Families (%)		0.92564	0.89262, 0.95928	0.00003
Education (%)		0.96646	0.95171, 0.98136	0.00001
Households Spending >30% on Shelter Costs (%)		1.01380	0.99972, 1.02817	0.05656

[a)] IRR: Incidence Rate Ratio. [b)] CI: 95% Confidence Interval of the IRR. [c)] Statistically significant p-value ≤ 0.05.

Table 8. Results of the multi-level mixed effects[a)] Poisson model for reported *Campylobacter* spp. infections in 2021 (n=2133 from 32 Public Health Units).

Predictor Variables		**IRR[b)]**	**95% CI[c)]**	**p-value[d)]**
(Intercept)		0.02009	0.00690, 0.05852	<0.00001
Household Food Insecurity (prevalence)		0.96803	0.94294, 0.99379	0.01530
Age	0 to 4 years	2.49278	1.99453, 3.11551	<0.00001
	5 to 9 years	1.34637	1.04559, 1.73368	0.02113
	10 to 19 years	Ref.	Ref.	Ref.
	20 to 29 years	1.24787	1.01199, 1.53873	0.03831
	30 to 39 years	1.24702	1.00947, 1.54047	0.04062
	40 to 49 years	1.30042	1.05008, 1.61043	0.01604
	50 to 59 years	1.42489	1.16090, 1.74891	0.00071
	60 and older	1.51620	1.25726, 1.82848	0.00001
Male sex (referent: female)		1.24260	1.12916, 1.36744	0.00001
Long-term Unemployment (%)		0.95916	0.92274, 0.99701	0.03473
Median Household Income		0.99998	0.99997, 0.99999	0.00127
Households with One-Parent Families (%)		0.93588	0.89896, 0.97431	0.00125
Education (%)		0.96758	0.95033, 0.98513	0.00033
Households Spending >30% on Shelter Costs (%)		1.00980	0.99086, 1.02910	0.31268

[a)] The Health Region of a PHU was the random intercept in the regression model. The variance (0.1078) and standard deviation (0.3283) of Health region random effects [b)] IRR: Incidence Rate Ratio. [c)] CI: 95% Confidence Interval of the IRR. [d)] Statistically significant p-value ≤ 0.05.

Table 9. Results of the Generalized Geographically Weighted Regression for reported *Campylobacter* spp. infections in Ontario, Canada (2021).

Predictor Variables	Min[a)]	Q1[b)]	Median	Q3[c)]	Max[d)]	Global[e)]
X Intercept	0.00995	0.01036	0.01133	0.01168	0.01192	0.01050
Household Food Insecurity (prevalence)	0.97900	0.97924	0.97940	0.97987	0.98202	0.98163
Long-term Unemployment (%)	0.95367	0.95466	0.95519	0.95725	0.95922	0.95906
Median Household Income	0.99998	0.99998	0.99998	0.99998	0.99998	0.99998
Households with One-Parent Families (%)	0.95552	0.95922	0.96074	0.96219	0.96267	0.95851
Education (%)	0.97268	0.97332	0.97369	0.97420	0.97475	0.97422

[a)] Min: Minimum coefficient value in the GGWR model. [b)] Q1: First quartile (25th percentile). [c)] Q3: Third quartile (75th percentile). [d)] Max: Maximum coefficient value in the GGWR model. [e)] Global: The value of the coefficients in a global Poisson regression model.

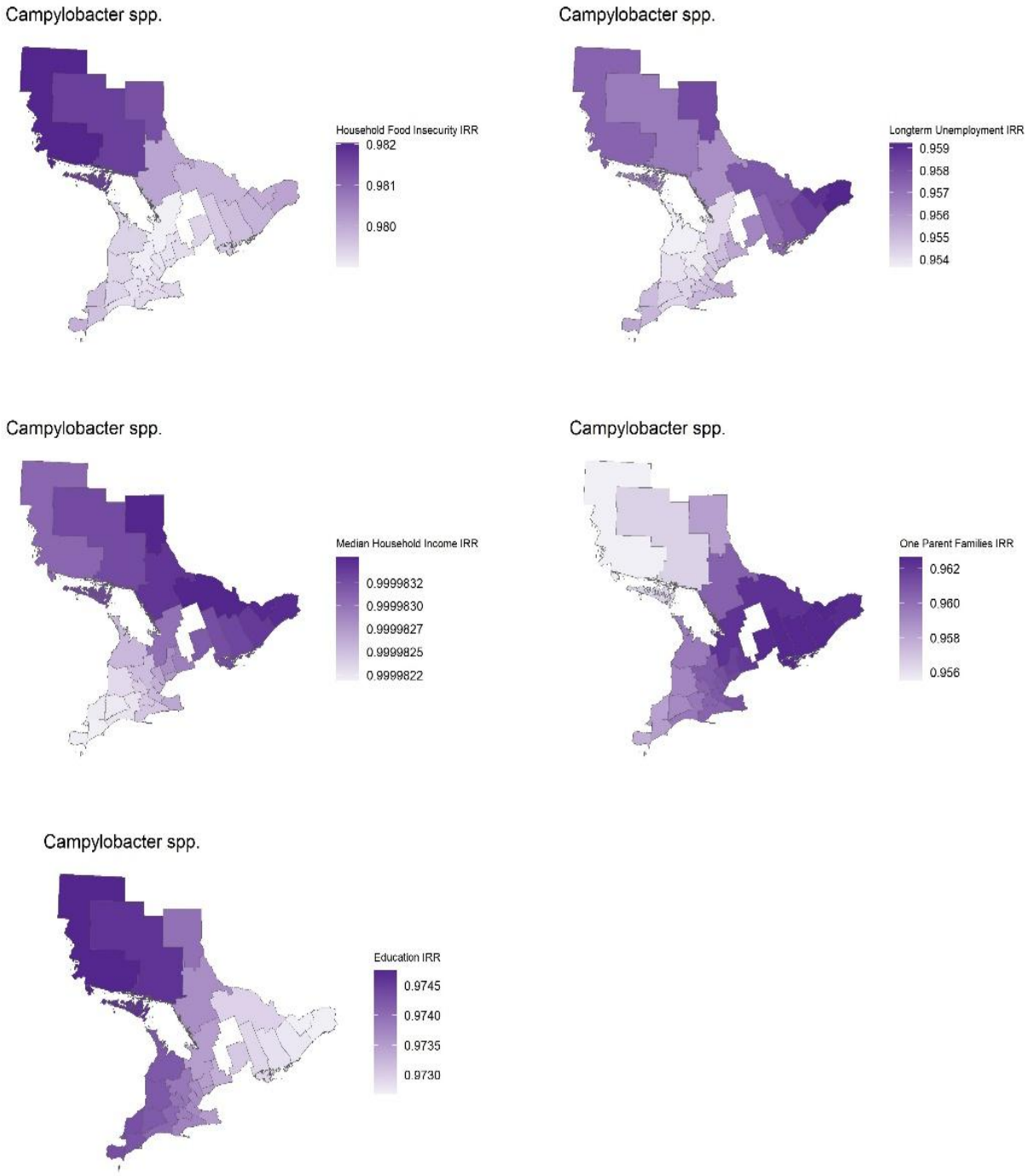


Figure 12. Spatial distribution of age- and sex-adjusted Incidence Rate Ratios (IRR) of reported *Campylobacter* spp. infections estimated from a generalized geographically weighted regression (GGWR) using a Poisson model, across 30 Public Health Units in 2021. Each map shows the association between the age- and sex-adjusted incidence rates of *Campylobacter* spp. and a predictor variable at the Public Health Unit level, holding all other predictor variables constant.

4.4.2 Determinants of Salmonella spp. Incidence across Public Health Units (2021)

The results of the univariable and multivariable models are shown in Tables 10-12. Household food insecurity was not significantly associated with *Salmonella* spp. incidence rates in the univariable model (IRR=1.02044, 95% CI 0.99140-1.05021). Additionally, this association was not significant in the full and final multivariable models indicating household food insecurity was not a significant predictor of age- and sex-adjusted *Salmonella* spp. incidence rates, after controlling for other covariates. The proportion of the population that has moved within Canada in the last five year and median household income were the only variables not included in the final multivariable model.

The proportion of households spending>30% of their income on shelter costs was the only census predictor significantly associated with the incidence rate of *Salmonella* spp. infections, in the univariable model (IRR=1.02, 95% CI 1.00-1.03) and multivariable models. A one-unit increase in the proportion of households spending>30% of their income on shelter costs was associated with approximately a 3% increase in the age- and sex-adjusted incidence rates of *Salmonella* spp., while holding all other variables constant (IRR=1.02649, 95% CI 1.00748-1.04604). All other census predictor variables were not significant in the univariable and multivariable models.

The results obtained from the multi-level mixed effects model (Table 13) were consistent with the final multivariable model (Table 12). The estimated variance of the random intercept (Health Region) was very small after adjusting for covariates, indicating the age- and sex-adjusted incidence rates of *Salmonella* spp. infections were relatively similar across health regions. Thus, there were no substantial changes in the direction, magnitude, or significance of the predictor variables in the mixed model compared to the fixed model.

The results from the GGWR (Table 14 and Figure 13) indicated that household food insecurity, long-term unemployment, median household income, one-parent families, and education had minimal spatial non-stationarity, suggesting that the association between age- and sex-adjusted *Salmonella* spp. incidence rates and these variables were similar across different Ontario PHUs. Moreover, the direction of the associations observed in the global Poisson model was the same as those estimated and the GGWR model.

Table 10. Results of the univariable Negative Binomial model for reported *Salmonella* spp. infections in 2021 (n=1177 from 32 Public Health Units).

Predictor Variables		**IRR[a)]**	**95% CI[b)]**	**p-value[c)]**
Household Food Insecurity (prevalence)		1.02044	0.99140, 1.05021	0.15741
Age Groups	0 to 4 years	4.46493	3.37507, 5.93595	<0.00001
	5 to 9 years	1.84168	1.32054, 2.56081	0.00031
	10 to 19 years	1.18441	0.86887, 1.61584	0.28601
	20 to 29 years	1.75955	1.33013, 2.33949	0.00008
	30 to 39 years	1.08849	0.80530, 1.47466	0.58492
	40 to 49 years	Ref.	Ref.	Ref.
	50 to 59 years	1.17068	0.86707, 1.58399	0.30188
	60 and older	1.68444	1.29932, 2.19948	0.00009
Female sex (referent: Male)		1.01858	0.86161, 1.20415	0.82829
Long-term Unemployment (%)		1.00015	0.95776, 1.04489	0.99470
Internal Migration (Five Years)		0.99293	0.97963, 1.00624	0.29487
Median Household Income		1.00000	1.00000, 1.00001	0.22451
Households with One-Parent Families (%)		1.00338	0.96675, 1.04185	0.86193
Education (%)		1.00547	0.99230, 1.01900	0.40833
Households Spending >30% on Shelter Costs (%)		1.01789	1.00461, 1.03169	0.00766

[a)] IRR: Incidence Rate Ratio. [b)] CI: 95% Confidence Interval of the IRR. [c)] Statistically significant p-value ≤ 0.05.

Table 11. Results of the full multivariable Negative Binomial model for reported *Salmonella* spp. infections in 2021 (n=1177 from 32 Public Health Units).

Predictor Variables		**IRR[a)]**	**95% CI[b)]**	**p-value[c)]**
Household Food Insecurity (prevalence)		1.01278	0.97673, 1.05012	0.49147
Age Groups	0 to 4 years	4.49732	3.41478, 5.95352	<0.00001
	5 to 9 years	1.84849	1.33049, 2.56034	0.00023
	10 to 19 years	1.18832	0.87537, 1.61446	0.26834
	20 to 29 years	1.76167	1.33773, 2.33233	0.00006
	30 to 39 years	1.08906	0.80908, 1.46925	0.57528
	40 to 49 years	Ref.	Ref.	Ref.
	50 to 59 years	1.17055	0.87047, 1.57769	0.29361
	60 and older	1.69975	1.31596, 2.21251	0.00005
Female sex (referent: Male)		1.00150	0.87872, 1.14143	0.98205
Long-term Unemployment (%)		0.95710	0.90535, 1.01017	0.11527
Internal Migration (Five Years)		1.00216	0.98416, 1.02046	0.81437
Median Household Income		1.00000	0.99999, 1.00001	0.84649
Households with One-Parent Families (%)		0.98292	0.92916, 1.03875	0.54784
Education (%)		0.99017	0.96597, 1.01503	0.43525
Households Spending >30% on Shelter Costs (%)		1.02648	1.00713, 1.04641	0.00716

[a)] IRR: Incidence Rate Ratio. [b)] CI: 95% Confidence Interval of the IRR. [c)] Statistically significant p-value ≤ 0.05.

Table 12. Results of the final multivariable Negative Binomial model for reported *Salmonella* spp. infections in 2021 (n=1177 from 32 Public Health Units).

Predictor Variables		**IRR[a)]**	**95% CI[b)]**	**p-value[c)]**
Household Food Insecurity (prevalence)		1.01200	0.97704, 1.04817	0.50469
Age Groups	0 to 4 years	4.49585	3.41335, 5.95213	<0.00001
	5 to 9 years	1.84828	1.33022, 2.56029	0.00023
	10 to 19 years	1.18802	0.87507, 1.61422	0.26915
	20 to 29 years	1.76120	1.33723, 2.33195	0.00006
	30 to 39 years	1.08847	0.80857, 1.46860	0.57782
	40 to 49 years	Ref.	Ref.	Ref.
	50 to 59 years	1.17041	0.87029, 1.57766	0.29405
	60 and older	1.69841	1.31501, 2.21065	0.00005
Female sex (referent: Male)		1.00158	0.87876, 1.14158	0.98105
Long-term Unemployment (%)		0.95969	0.91018, 1.01061	0.12179
Households with One-Parent Families (%)		0.97643	0.93795, 1.01630	0.24375
Education (%)		0.98983	0.97064, 1.00933	0.30265
Households Spending >30% on Shelter Costs (%)		1.02649	1.00748, 1.04604	0.00620

[a)] IRR: Incidence Rate Ratio. [b)] CI: 95% Confidence Interval of the IRR. [c)] Statistically significant p-value ≤ 0.05.

Table 13. Results of the multi-level mixed effects[a)] Negative Binomial model for reported *Salmonella* spp. infections in 2021 (n=1177 from 32 Public Health Units).

Predictor Variables		**IRR[b)]**	**95% CI[c)]**	**p-value[d)]**
(Intercept)		0.00009	0.00002, 0.00040	<0.00001
Household Food Insecurity (prevalence)		1.01200	0.97706, 1.04820	0.50574
Age	0 to 4 years	4.49585	3.39091, 5.96085	<0.00001
	5 to 9 years	1.84828	1.33200, 2.56467	0.00024
	10 to 19 years	1.18802	0.87405, 1.61479	0.27122
	20 to 29 years	1.76120	1.33389, 2.32539	0.00007
	30 to 39 years	1.08847	0.80584, 1.47023	0.58050
	40 to 49 years	Ref.	Ref.	Ref.
	50 to 59 years	1.17041	0.86906, 1.57626	0.30020
	60 and older	1.69841	1.30909, 2.20351	0.00007
Female sex (referent: Male)		1.00158	0.87796, 1.14260	0.98124
Long-term Unemployment (%)		0.95969	0.91070, 1.01130	0.12370
Households with One-Parent Families (%)		0.97643	0.93800, 1.01644	0.24441
Education (%)		0.98983	0.97066, 1.00939	0.30597
Households Spending >30% on Shelter Costs (%)		1.02649	1.00740, 1.04594	0.00635

[a)] The Health Region of a PHU was the random intercept in the regression model. The variance (0.0000000004306) and standard deviation (0.00002075) of Health region random effects [b)] IRR: Incidence Rate Ratio. [c)] CI: 95% Confidence Interval of the IRR. [d)] Statistically significant p-value ≤ 0.05.

Table 14. Results of the Generalized Geographically Weighted Regression for *Salmonella* spp. infections in Ontario, Canada (2021).

Predictor Variables	Min[a)]	Q1[b)]	Median	Q3[c)]	Max[d)]	Global[e)]
X Intercept	0.00039	0.00041	0.00042	0.00042	0.00043	0.00040
Household Food Insecurity (prevalence)	1.01346	1.01421	1.01436	1.01464	1.01514	1.01558
Long-term Unemployment (%)	0.96017	0.96239	0.96543	0.97059	0.97705	0.96874
Households with One-Parent Families (%)	0.96648	0.96805	0.96931	0.97045	0.97081	0.96757
Education (%)	0.99034	0.99055	0.99108	0.99137	0.99176	0.99104
Households Spending >30% on Shelter Costs (%)	1.02440	1.02450	1.02472	1.02496	1.02510	1.02514

[a)] Min: Minimum coefficient value in the GGWR model. [b)] Q1: First quartile (25th percentile). [c)] Q3: Third quartile (75th percentile). [d)] Max: Maximum coefficient value in the GGWR model. [e)] Global: The value of the coefficients in a regular Poisson regression model (glm).

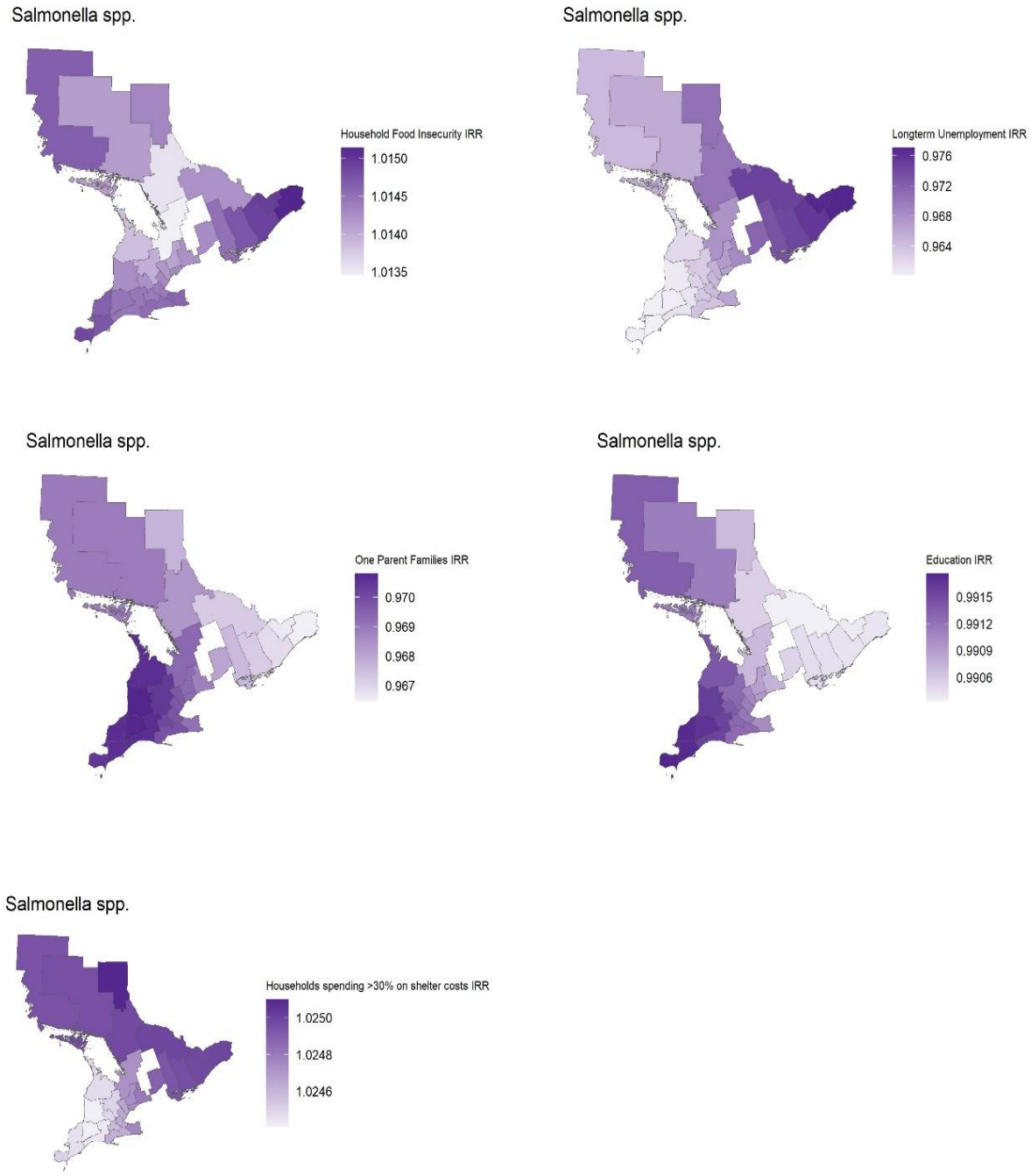


Figure 13. Spatial distribution of age- and sex-adjusted Incidence Rate Ratios (IRR) of reported *Salmonella* spp. infections estimated from a generalized geographically weighted regression (GGWR) using a Poisson model, across 30 Public Health Units in 2021. Each map shows the association between the age- and sex-adjusted incidence rates of *Salmonella* spp. and a predictor variable at the Public Health Unit level, holding all other predictor variables constant.

4.4.3 Determinants of STEC Incidence across Public Health Units (2021)

The results of the univariable and multivariable models are shown in Tables 15-17. The proportion of households experiencing food insecurity was not significantly associated with the incidence rates of STEC infections in the univariable model (IRR=0.94831, 95% CI 0.89886-1.00082). However, household food insecurity was significant in the full and final multivariable models. In the final multivariable model, a one-unit increase in the prevalence of household insecurity was associated with an approximate 10% decrease in the age- and sex-adjusted incidence rates of STEC, while holding all other variables constant (IRR=0.90553, 95% CI 0.83315-0.98399). The proportion of the population that experienced long-term unemployment, the proportion of the population that has moved within Canada in the last five years, and median household income were the only variables not included in the final multivariable model.

All census predictors were significantly associated with the incidence rates of STEC in the univariable model. The proportion of households with one-parent families (%), the proportion of the population with a postsecondary certificate, diploma, or degree, and the proportion of households spending>30% on shelter costs, were the only census variables that were statistically significant in the multivariable models.

The results obtained from the multi-level mixed effects model (Table 18), were mostly consistent with the final multivariable model (Table 17). However, household food insecurity was no longer significantly associated with the age- and-sex adjusted incidence rates of STEC in the random-effects model (IRR=0.93600, 95% CI 0.85062-1.02996). The IRRs for the proportion of households with one-parent families (%), the proportion of the population with a postsecondary certificate, diploma, or degree, and the proportion of households spending>30% on shelter costs, remained significant in the multi-level model.

Table 15. Results of the univariable Poisson model for reported STEC infections in 2021 (n=165 from 32 Public Health Units).

Predictor Variables		**IRR[a)]**	**95% CI[b)]**	**p-value[c)]**
Household Food Insecurity (prevalence)		0.94831	0.89886, 1.00082	0.05268
Age Groups	0 to 4 years	7.27530	3.83665, 14.73931	<0.00001
	5 to 9 years	4.11786	2.02285, 8.72331	0.00012
	10 to 19 years	1.96691	0.96622, 4.16672	0.06657
	20 to 29 years	1.78063	0.89643, 3.71501	0.10789
	30 to 39 years	1.06001	0.48079, 2.35658	0.88426
	40 to 49 years	1.72210	0.84596, 3.64811	0.14046
	50 to 59 years	Ref.	Ref.	Ref.
	60 and older	1.39913	0.73500, 2.84155	0.32547
Female sex (referent: Male)		1.40120	1.02998, 1.91703	0.03294
Long-term Unemployment (%)		0.86642	0.79929, 0.93996	0.00052
Internal Migration (Five Years)		1.03512	1.01222, 1.05851	0.00245
Median Household Income		1.00002	1.00000, 1.00003	0.01314
Households with One-Parent Families (%)		0.82669	0.77077, 0.88496	<0.00001
Education (%)		0.98633	0.96249, 1.01104	0.27251
Households Spending >30% on Shelter Costs (%)		0.98242	0.96162, 1.00297	0.09805

[a)] IRR: Incidence Rate Ratio. [b)] CI: 95% Confidence Interval of the IRR. [c)] Statistically significant p-value ≤ 0.05.

Table 16. Results of the full multivariable Poisson model for reported STEC infections in 2021 (n=165 from 32 Public Health Units).

Predictor Variables		**IRR[a)]**	**95% CI[b)]**	**p-value[c)]**
Household Food Insecurity (prevalence)		0.89944	0.81930, 0.98597	0.02466
Age Groups	0 to 4 years	7.31518	3.85703, 14.82218	<0.00001
	5 to 9 years	4.11393	2.02069, 8.71591	0.00013
	10 to 19 years	1.95944	0.96240, 4.15150	0.06818
	20 to 29 years	1.87010	0.94103, 3.90327	0.08130
	30 to 39 years	1.10620	0.50162, 2.45987	0.80101
	40 to 49 years	1.73680	0.85309, 3.67962	0.13442
	50 to 59 years	Ref.	Ref.	Ref.
	60 and older	1.38384	0.72653, 2.81186	0.34196
Female sex (referent: Male)		1.43375	1.05365, 1.96202	0.02283
Long-term Unemployment (%)		1.00730	0.86620, 1.15525	0.92070
Internal Migration (Five Years)		0.98037	0.93531, 1.02690	0.40429
Median Household Income		1.00000	0.99997, 1.00003	0.94189
Households with One-Parent Families (%)		0.74422	0.63513, 0.86089	0.00014
Education (%)		0.91977	0.86282, 0.97942	0.00962
Households Spending >30% on Shelter Costs (%)		1.09071	1.03853, 1.14850	0.00069

[a)] IRR: Incidence Rate Ratio. [b)] CI: 95% Confidence Interval of the IRR. [c)] Statistically significant p-value ≤ 0.05.

Table 17. Results of the final multivariable Poisson model for reported STEC infections in 2021 (n=165 from 32 Public Health Units).

Predictor Variables		**IRR[a)]**	**95% CI[b)]**	**p-value[c)]**
Household Food Insecurity (prevalence)		0.90553	0.83315, 0.98399	0.01932
Age Groups	0 to 4 years	7.32836	3.86424, 14.84808	<0.00001
	5 to 9 years	4.12087	2.02420, 8.73019	0.00012
	10 to 19 years	1.96324	0.96433, 4.15927	0.06736
	20 to 29 years	1.87803	0.94509, 3.91954	0.07923
	30 to 39 years	1.10731	0.50214, 2.46224	0.79907
	40 to 49 years	1.73775	0.85357, 3.68158	0.13403
	50 to 59 years	Ref.	Ref.	Ref.
	60 and older	1.38344	0.72644, 2.81070	0.34228
Female sex (referent: Male)		1.43359	1.05353, 1.96180	0.02287
Households with One-Parent Families (%)		0.76076	0.69505, 0.83120	<0.00001
Education (%)		0.92871	0.88630, 0.97170	0.00158
Households Spending >30% on Shelter Costs (%)		1.09585	1.04463, 1.15240	0.00025

[a)] IRR: Incidence Rate Ratio. [b)] CI: 95% Confidence Interval of the IRR. [c)] Statistically significant p-value ≤ 0.05.

Table 18. Results of the multi-level mixed effects[a)] Poisson model for reported STEC infections in 2021 (n=165 from 32 Public Health Units).

Predictor Variables		**IRR[a)]**	**95% CI[b)]**	**p-value[c)]**
(Intercept)		0.00465	0.00014, 0.15556	0.00271
Household Food Insecurity (prevalence)		0.93600	0.85062, 1.02996	0.17540
Age Groups	0 to 4 years	7.23254	3.71371, 14.08553	<0.00001
	5 to 9 years	4.07857	1.97962, 8.40299	0.00014
	10 to 19 years	1.94509	0.94406, 4.00756	0.07125
	20 to 29 years	1.85829	0.91927, 3.75649	0.08443
	30 to 39 years	1.09506	0.49953, 2.40055	0.82062
	40 to 49 years	1.72374	0.83666, 3.55137	0.13983
	50 to 59 years	Ref.	Ref.	Ref.
	60 and older	1.38491	0.70873, 2.70620	0.34074
Female sex (referent: Male)		1.43329	1.05100, 1.95463	0.02295
Households with One-Parent Families (%)		0.74630	0.66996, 0.83134	<0.00001
Education (%)		0.93900	0.89579, 0.98430	0.00883
Households Spending >30% on Shelter Costs (%)		1.10541	1.04071, 1.17414	0.00113

[a)] The Health Region of a PHU was the random intercept in the regression model. The variance (0.1078) and standard deviation (0.3283) of Health region random effects [b)] IRR: Incidence Rate Ratio. [c)] CI: 95% Confidence Interval of the IRR. [d)] Statistically significant p-value ≤ 0.05.

4.4.4 Determinants of Listeria monocytogenes Incidence across Public Health Units (2021)

Age group categories were collapsed into 0 to 9 years, 10 to 49 years, 50 to 59 years, and 60 and older due to zero case counts of *Listeria monocytogenes* in several age groups. The prevalence of household food insecurity had a positive association with the age- and sex-adjusted incidence rates of *Listeria monocytogenes* (IRR>1.0) in the univariable, full, and final multivariable models (Tables 19-21). However, the association between age- and sex-adjusted *Listeria monocytogenes* incidence rates and the proportion of households experiencing food insecurity was not statistically significant in any of the models. The proportion of the population that has moved within Canada in the last five years (%) and the proportion of households with one-parent families (%) were the only variables not included in the final multivariable model.

Among the census predictor variables, the proportion of the population that experienced long-term unemployment (%), was the only census predictor variable significantly associated with *Listeria monocytogenes* incidence rates in the final multivariable model. A one-unit increase in the proportion of the population that experienced long-term unemployment was associated with an approximate 22% decrease in the age- and sex-adjusted incidence rates of *Listeria monocytogenes*, while holding all other variables constant (IRR=0.78082, 95% CI 0.59886-0.97395). No other census predictor variables were significant in the univariable or multivariable models.

Table 19. Results of the univariable Poisson model for reported *Listeria monocytogenes* infections in 2021 (n=72 from 32 Public Health Units).

Predictor Variables		**IRR[a)]**	**95% CI[b)]**	**p-value[c)]**
Household Food Insecurity (prevalence)		1.00911	0.90750, 1.12100	0.86756
Age Groups	0 to 9 years	6.14392	1.84691, 21.35624	0.00277
	10 to 49 years	Ref.	Ref.	Ref.
	50 to 59 years	6.83926	2.35396, 22.32790	0.00059
	60 and older	21.61345	9.47825, 62.29387	<0.00001
Female sex (referent: Male)		1.01572	0.55560, 1.85839	0.96072
Long-term Unemployment (%)		0.91667	0.78750, 1.07216	0.29142
Internal Migration (Five Years)		0.98217	0.93530, 1.02840	0.47009
Median Household Income		0.99999	0.99996, 1.00002	0.38144
Households with One-Parent Families (%)		1.02152	0.89671, 1.17119	0.76415
Education (%)		1.00540	0.96055, 1.05461	0.82799
Households Spending >30% on Shelter Costs (%)		1.00446	0.96301, 1.05040	0.84888

[a)] IRR: Incidence Rate Ratio. [b)] CI: 95% Confidence Interval of the IRR. [c)] Statistically significant p-value ≤ 0.05.

Table 20. Results of the full multivariable Poisson model for reported *Listeria monocytogenes* infections in 2021 (n=72 from 32 Public Health Units).

Predictor Variables		**IRR[a)]**	**95% CI[b)]**	**p-value[c)]**
Household Food Insecurity (prevalence)		1.06800	0.92407, 1.24233	0.37920
Age Groups	0 to 9 years	6.30254	1.89753, 21.87600	0.00237
	10 to 49 years	Ref.	Ref.	Ref.
	50 to 59 years	6.94853	2.40008, 22.61917	0.00051
	60 and older	22.71378	9.99239, 65.33792	<0.00001
Female sex (referent: Male)		0.94836	0.59655, 1.51066	0.82222
Long-term Unemployment (%)		0.77447	0.56728, 0.99422	0.06986
Internal Migration (Five Years)		0.99423	0.92064, 1.07200	0.88070
Median Household Income		0.99998	0.99994, 1.00002	0.36090
Households with One-Parent Families (%)		1.02119	0.78776, 1.29314	0.86721
Education (%)		1.06238	0.96745, 1.17033	0.21129
Households Spending >30% on Shelter Costs (%)		1.02695	0.96050, 1.10070	0.44169

[a)] IRR: Incidence Rate Ratio. [b)] CI: 95% Confidence Interval of the IRR. [c)] Statistically significant p-value ≤ 0.05.

Table 21. Results of the final multivariable Poisson model for reported *Listeria monocytogenes* infections in 2021 (n=72 from 32 Public Health Units).

Predictor Variables		**IRR[a)]**	**95% CI[b)]**	**p-value[c)]**
Household Food Insecurity (prevalence)		1.06999	0.93151, 1.23267	0.34165
Age Groups	0 to 9 years	6.30252	1.89752, 21.87591	0.00237
	10 to 49 years	Ref.	Ref.	Ref.
	50 to 59 years	6.94034	2.39730, 22.59215	0.00051
	60 and older	22.66316	9.97113, 65.18846	<0.00001
Female sex (referent: Male)		0.94832	0.59652, 1.51060	0.82209
Long-term Unemployment (%)		0.78082	0.59886, 0.97395	0.04439
Median Household Income		0.99998	0.99995, 1.00000	0.11373
Education (%)		1.06877	0.98876, 1.15492	0.09156
Households Spending >30% on Shelter Costs (%)		1.03146	0.97057, 1.09927	0.32758

[a)] IRR: Incidence Rate Ratio. [b)] CI: 95% Confidence Interval of the IRR. [c)] Statistically significant p-value ≤ 0.05.

4.4.5 Determinants of Shigella spp. Incidence across Public Health Units (2021)

The results of the univariable and multivariable models are shown in Tables 22-24. Household food insecurity was not significantly associated with age- and sex-adjusted incidence rates *Shigella* spp. in any of the univariable and multivariable models (IRR=1.00995, 95% CI 0.94896-1.07575, IRR=0.97022, 95% CI 0.84147-1.12021, and IRR=1.01355, 95% CI 0.89885-1.14945).

In the univariable model, all census covariates had a significant association with *Shigella* spp. incidence rates. However, none of the census covariates were significant in the full multivariable model. After excluding the proportion of the population that has moved within Canada in the last five years (%), median household income, and the proportion of households spending>30% on shelter costs from the full multivariable model, the only significant predictors in the final model were the proportion of households with one-parent families (%) and the proportion of the population with a postsecondary certificate, diploma, or degree (%).

The results obtained from the multi-level mixed effects model (Table 25) were consistent with the final multivariable model (Table 24). The estimated variance of the random intercept (Health Region) was minimal after adjusting for covariates, similar to the findings for the *Salmonella* spp. mixed model. The age- and sex-adjusted incidence rates of *Shigella* spp. infections were relatively similar across health regions. Therefore, there were no substantial changes in the direction, magnitude, or significance of the predictor variables in the mixed model compared to the fixed effects model.

Table 22. Results of the univariable Poisson model for reported *Shigella* spp. infections in 2021 (n=125 from 32 Public Health Units).

Predictor Variables		**IRR[a)]**	**95% CI[b)]**	**p-value[c)]**
Household Food Insecurity (prevalence)		1.00995	0.94896, 1.07575	0.75685
Age Groups	0 to 4 years	7.12885	3.42994, 15.29596	<0.00001
	5 to 9 years	3.09805	1.21383, 7.48861	0.01323
	10 to 19 years	1.10985	0.38638, 2.85782	0.83488
	20 to 29 years	3.47092	1.77049, 7.18198	0.00043
	30 to 39 years	4.07949	2.12496, 8.33013	0.00005
	40 to 49 years	2.59123	1.23163, 5.60128	0.01266
	50 to 59 years	2.08463	0.96237, 4.58604	0.06186
	60 and older	Ref.	Ref.	Ref.
Male sex (referent: Female)		2.42127	1.66378, 3.59536	0.00001
Long-term Unemployment (%)		1.17500	1.06199, 1.30375	0.00204
Internal Migration (Five Years)		0.88430	0.85273, 0.91458	<0.00001
Median Household Income		0.99997	0.99996, 0.99999	0.00684
Households with One-Parent Families (%)		1.31824	1.21970, 1.42900	<0.00001
Education (%)		1.08108	1.04778, 1.11684	<0.00001
Households Spending >30% on Shelter Costs (%)		1.08068	1.05606, 1.10658	<0.00001

[a)] IRR: Incidence Rate Ratio. [b)] CI: 95% Confidence Interval of the IRR. [c)] Statistically significant p-value ≤ 0.05.

Table 23. Results of the full multivariable Poisson model for reported *Shigella* spp. infections in 2021 (n=125 from 32 Public Health Units).

Predictor Variables		**IRR[a)]**	**95% CI[b)]**	**p-value[c)]**
Household Food Insecurity (prevalence)		0.97022	0.84147, 1.12021	0.67671
Age Groups	0 to 4 years	6.74166	3.24225, 14.47094	<0.00001
	5 to 9 years	2.98290	1.16821, 7.21377	0.01671
	10 to 19 years	1.07252	0.37319, 2.76344	0.88870
	20 to 29 years	2.92957	1.49271, 6.06761	0.00240
	30 to 39 years	3.43963	1.78952, 7.03069	0.00035
	40 to 49 years	2.38119	1.13115, 5.15001	0.02320
	50 to 59 years	1.97545	0.91169, 4.34714	0.08366
	60 and older	Ref.	Ref.	Ref.
Male sex (referent: Female)		2.37555	1.63201, 3.52817	0.00001
Long-term Unemployment (%)		0.83199	0.64342, 1.03326	0.12285
Internal Migration (Five Years)		0.96627	0.89505, 1.03894	0.36350
Median Household Income		0.99998	0.99995, 1.00002	0.41659
Households with One-Parent Families (%)		1.19203	0.94658, 1.47289	0.11635
Education (%)		1.04879	0.96097, 1.14740	0.29082
Households Spending >30% on Shelter Costs (%)		1.02418	0.96352, 1.08915	0.44260

[a)] IRR: Incidence Rate Ratio. [b)] CI: 95% Confidence Interval of the IRR. [c)] Statistically significant p-value ≤ 0.05.

Table 24. Results of the final multivariable Poisson model for reported *Shigella* spp. infections in 2021 (n=125 from 32 Public Health Units).

Predictor Variables		**IRR[a)]**	**95% CI[b)]**	**p-value[c)]**
Household Food Insecurity (prevalence)		1.01355	0.89885, 1.14945	0.82927
Age Groups	0 to 4 years	6.68605	3.21611, 14.34906	<0.00001
	5 to 9 years	2.95498	1.15746, 7.14492	0.01764
	10 to 19 years	1.06223	0.36968, 2.73629	0.90393
	20 to 29 years	2.92916	1.49282, 6.06567	0.00240
	30 to 39 years	3.43311	1.78649, 7.01615	0.00036
	40 to 49 years	2.36702	1.12464, 5.11843	0.02412
	50 to 59 years	1.96613	0.90749, 4.32616	0.08578
	60 and older	Ref.	Ref.	Ref.
Male sex (referent: Female)		2.37631	1.63253, 3.52930	0.00001
Long-term Unemployment (%)		0.81030	0.64868, 0.99186	0.05123
Households with One-Parent Families (%)		1.37489	1.23501, 1.53793	<0.00001
Education (%)		1.08240	1.03526, 1.13827	0.00100

[a)] IRR: Incidence Rate Ratio. [b)] CI: 95% Confidence Interval of the IRR. [c)] Statistically significant p-value ≤ 0.05.

Table 25. Results of the multi-level mixed effects[a)] Poisson model for reported *Shigella* spp. infections in 2021 (n=125 from 32 Public Health Units).

Predictor Variables		**IRR[b)]**	**95% CI[c)]**	**p-value[d)]**
(Intercept)		0.00000	0.00000, 0.00000	<0.00001
Household Food Insecurity (prevalence)		1.01355	0.89688, 1.14539	0.82926
Age Groups	0 to 4 years	6.68605	3.19250, 14.00258	<0.00001
	5 to 9 years	2.95498	1.20756, 7.23107	0.01764
	10 to 19 years	1.06223	0.39853, 2.83128	0.90393
	20 to 29 years	2.92916	1.46362, 5.86218	0.00240
	30 to 39 years	3.43311	1.74417, 6.75753	0.00036
	40 to 49 years	2.36702	1.11939, 5.00522	0.02412
	50 to 59 years	1.96613	0.90922, 4.25166	0.08578
	60 and older	Ref.	Ref.	Ref.
Male sex (referent: Female)		2.37631	1.61820, 3.48959	0.00001
Long-term Unemployment (%)		0.81030	0.65585, 1.00111	0.05122
Households with One-Parent Families (%)		1.37489	1.23216, 1.53416	<0.000001
Education (%)		1.08240	1.03258, 1.13463	0.00099

[a)] The Health Region of a PHU was the random intercept in the regression model. The variance (0.0000000004912) and standard deviation (0.00002216) of Health region random effects [b)] IRR: Incidence Rate Ratio. [c)] CI: 95% Confidence Interval of the IRR. [d)] Statistically significant p-value ≤ 0.05.

4.4.6 Determinants of Cyclospora cayetanensis Incidence across Public Health Units (2021)

The results of the univariable and multivariable models are shown in Tables 26-28. Household food insecurity was not significantly associated with the age- and sex-adjusted incidence rates of *Cyclospora cayetanensis* in any of the univariable or multivariable models. However, the direction of the association changed between the models. The univariable model had an inverse association (IRR=0.96812, 95% CI 0.90298-1.03872). In contrast, the full and final multivariable models showed a positive association (IRR=1.06769, 95% CI 0.95461-1.19570, and IRR=1.05841, 95% CI 0.94928-1.18227).

In the univariable model, the proportion of households spending >30% of their income on shelter costs was the only census covariate significantly associated with *Cyclospora cayetanensis* incidence rates. None of the census covariates were significant in the full and final multivariable models.

The results obtained from the multi-level mixed effects model (Table 29) were consistent with the final multivariable model (Table 28). The estimated variance of the random intercept (Health Region) was minimal after adjusting for covariates, similar to the findings for the *Salmonella* spp. and *Shigella* spp. mixed model, indicating the incidence rates of *Cyclospora cayetanensis* infections were relatively similar across health regions. Therefore, no substantial changes in the direction, magnitude, or significance were observed in the mixed model compared to the fixed effects model.

Table 26. Results of the univariable Poisson model for reported *Cyclospora cayetanensis* infections in 2021 (n=98 from 32 Public Health Units).

Predictor Variables		**IRR[a)]**	**95% CI[b)]**	**p-value[c)]**
Household Food Insecurity (prevalence)		0.96812	0.90298, 1.03872	0.36394
Age Groups	0 to 4 years	1.13352	0.05268, 11.83436	0.91847
	5 to 9 years	1.04678	0.04865, 10.92883	0.97021
	10 to 19 years	Ref.	Ref.	Ref.
	20 to 29 years	2.34554	0.54041, 16.00878	0.29635
	30 to 39 years	5.90740	1.66707, 37.48810	0.01827
	40 to 49 years	7.44204	2.13435, 46.94205	0.00724
	50 to 59 years	8.04985	2.35111, 50.42763	0.00491
	60 and older	8.10921	2.47977, 49.90787	0.00396
Female sex (referent: Male)		1.30971	0.88004, 1.96417	0.18624
Long-term Unemployment (%)		0.92248	0.82992, 1.02733	0.13791
Internal Migration (Five Years)		1.02978	1.00022, 1.06007	0.04737
Median Household Income		1.00000	0.99999, 1.00002	0.66026
Households with One-Parent Families (%)		0.93067	0.85445, 1.01191	0.09533
Education (%)		0.99639	0.96510, 1.02927	0.82521
Households Spending >30% on Shelter Costs (%)		0.97183	0.94422, 0.99882	0.04575

[a)] IRR: Incidence Rate Ratio. [b)] CI: 95% Confidence Interval of the IRR. [c)] Statistically significant p-value ≤ 0.05.

Table 27. Results of the full multivariable Poisson model for reported *Cyclospora cayetanensis* infections in 2021 (n=98 from 32 Public Health Units).

Predictor Variables		**IRR[a)]**	**95% CI[b)]**	**p-value[c)]**
Household Food Insecurity (prevalence)		1.06769	0.95461, 1.19570	0.25273
Age Groups	0 to 4 years	1.13851	0.05291, 11.88735	0.91564
	5 to 9 years	1.04452	0.04854, 10.90538	0.97163
	10 to 19 years	Ref.	Ref.	Ref.
	20 to 29 years	2.44304	0.56261, 16.67900	0.27407
	30 to 39 years	6.08119	1.71514, 38.60126	0.01651
	40 to 49 years	7.49120	2.14811, 47.25562	0.00707
	50 to 59 years	8.07518	2.35806, 50.59074	0.00486
	60 and older	8.00831	2.44606, 49.31175	0.00421
Female sex (referent: Male)		1.26264	0.84816, 1.89411	0.25360
Long-term Unemployment (%)		0.97098	0.80806, 1.14390	0.73756
Internal Migration (Five Years)		1.04363	0.98760, 1.10414	0.13160
Median Household Income		0.99999	0.99996, 1.00003	0.74958
Households with One-Parent Families (%)		1.05041	0.87895, 1.24213	0.57544
Education (%)		1.07493	0.99454, 1.16346	0.07056
Households Spending >30% on Shelter Costs (%)		0.95454	0.90136, 1.01133	0.11192

[a)] IRR: Incidence Rate Ratio. [b)] CI: 95% Confidence Interval of the IRR. [c)] Statistically significant p-value ≤ 0.05.

Table 28. Results of the final multivariable Poisson model for reported *Cyclospora cayetanensis* infections in 2021 (n=98 from 32 Public Health Units).

Predictor Variables		**IRR[a)]**	**95% CI[b)]**	**p-value[c)]**
Household Food Insecurity (prevalence)		1.05841	0.94928, 1.18227	0.30986
Age Groups	0 to 4 years	1.14389	0.05316, 11.94320	0.91259
	5 to 9 years	1.04726	0.04867, 10.93392	0.96992
	10 to 19 years	Ref.	Ref.	Ref.
	20 to 29 years	2.45752	0.56601, 16.77684	0.27088
	30 to 39 years	6.13518	1.73079, 38.93955	0.01597
	40 to 49 years	7.51559	2.15520, 47.40864	0.00697
	50 to 59 years	8.10457	2.36683, 50.77299	0.00478
	60 and older	8.06811	2.46541, 49.67059	0.00406
Female sex (referent: Male)		1.26294	0.84836, 1.89455	0.25312
Internal Migration (Five Years)		1.02822	0.98555, 1.07322	0.19943
Education (%)		1.05487	0.99531, 1.12020	0.07568
Households Spending >30% on Shelter Costs (%)		0.95817	0.91150, 1.00841	0.09631

[a)] IRR: Incidence Rate Ratio. [b)] CI: 95% Confidence Interval of the IRR. [c)] Statistically significant p-value ≤ 0.05.

Table 29. Results of the multi-level mixed effects[a)] Poisson model for reported *Cyclospora cayentanensis* infections in 2021 (n=98 from 32 Public Health Units).

Predictor Variables		**IRR[b)]**	**95% CI[c)]**	**p-value[d)]**
(Intercept)		0.00000	0.00000, 0.00003	<0.00001
Household Food Insecurity (prevalence)		1.05934	0.93552, 1.19956	0.36336
Age Groups	0 to 4 years	1.14348	0.10368, 12.61153	0.91283
	5 to 9 years	1.04708	0.09494, 11.54754	0.97004
	10 to 19 years	Ref.	Ref.	Ref.
	20 to 29 years	2.45637	0.49558, 12.17520	0.27117
	30 to 39 years	6.13096	1.40137, 26.82287	0.01604
	40 to 49 years	7.51351	1.73571, 32.52428	0.00699
	50 to 59 years	8.10201	1.89354, 34.66669	0.00479
	60 and older	8.06161	1.93942, 33.50982	0.00409
Female sex (referent: Male)		1.26292	0.84625, 1.88474	0.25316
Internal Migration (Five Years)		1.02942	0.95904, 1.10496	0.42231
Education (%)		1.05527	0.98753, 1.12767	0.11201
Households Spending >30% on Shelter Costs (%)		0.95892	0.90393, 1.01726	0.16388

[a)] The Health Region of a PHU was the random intercept in the regression model. The variance (0.00253) and standard deviation (0.0503) of Health region random effects [b)] IRR: Incidence Rate Ratio. [c)] CI: 95% Confidence Interval of the IRR. [d)] Statistically significant p-value ≤ 0.05.

4.4.7 Determinants of Giardia duodenalis Incidence across Public Health Units (2021)

The results of the univariable and multivariable models are shown in Tables 30-32. The univariable model showed that the household food insecurity was not significantly associated with *Giardia duodenalis* incidence rates (IRR=0.96937, 95% CI 0.93306-1.00680). However, in both of the full and final multivariable models, household food insecurity had a significant inverse association with age- and sex-adjusted incidence rates of *Giardia duodenalis*. In the final multivariable model, a one-unit increase in the prevalence of household insecurity was associated with an approximate 9% decrease in the age- and sex-adjusted incidence rates of *Giardia duodenalis*, while holding all other variables constant (IRR=0.91538, 95% CI 0.87714-0.95489).

All the census predictor variables were significantly associated with the *Giardia duodenalis* incidence rates in the univariable model. Long-term unemployment (%), internal migration (five years), education (%), and the proportion of households spending >30% on shelter costs were the only census variables that remained statistically significant in the full and final multivariable models.

The results from the multi-level mixed effects model (Table 33) were consistent with the final multivariable model. Household food insecurity still had a significant negative association with the age- and sex-adjusted *Giardia duodenalis* incidence rates, while holding all other variables constant and accounting for clustering in an administrative health region (IRR=0.92756, 95% CI 0.88425,0.97299). Most of the demographic and socioeconomic predictor variables remained significant with the same direction of association. However, one difference was that median household income became statistically significant in the mixed model, with a weak positive association (IRR=0.99998 95% CI 0.99996-0.99999).

The GGWR results (Table 34 and Figure 14) indicated that household food insecurity, internal migration (five years), long-term unemployment, median household income, one-parent families, and education had minimal spatial non-stationarity. Thus, the association with age- and sex-adjusted *Giardia duodenalis* incidence rates and predictor variables were similar across Ontario PHUs. The range of IRRs for household food insecurity was quite small and similar to the other pathogens. The direction of the associations observed in the global Poisson model was the same as those estimated and the GGWR model.

Table 30. Results of the univariable Negative Binomial model for reported *Giardia duodenalis* infections in 2021 (n=751 from 32 Public Health Units).

Predictor Variables		**IRR[a)]**	**95% CI[b)]**	**p-value[c)]**
Household Food Insecurity (prevalence)		0.96937	0.93306, 1.00680	0.09512
Age Groups	0 to 4 years	3.26830	1.87295, 5.73419	0.00003
	5 to 9 years	2.39875	1.34557, 4.27917	0.00318
	10 to 19 years	Ref.	Ref.	Ref.
	20 to 29 years	2.75114	1.66765, 4.61047	0.00010
	30 to 39 years	4.43399	2.73630, 7.31454	<0.00001
	40 to 49 years	3.59540	2.19753, 5.98054	<0.00001
	50 to 59 years	3.62086	2.22911, 5.98513	<0.00001
	60 and older	2.97610	1.86415, 4.84476	0.00001
Male sex (referent: Female)		1.56051	1.26180, 1.93181	0.00003
Long-term Unemployment (%)		0.89587	0.84930, 0.94538	0.00005
Internal Migration (Five Years)		1.03914	1.02299, 1.05540	<0.00001
Median Household Income		0.99998	0.99997, 0.99999	0.00077
Households with One-Parent Families (%)		0.95171	0.90800, 0.99815	0.04461
Education (%)		0.95912	0.94393, 0.97470	0.00000
Households Spending >30% on Shelter Costs (%)		0.97725	0.96165, 0.99357	0.00853

[a)] IRR: Incidence Rate Ratio. [b)] CI: 95% Confidence Interval of the IRR. [c)] Statistically significant p-value ≤ 0.05.

Table 31. Results of the full multivariable Negative Binomial model for reported *Giardia duodenalis* infections in 2021 (n=751 from 32 Public Health Units).

Predictor Variables		**IRR[a)]**	**95% CI[b)]**	**p-value[c)]**
Household Food Insecurity (prevalence)		0.91467	0.87614, 0.95453	0.00004
Age Groups	0 to 4 years	2.92727	1.81503, 4.75748	0.00001
	5 to 9 years	2.20144	1.33100, 3.64539	0.00223
	10 to 19 years	Ref.	Ref.	Ref.
	20 to 29 years	2.46214	1.63039, 3.80413	0.00004
	30 to 39 years	3.57245	2.40258, 5.45190	<0.00001
	40 to 49 years	3.03125	2.01529, 4.66857	<0.00001
	50 to 59 years	3.08903	2.07023, 4.72689	<0.00001
	60 and older	2.39758	1.62780, 3.63108	0.00002
Male sex (referent: Female)		1.63840	1.38691, 1.93845	<0.00001
Long-term Unemployment (%)		0.92916	0.86896, 0.99129	0.02566
Internal Migration (Five Years)		1.04549	1.02236, 1.06933	0.00012
Median Household Income		0.99999	0.99998, 1.00000	0.07776
Households with One-Parent Families (%)		0.99103	0.92653, 1.05889	0.79020
Education (%)		0.93435	0.90500, 0.96444	0.00002
Households Spending >30% on Shelter Costs (%)		1.08560	1.05751, 1.11520	<0.00001

[a)] IRR: Incidence Rate Ratio. [b)] CI: 95% Confidence Interval of the IRR. [c)] Statistically significant p-value ≤ 0.05.

Table 32. Results of the final multivariable Negative Binomial model for reported *Giardia duodenalis* infections in 2021 (n=751 from 32 Public Health Units).

Predictor Variables		**IRR[a)]**	**95% CI[b)]**	**p-value[c)]**
Household Food Insecurity (prevalence)		0.91538	0.87714, 0.95489	0.00004
Age Groups	0 to 4 years	2.92745	1.81513, 4.75782	0.00001
	5 to 9 years	2.20138	1.33095, 3.64531	0.00223
	10 to 19 years	Ref.	Ref.	Ref.
	20 to 29 years	2.46237	1.63054, 3.80449	0.00004
	30 to 39 years	3.57252	2.40261, 5.45205	<0.00001
	40 to 49 years	3.03092	2.01507, 4.66807	<0.00001
	50 to 59 years	3.08924	2.07036, 4.72721	<0.00001
	60 and older	2.39897	1.62879, 3.63311	0.00002
Male sex (referent: Female)		1.63849	1.38699, 1.93856	<0.00001
Long-term Unemployment (%)		0.92515	0.87246, 0.97914	0.00710
Internal Migration (Five Years)		1.04689	1.02616, 1.06836	0.00001
Median Household Income		0.99999	0.99998, 1.00000	0.07548
Education (%)		0.93542	0.90724, 0.96448	0.00002
Households Spending >30% on Shelter Costs (%)		1.08438	1.05776, 1.11241	<0.00001

[a)] IRR: Incidence Rate Ratio. [b)] CI: 95% Confidence Interval of the IRR. [c)] Statistically significant p-value ≤ 0.05.

Table 33. Results of multi-level mixed effects[a)] Negative Binomial model for reported *Giardia duodenalis* infections in 2021 (n=751 from 32 Public Health Units).

Predictor Variables		**IRR[b)]**	**95% CI[c)]**	**p-value[d)]**
(Intercept)		0.00097	0.00011, 0.00835	<0.00001
Household Food Insecurity (prevalence)		0.92756	0.88425, 0.97299	0.00206
Age Groups	0 to 4 years	2.91415	1.80740, 4.69861	0.00001
	5 to 9 years	2.18671	1.32749, 3.60205	0.00212
	10 to 19 years	Ref.	Ref.	Ref.
	20 to 29 years	2.45543	1.61539, 3.73232	0.00003
	30 to 39 years	3.53203	2.34942, 5.30992	<0.00001
	40 to 49 years	2.99668	1.97269, 4.55221	<0.00001
	50 to 59 years	3.07246	2.04207, 4.62277	<0.00001
	60 and older	2.36783	1.59051, 3.52504	0.00002
Male sex (referent: Female)		1.64739	1.39367, 1.94731	<0.00001
Long-term Unemployment (%)		0.88976	0.83093, 0.95277	0.00082
Internal Migration (Five Years)		1.04899	1.02523, 1.07330	0.00004
Median Household Income		0.99998	0.99996, 1.00000	0.01959
Education (%)		0.95956	0.92452, 0.99592	0.02961
Households Spending >30% on Shelter Costs (%)		1.06857	1.03005, 1.10854	0.00040

[a)] The Health Region of a PHU was the random intercept in the regression model. The variance (0.0583) and standard deviation (0.2414) of Health region random effects [b)] IRR: Incidence Rate Ratio. [c)] CI: 95% Confidence Interval of the IRR. [d)] Statistically significant p-value ≤ 0.05.

Table 34. Results of Generalized Geographically Weighted Regression for *Giardia duodenalis* infections in Ontario, Canada (2021).

Predictor Variables	Min[a)]	Q1[b)]	Median	Q3[c)]	Max[d)]	Global[e)]
X Intercept	0.00164	0.00180	0.00195	0.00295	0.00464	0.00350
Household Food Insecurity	0.91723	0.92182	0.92712	0.92789	0.92898	0.91847
Long-term Unemployment (%)	0.90873	0.91077	0.91363	0.92524	0.93313	0.92616
Internal Migration (5 Years)	1.04856	1.05607	1.05763	1.05847	1.05898	1.05425
Median Household Income	0.99999	0.99999	0.99999	0.99999	0.99999	0.99999
Education (%)	0.92902	0.93184	0.93777	0.94014	0.94124	0.93096
Households Spending >30% on Shelter Costs (%)	1.08947	1.09546	1.09872	1.10121	1.10631	1.09893

[a)] Min: Minimum coefficient value in the GGWR model. [b)] Q1: Fincidence ratest quartile (25th percentile). [c)] Q3: Third quartile (75th percentile). [d)] Max: Maximum coefficient value in the GGWR model. [e)] Global: The value of the coefficients in a regular Poisson regression model (glm).

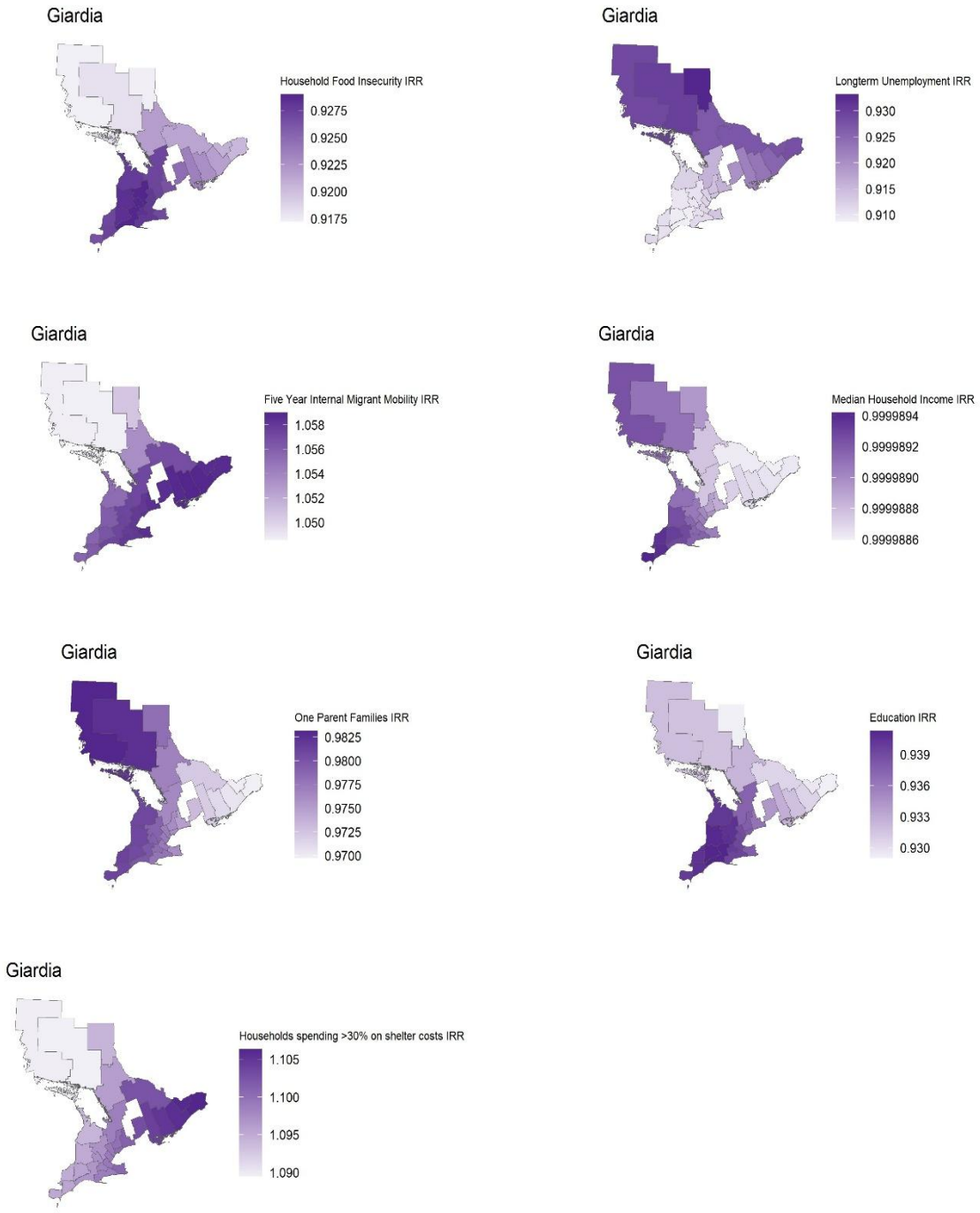


Figure 14. Spatial distribution of age- and sex-adjusted Incidence Rate Ratios (IRR) of reported *Giardia duodenalis* infections estimated from a generalized geographically weighted regression (GGWR) using a Poisson model, across 30 Public Health Units in 2021. Each map shows the association between the age- and sex-adjusted incidence rates of *Giardia duodenalis* and a predictor variable at the Public Health Unit level, holding all other predictor variables constant.

4.4.8 Determinants of hepatitis A Incidence across Public Health Units (2021)

The results of the univariable and multivariable models are shown in Tables 35-37. Household food insecurity had a positive association with the age- and sex-adjusted incidence of hepatitis A in the univariable, full, and final multivariable models. However, none of the associations between the age- and sex-adjusted incidence rates of hepatitis A and proportion of households experiencing household food insecurity were statistically significant while holding all other variables constant (IRR=1.03548, 95% CI 0.93889-1.14458, IRR=1.08549, 95% CI 0.87295-1.35574, and IRR=1.03178, 95% CI 0.92322-1.14455).

Among the census predictor variables, the proportion of the population that has moved within Canada in the last five years (%) was the only predictor variable significantly associated with hepatitis A incidence rates in the univariable and multivariable models. In the final multivariable model, a one-unit increase in the proportion of the population that has moved within Canada in the last five years (%) was associated with a 12% decrease in the age- and sex-adjusted incidence rates of hepatitis A, holding all other variables constant. The proportion of the population with a postsecondary certificate, diploma, or degree (%) and the proportion of households spending>30% on shelter costs (%) were the only significant predictors in the univariable models, they were not statistically significant in the multivariable models.

Table 35. Results of the univariable Poisson model for reported hepatitis A infections in 2021 (n=51 from 32 Public Health Units).

Predictor Variables		**IRR[a)]**	**95% CI[b)]**	**p-value[c)]**
Household Food Insecurity (prevalence)		1.03548	0.93889, 1.14458	0.48976
Age Groups	0 to 4 years	8.44873	1.08169, 170.80164	0.06459
	5 to 9 years	23.40677	4.39909, 431.66741	0.00278
	10 to 19 years	11.18033	2.10124, 206.18762	0.02201
	20 to 29 years	15.54007	3.17356, 280.48097	0.00778
	30 to 39 years	2.93541	0.37582, 59.34294	0.35104
	40 to 49 years	3.26292	0.41775, 65.96399	0.30575
	50 to 59 years	Ref.	Ref.	Ref.
	60 and older	3.91757	0.69716, 73.23052	0.20150
Male sex (referent: Female)		1.45433	0.83732, 2.57307	0.18803
Long-term Unemployment (%)		1.08257	0.92928, 1.26866	0.31705
Internal Migration (Five Years)		0.91357	0.86725, 0.95778	0.00033
Median Household Income		1.00001	0.99999, 1.00004	0.38030
Households with One-Parent Families (%)		1.10063	0.98168, 1.23545	0.10087
Education (%)		1.06533	1.01601, 1.12006	0.01073
Households Spending >30% on Shelter Costs (%)		1.04322	1.00697, 1.08093	0.01869

[a)] IRR: Incidence Rate Ratio. [b)] CI: 95% Confidence Interval of the IRR. [c)] Statistically significant p-value ≤ 0.05.

Table 36. Results of the full multivariable Poisson model for reported hepatitis A infections in 2021 (n=51 from 32 Public Health Units).

Predictor Variables		**IRR[a)]**	**95% CI[b)]**	**p-value[c)]**
Household Food Insecurity (prevalence)		1.08549	0.87295, 1.35574	0.45910
Age Groups	0 to 4 years	8.45622	1.08258, 170.95893	0.06448
	5 to 9 years	23.38091	4.39341, 431.21820	0.00279
	10 to 19 years	11.03181	2.07273, 203.46874	0.02276
	20 to 29 years	14.36781	2.93264, 259.36552	0.00974
	30 to 39 years	2.78564	0.35652, 56.32519	0.37503
	40 to 49 years	3.18157	0.40731, 64.32120	0.31620
	50 to 59 years	Ref.	Ref.	Ref.
	60 and older	4.13946	0.73629, 77.39168	0.18398
Male sex (referent: Female)		1.39291	0.80158, 2.46549	0.24452
Long-term Unemployment (%)		0.92219	0.63406, 1.24190	0.62517
Internal Migration (Five Years)		0.89371	0.79606, 0.98773	0.03851
Median Household Income		1.00002	0.99996, 1.00007	0.51031
Households with One-Parent Families (%)		1.01613	0.69485, 1.40483	0.92763
Education (%)		1.02902	0.90167, 1.18324	0.67748
Households Spending >30% on Shelter Costs (%)		0.96891	0.88338, 1.05949	0.49146

[a)] IRR: Incidence Rate Ratio. [b)] CI: 95% Confidence Interval of the IRR. [c)] Statistically significant p-value ≤ 0.05.

Table 37. Results of the final multivariable Poisson model for reported hepatitis A infections in 2021 (n=51 from 32 Public Health Units).

Predictor Variables		**IRR[a)]**	**95% CI[b)]**	**p-value[c)]**
Household Food Insecurity (prevalence)		1.03178	0.92322, 1.14455	0.56705
Age Groups	0 to 4 years	8.46418	1.08362, 171.11808	0.06436
	5 to 9 years	23.40019	4.39709, 431.57194	0.00278
	10 to 19 years	11.02884	2.07217, 203.41381	0.02278
	20 to 29 years	14.36973	2.93306, 259.39927	0.00973
	30 to 39 years	2.79199	0.35734, 56.45305	0.37396
	40 to 49 years	3.18411	0.40764, 64.37241	0.31586
	50 to 59 years	Ref.	Ref.	Ref.
	60 and older	4.14155	0.73667, 77.43036	0.18382
Male sex (referent: Female)		1.39192	0.80101, 2.46374	0.24553
Internal Migration (Five Years)		0.87902	0.81179, 0.94610	0.00087
Median Household Income		1.00002	0.99999, 1.00005	0.11144
Households Spending >30% on Shelter Costs (%)		0.96821	0.91843, 1.02395	0.24216

[a)] IRR: Incidence Rate Ratio. [b)] CI: 95% Confidence Interval of the IRR. [c)] Statistically significant p-value ≤ 0.05.

5.0 Discussion

5.1 Overview of Thesis Findings

This thesis aimed to explore the association between the prevalence of household-level food insecurity and the incidence of enteric infections at the PHU. Using reported cases of enteric illness from PHO infectious disease tool and household food insecurity prevalence estimates from PHO, a stepwise approach similar to that used by Varga et al. (112) was adopted and employed. This methodology uses a combination of spatial and temporal exploratory and statistical methods. This allowed for a more in depth understanding of the distribution and clustering of enteric pathogens at the PHU level (2019-2022), and which demographic and socioeconomic factors were associated with the incidence of eight enteric pathogens across Ontario PHUs in 2021. The regression analysis only included case counts, population counts, and food insecurity estimates from 2021, since the socioeconomic predictor variables from the Canadian Census were only measured that year.

The incidence rates for most enteric pathogens significantly declined after 2019, except for *Listeria monocytogenes*. Significant high-infection rate spatial, temporal, and space-time clusters were detected across many different PHUs. However, pathogen-specific incidence rates displayed inconsistent global and local spatial autocorrelation patterns throughout the study period. Moreover, a higher prevalence of PHU level household food insecurity was significantly associated with lower incidence rates of *Campylobacter* spp., STEC, and *Giardia duodenalis* infections in 2021. While, the incidence rates *Salmonella* spp., *Listeria monocytogenes*, *Shigella* spp., *Cyclospora cayetanensis*, and hepatis A were not significantly associated with the prevalence of household food insecurity in 2021. GGWR revealed small amounts of spatial non-stationarity in these associations. The direction of the associations between household food

insecurity and the incidence rates of *Campylobacter* spp., *Salmonella* spp., and *Giardia duodenalis* across PHUs were consistent with the results from the multivariable models.

5.2 Changes in Enteric Pathogens Incidence from 2019-2022

The distribution of reported cases by year and the disease maps showed that the incidence rates per 100,000 population years in Ontario declined after 2019 and began to rise again in 2022. The COVID-19 pandemic was likely responsible for the decline in reported cases due to government restrictions such as reduced social interactions, limits on the size of social gatherings, restaurant and school closures, and travel restrictions (15, 228). Moreover, changes in health-seeking behaviour, availability of health care, public health follow-up, and entering cases are other factors contributing to the decline in reported cases (15,198, 229). The increase in reported enteric infection cases in 2022 likely happened because travel and social restrictions were gradually lifted (228,230). *Listeria monocytogenes* was the only pathogen that had a similar number of annual reported cases throughout the study period. This is likely due to most cases experiencing severe illness, thus seeking medical attention (15).

5.3 Spatial Distribution of Enteric Pathogens across Ontario's Public Health Units

Campylobacter spp. and *Giardia duodenalis* high-infection rate spatial clusters were widely distributed across urban and rural PHUs. Another study examining the spatial distribution of *Campylobacter* in Manitoba observed similar widespread spatial patterns and hypothesized that a significant amount of the population relies on a centralized food system that supplies urban and rural areas is endemically contaminated with *Campylobacter* spp. (118). This hypothesis is supported by surveillance data that identified 42% of chicken product samples sold in retail settings were contaminated with *Campylobacter* (231). Additionally, an estimated 20% to 30% of human *Campylobacter* spp. infections can be attributed to the handling, preparation and

consumption of poultry meat (232). Canada's total poultry meat consumption per capita has steadily increased over time along with the country's population growth (233). As a result, more people are exposed to handling, preparing and consuming poultry meat, which could lead to an elevated risk of campylobacteriosis at the population level. Moreover, *Campylobacter* spp. has numerous different animal reservoirs, pathways, exposures, and individual risk factors that are associated with campylobacteriosis (234).

In this study, *Giardia duodenalis* was the only pathogen that showed purely spatial clustering in the North-East region. A previous epidemiological study conducted in Ontario mainly reported high-rate spatial clusters of giardiasis in Central- and South-West Ontario regions, which did not align with the findings in our study (235). However, this same study also reported a large cluster in areas along the coasts of Georgian Bay and Lake Huron (235). Similarly, in our study, a large cluster was found in PHUs on the coast of Georgian Bay, Lake Huron, and Lake Superior. The Great Lakes supply drinking water to an estimated 24 million people, and an additional nine million people obtain their drinking water from rivers, wells, and small lakes in the surrounding watershed (236). *Giardia duodenalis* spp. is the most common pathogen found 2 km offshore in the Great Lakes (237). These regions on the coasts of the Great Lakes are a popular summer vacation spot with many rental cottages and lake houses, which could increase an individual's exposure to giardiasis through drinking or contact with contaminated water (235).

Salmonella spp. and STEC infections mainly clustered in the Central and Southwestern regions of the province. The incidence rates for both pathogens were the highest in Grey Bruce, Wellington-Dufferin-Guelph, and Huron-Perth. These PHUs notably have the greatest density of livestock and poultry farms in Ontario (238). Previous research has identified that livestock,

particularly broilers, cattle, and pigs are associated with *Salmonella* spp. infections and cattle is the primary reservoir for STEC (239-241). In regions with a high density of farm animals more intensive management practices such as animal mixing, crowding, and transportation are required (242). These practices can induce more stress on the animals and may be responsible for more frequent fecal shedding and herd infection (242). Livestock manure is a known reservoir for both *Salmonella* spp. and STEC and can contaminate water sources that are used for drinking and irrigation practices (240). These agricultural factors may explain the elevated infection rates observed in these PHUs in comparison to surrounding PHUs.

Listeria monocytogenes was the only pathogen that did not have any significant high-rate purely spatial or space-time clusters. Listeriosis is considered a rare disease in Canada (243). This was reflected in the low annual incidence rates across different PHUs (2019-2022). It is possible that the case counts were too low across Ontario PHUs for the scan statistic to detect any significant clusters. Another researcher found one significant high-rate cluster of *Listeria monocytogenes* infections in the City of Toronto over a seven-year period, suggesting that the PHU level may not be the optimal scale to detect significant spatial clusters of rare diseases (113).

In this study, spatial clusters of *Shigella* spp. and *Cyclospora cayetanensis* were identified in higher-populated PHUs, including Ottawa and Toronto. A higher risk of infection in these regions may be associated with an estimated 57% of *Shigella* spp. and 71% of *Cyclospora cayetanensis* cases in Canada being travel-related (8). Ottawa and Toronto are home to some of the largest international airports in Canada and experience a considerable volume of international travel to endemic regions, potentially increasing the risk of infection (244). Additionally, urban centers have larger homeless populations that often experience inadequate access to proper

sanitation and overcrowded living conditions (245). These living conditions can increase the risk of person-to-person transmission of *Shigella* spp. infections, which could lead to local outbreaks (245).

Canada has reported lower hepatitis A infection rates than low income and low-middle resource countries (246). However, high-infection rate spatial clusters were identified in the Halton, Peel, and Middlesex-London regions. Previous research has also indicated that urban areas in the province of Ontario have reported the highest rates of hepatitis A infections (155,246). Both Peel Public Health and Middlesex-London Health Unit reported some of the highest rates of infections from 2019-2022 (155). The greater incidence rates in the Halton and Peel regions were likely due to a large proportion of the populations residing in these areas being new immigrants from endemic regions such as Central Asia, South Asia, the Middle East, North Africa, and Sub-Saharan Africa (247,248).

Middlesex-London's population has a lower proportion of immigrants compared to the provincial average. However, the region reported a significant increase in the number of individuals experiencing homelessness from 2018-2025 (247,249,250). Illicit drug use is disproportionately high among individuals experiencing homelessness (251). Drug use has been identified as a significant risk factor associated with sporadic and outbreaks of hepatitis A cases (155). A significant increase in the homeless population and illicit drug use may have contributed to elevated infections in this region.

5.3 Temporal Patterns and Cluster Detection Identifying Potential Outbreaks

Temporal and space-time analyses revealed that high-rate clusters of *Campylobacter* spp., STEC, *Listeria monocytogenes*, and *Cyclospora cayetanensis* infections occurred primarily in the warmer months of the year (late spring, summer, early fall). The seasonal patterns for these pathogens are consistent with findings from research conducted in Canada, the USA, and Europe (113,252-254). This could be associated with several different risk factors being more common in the summer months including picnics, barbecuing, recreational and outdoor activities, frequent dining out, optimal environmental conditions for sporulation and growth, and a higher prevalence of infection in livestock (255-258) Interestingly, *Salmonella* spp. and *Giardia duodenalis* did not display any distinct temporal patterns. Despite prior research reporting that the highest rates of salmonellosis and giardiasis occur during the summer months (117, 258). Similarly, *Shigella* spp. and hepatitis A did not appear to have any distinct seasonal patterns. Canadian surveillance data did not identify a distinct seasonal pattern for *Shigella* spp. (259). Although another study in Quebec found that most cases occurred in the winter months due to individuals traveling to warmer countries and visiting resorts (80). Hepatitis A is a vaccine-preventable enteric infection for travellers, which could explain why hepatitis A infections did not have a consistent temporal pattern (248).

A space-time analysis was used to detect any possible local outbreaks by detecting any high-infection rate clusters during a shorter temporal window in specific PHUs. The majority of *Campylobacter* spp. and *Giardia duodenalis* space-time clusters spanned many different PHUs and had consistently low RR values, suggesting most cases were sporadic. These findings are consistent with other research conducted in high-resource countries (260, 261).

A high-infection rate space-time cluster of *Salmonella* (RR=32.04) was detected in Lambton Public Health during October 2020, indicating a potential outbreak. Lambton Public Health released a statement on November 12th, 2020, and confirmed an outbreak of salmonellosis linked to individuals who ingested food from the Barakat Restaurant and food truck in Sarnia, Ontario, from October 19th-29th, 2020 (262).

Two high-rate space-time clusters of STEC infections were identified in Grey Bruce, Wellington-Dufferin-Guelph, and Huron-Perth from June-July 2020 and June-September 2021. These clusters had significantly higher RR (14.53 and 9.86) compared to the other STEC space-time clusters in this study. There was no official press release confirming that a large outbreak of STEC occurred. However, the high cattle density in these regions has been identified as a major risk factor associated with the incidence of STEC infections in Southern Ontario (263). Potential factors that may have contributed to high infection rates include direct human-to-cattle contact, consistent exposure to livestock environments, and contamination of drinking or recreational water sources (wells, streams, rivers, or lakes) from agricultural runoff (241,263-265).

All *Shigella* spp. space-time clusters were detected in the City of Toronto. The RR values (3.19-5.01) associated with these clusters did not indicate that a large-scale outbreak of shigellosis occurred. However, this does show that the City of Toronto experienced a greater number of cases during these time periods than what would be expected. Similarly, a recent increase in *Shigella sonnei* infections have been reported in Vancouver (266). Primarily, affecting men who have sex with men and persons experiencing homelessness (266). Men who have sex with men are more likely to engage in sexual activity involving stool exposure, and people experiencing homelessness may experience unique challenges in their living conditions such as overcrowding, poor access to hygiene and sanitation resources (267) The City of Toronto has the

largest number of same sex couples in Canada and has the most shelter beds per capita, with shelters often being at or over capacity (268,269). Since, the City of Toronto is home to a large population of same sex couples and people experiencing homelessness, this could explain an elevated number of *Shigella* spp. cases observed in the city.

High-rate space-time clusters of *Cyclospora cayetanensis* infections were identified across multiple regions in Ontario. Interestingly, the space-time clusters all occurred during the summer months and consistently had the highest RR values among all pathogens analyzed (4.5-12.98). These findings support existing evidence that Canada has experienced an increase in the number of non-travel cyclosporiasis cases each summer, linked to imported fresh produce (270,271). Increased consumption of fresh produce in the summer months, such as raspberries and blackberries, is often contaminated with oocysts, even after washing them, which may contribute to seasonal foodborne outbreaks (272,273).

Two space-time clusters of hepatitis A were detected in Middlesex-London and Peel region, with significantly high RR values of 23.42 and 10.35. The elevated RR values suggest an outbreak may have occurred in these PHUs. An outbreak report released by the Middlesex-London Health Unit confirmed that there was an increase in non-travel-related hepatitis A cases from January 2018 to July 2019 (274). Among reported cases, 68.2% of the non-travel-related cases reported drug use, 39.4% reported injecting drugs, and 36.4% reported being underhoused or homeless, indicating individuals of low SES were disproportionately affected (274). Although Peel Public Health did not release a statement confirming an outbreak occurred during September 2022. Paphitis et al. (155) reported that Peel region had the highest incidence rates of hepatitis A infections from 2015 to 2022. The elevated incidence rates were likely associated with this region's large immigrant population from endemic regions (155).

5.4 Global and Local Spatial Autocorrelation Patterns of Enteric Pathogen Incidence Rates

The incremental autocorrelation analysis revealed that global spatial autocorrelation was not consistent across all pathogens or over time. In certain years, specific pathogens such as *Campylobacter* spp. (2019), *Salmonella* spp. (2021), *E. coli* (2020, 2022), *Listeria monocytogenes* (2022), *Cyclospora cayetanensis* (2020, 2021), *Giardia duodenalis* (2020, 2021), and hepatitis A (2020, 2021) demonstrated significant global clustering, indicating that high or low incidence rates clustered together across Ontario PHUs. However, other years showed no significant global spatial autocorrelation for these pathogens, suggesting complete spatial randomness of incidence rates.

Furthermore, the distance band where clustering of incidence rates occurred was different among pathogens. *Campylobacter* spp. *Cyclospora cayetanensis* and *Giardia duodenalis* clusters were detected at larger distance bands, suggesting that these infections are widespread across the province, which may be driven by the contamination in the food system or water supplies. *Salmonella* spp., STEC, *Listeria monocytogenes*, and hepatitis A had maximum global clustering at smaller distance bands, which demonstrates that clustering occurs at a more localized scale and local risk factors could be responsible for higher infection rates.

The global Moran's I statistics have certain limitations and may not be the optimal method for analyzing clustering of incidence rates that have substantial local variation (117). In this study, certain pathogens had small annual case counts, which contributed to variability in the incidence rates across PHUs. Since the global Moran's I includes all incidence rates across the entire study area, it can underestimate or ignore spatial autocorrelation in specific local areas (117). Thus, a local cluster and outlier analysis using Local Moran's I was conducted to identify clustering of incidence rates in specific PHUs.

The local Moran's I cluster and outlier analysis revealed that most pathogens' IRs had different clustering patterns throughout the duration of the study period. Suggesting, each pathogen had unique transmission patterns and local or global risk factors responsible for exposure and infection. For example, the incidence rates of *Salmonella* spp., and STEC had high-high clusters and low-high outliers generally located in the central and South-western regions, although the size of the high-high clusters differed annually. These findings align with the disease maps, and the scan statistic results, suggesting that localized environmental risk factors unique to this region of Ontario may be responsible for increased infection rates of these pathogens. *Cyclospora cayetanensis* had the largest high-high and low-low incidence rate clusters across PHUs in comparison to any other pathogen in this study. This pattern suggests that the high-high clusters may reflect localized outbreaks rather than sporadic cases. This interpretation is consistent with known substantial increases of multi-jurisdictional outbreaks of *Cyclospora cayetanensis* over the last 5 years in both Canada and the US (275). *Giardia duodenalis* was generally located in rural PHUs across different regions of Ontario. These findings align with another study that examined local clusters of *Giardia duodenalis* in rural Census Subdivisions in Southwestern Ontario (117).

Campylobacter spp.*, Listeria monocytogenes, Shigella* spp., and hepatitis A did not show any distinct or consistent patterns of spatial clustering in the local Moran's I analysis. The sporadic nature of *Campylobacter* spp. infections in Canada may explain limited local clustering, as infections are hypothesized to be widespread due to a contaminated food system (118). Listeriosis is a rare disease and has limited reported cases from 2019-2022, which is likely the reason why limited local incidence rate clusters were detected. These findings also align with the scan statistic results showing no significant space or space-time clusters. Unexpectedly, *Shigella*

spp. and hepatis A did not appear to have any high-high incidence rate clusters in major urban PHUs, which is not consistent with the findings observed in the incidence rate disease maps and the scan statistic analyses.

5.5 Association Between Household Food Insecurity and Incidence of Enteric Pathogens

In the final negative binomial multivariable models, it was observed that the incidence rates of *Campylobacter* spp., STEC, and *Giardia duodenalis* infections decreased when household food insecurity prevalence was higher in a PHU in 2021, suggesting a protective effect. Additionally, the GGWR identified the association between *Campylobacter* spp., and *Giardia duodenalis* infections, and household food insecurity had little spatial variation across PHUs while adjusting for other covariates. These findings are consistent with other studies that have examined the incidence of these enteric pathogens and important socioeconomic indicators of food insecurity. Researchers have reported higher incidence rates with increasing income and education, lower proportions of unemployment, greater proportion of the population below the poverty level, and decreased socioeconomic deprivation (142,144,145,276-278).

The inverse association of *Campylobacter* spp. infections may be explained by the consumption patterns of fresh poultry products. Considering fresh poultry is often more expensive than frozen poultry, food-insecure households may be less likely to consume fresh poultry as frequently (142). Similarly, STEC infections may be more common in high SES populations due to a greater consumption of undercooked or raw meat, fresh fruits and vegetables, and dining at sit-down restaurants (178, 279, 280). These behaviours are less likely to be prevalent in food insecure populations (281, 282).

Risk factors that may have contributed to an inverse association between food insecurity and the incidence rate of *Giardia duodenalis* infections are reduced non-essential international

travel and the ability to travel across the province and engage in outdoor recreational activities such as camping (277, 283, 284). Future epidemiological research must explore these associations further to develop more meaningful conclusions and gain a deeper understanding of the potential risk factors.

No significant associations were found between household food insecurity and the incidence rates of *Salmonella* spp.*, Listeria monocytogenes*, *Shigella* spp., *Cyclospora cayetanensis*, and hepatitis A in the univariate or multivariate regression models. A potential explanation for this outcome is that the measure of household food insecurity used in this study, did not account for the different experiences of household food insecurity within the population. Specifically, it did not measure whether households were food insecure without hunger, moderate hunger, or severe hunger, or whether a household was experiencing acute or chronic food insecurity (285). Since, the measure combined different levels of food insecurity into a single prevalence estimate, it likely did not capture how the incidence of enteric infections varies across households that experience different levels of food insecurity. Thus, because the levels of household food insecurity likely differ from both within and between PHUs, the ecologic estimates of these contextual effects may be biased (286). Moreover, the incidence rates of *Listeria monocytogenes, Shigella* spp., *Cyclospora cayetanensis*, and hepatitis A were relatively low during 2021, which likely reduced the statistical power to detect significant associations between these pathogens and the prevalence of household food insecurity.

The proportion of households spending >30% of their income on shelter costs was the only economic covariate significantly associated with the incidence rates of Salmonella spp. infections. A previous study also observed a positive association between the proportion of households spending >30% of their income on shelter costs at the census subdivision level and

the incidence of *Salmonella* Heidelberg and *Salmonella* Typhimurium, though it was not significant (116). The relationship between SES measures and the incidence of salmonellosis at an aggregate level is complex, with inconsistent results possibly due to different serotypes, unique transmission pathways (142,143). Another possible explanation for differences between the results is that our study was conducted at the PHU rather than the census subdivision level. This is common issue when conducting spatial analyses, associations between two variables can differ depending on the geographic scale the data is aggregated to. Additionally, the GGWR identified a higher IRR of this association in PHUs located in the central-eastern, eastern, and northeastern regions of the province, suggesting limited spatial variation in the relationship while adjusting for other covariates.

In the fitted multivariable model, long-term unemployment (%) was the only variable found to have a significant inverse association with the adjusted incidence rates of *Listeria monocytogenes* infections. The direction of this association in our study was unexpected, since a previous study conducted in England reported a positive association between listeriosis and areas of increased socioeconomic deprivation (150). However, Gillespie et al. (150) originally hypothesized that listeriosis would have a greater incidence in less deprived populations due to more frequent consumption of high-risk food such as pate and soft-mould cheeses.

In the final multivariable model one-parent families and education level were both found to have positive and significant associations with the incidence rates of *Shigella* spp. Simonsen et al. (142) also reported a positive association between education and the risk of *Shigella* spp. infection, most likely due to international travel. However, *Shigella* spp. infections have also been found to be associated with poverty in high-resource countries (130). In Canada, approximately 25% of one-parent families live below the poverty line, which could explain why

areas with a greater prevalence of one-parent families are associated with shigellosis at a population level (287).

None of the socioeconomic predictors displayed a significant association with the incidence rate of *Cyclospora cayetanensis* in the adjusted multivariate model. Education (%) had a very small significant association, suggesting that PHUs with more educated populations had an increased incidence rate of *Cyclospora cayetanensis* infections. The likely explanation of this finding is that *Cyclospora cayetanensis* is primarily acquired through international travel in high-resource countries, educated individuals were more likely to travel during the COVID-19 pandemic, increasing their risk of exposure (288).

The only predictor variable outside of age and sex that was significantly associated with the incidence rates of hepatitis A in the fitted multivariable model was five-year internal migration (%). Higher levels of internal migration were associated with lower incidence rate of hepatitis A at the PHU level. The underlying explanation for this relationship is not clear and further research is needed.

5.6 The Role of Age and Sex on the Incidence of Enteric Pathogens

The findings from this study show that the incidence of enteric disease is different between males and females in different age groups, supporting the role that the age and sex of an individual can influence their susceptibility and immunity to different communicable infections (289). The regression analysis identified that the infection rates of *Campylobacter* spp., *Salmonella* spp., STEC, and *Shigella* spp., were significantly higher in individuals aged 0-4 years. However, older adults aged 60 and older had the highest incidence of *Listeria monocytogenes* and *Cyclospora cayetanensis* infections. Children aged five and under and older adults (60 and over) are at an increased risk of enteric disease due to developing immune systems or weakened immune

systems (290). Our findings further support that infants, young children, and older adults are high-risk populations that have increased susceptibility to communicable diseases.

Sex-based differences in infection rates were also observed. Males had significantly higher infection rates of *Campylobacter* spp., *Shigella* spp., and *Giardia duodenalis*, while females had significantly higher infection rates of *STEC*. These findings are consistent with prior epidemiological studies suggesting many different factors could be responsible for differences in the incidence of these illnesses across males and females, including different food consumption patterns, sexual transmission, and occupation (93, 291-295). The regression analysis identified important demographic trends of specific enteric infections, the risk factors responsible for these differences are unclear.

5.7 Strengths and Limitations

This study had multiple methodological strengths. This included the use of GGWR to determine whether the association between the incidence rates of enteric infection and the prevalence of household food insecurity was different across PHUs. Additionally, employing both scan statistics and Moran's I statistics into the analysis provided a more in depth understanding of the spatial clustering patterns of different enteric pathogen over the study period in Ontario. However, it is also important to consider that this study also had several limitations.

First, the findings from this study need to be interpreted with caution since passive surveillance data were used. Foodborne illnesses are severely under-reported by regional public health surveillance systems (9, 296). The Ministry of Health and Long-Term Care estimates that only 4% of foodborne illness cases are reported to PHUs (297). Under-reporting is primarily due to underdiagnosis, as many cases only have mild symptoms and do not necessarily require medical care and are not tested (9, 296). In some instances, positive laboratory test results may

not be reported to certain public health surveillance systems (9, 296). There is also the potential for differences in underreporting, particularly in low socioeconomic status areas and ethnic populations, due to disparities in access to healthcare (298). Moreover, underreporting of cases (from 2019-2022) was most likely exacerbated because of the COVID-19 pandemic, which disrupted many different public health practices (15). The pandemic also had a significant impact on the changes to supply chains and consumer behaviours, which could have influenced exposure patterns to foodborne illnesses (299). Additionally, COVID-19 presented some challenges for data quality issues for the 2021 census of population estimates. However, there was a 98% response rate during the third wave of the pandemic, supporting the reliability of the 2021 census estimates compared to previous years (300).

A second limitation of this study is that the case counts of STEC*, Listeria monocytogenes, Shigella* spp., *Cyclospora cayetanensis*, and hepatitis A were not large enough to determine an appropriate optimal bandwidth and perform a GGWR. Thus, spatial stationarity could not be further explored. The limited number of cases likely resulted in inaccurate local coefficient estimates and impacted the accuracy of the spatial relationships for these pathogens. However, the IRR results of the GGWR for *Campylobacter* spp., *Salmonella* spp., and *Giardia duodenalis* showed minimal variation across PHUs, suggesting the spatial variability may have also been minimal for the other pathogens.

A third potential limitation in this study was the inability to address the Modifiable Areal Unit Problem (MAUP). The MAUP is an issue that occurs when the size and shape, of polygons are modified with aggregated spatial data (301). If a polygon is altered the number of observations within each polygon can have an infinite number of arrangements and yield different results (301). Due to constraints in data availability, the analyses were conducted at the

PHU level, which is a relatively large spatial scale. Although the PHU has been identified as a more relevant scale for public health planning, the findings from this thesis should be interpreted as exploratory due to the MAUP (198). Future research should consider using smaller spatial scales such as the census subdivision and forward sortation area, to make more granular conclusions closer to the individual-level and reduce ecological bias.

A fourth limitation was that reported cases were excluded from the regression analysis due to specific PHUs not having a reportable estimate of household food insecurity in 2021. The missing data could reduce the statistical power and may have impacted the ability to detect significant associations (302). Additionally, the exclusion of these PHUs could influence the generalizability of the study's findings, since these specific PHUs could have significantly different infection rates compared to the PHUs included in the analysis. However, these PHUs only accounted for a small number of the cases, and >95% of the cases for each enteric pathogens were retained in the analysis.

Finally, this was an exploratory ecological study that used aggregate level estimates of food insecurity and other socioeconomic variables and does not properly reflect individual-level associations (303). Thus, individual-level exposure information on risk factors such as food, water, animals, and travel were not assessed in this study, limiting the ability to identify specific environmental and behavioural determinants of infection. Future case-control studies are needed to identify specific risk factors that are associated with different serotypes of enteric pathogens.

5.8 Implications for Public Health Practice and Sustainable Food Production

The findings from this thesis recognize food insecurity as a potential intermediate variable that influences food safety, supporting the need for a One Health approach that simultaneously addresses food safety and food insecurity as public health challenges (304). With a growing global population and extreme weather, more stress is placed on food systems which contributes to reduced availability and access to safe and healthy foods (304). This has serious implications on human health, especially on vulnerable populations. To address these public health challenges, experts in food safety, food security, agriculture and communicable diseases must collaborate and form partnerships with farmers, government agencies, food assistance programs, and consumers to inform knowledge translation and data driven regulations, practices and developing clean technology that strengthen food safety policies and create sustainable agriculture systems (304). Adopting a One Health approach could ultimately improve health outcomes across the province of Ontario.

Furthermore, the results from the spatial and temporal analyses can help specific PHUs identify local risk factors responsible for high infection rates of specific pathogens. Future research should identify environmental, economic, and seasonal local risk factors that are responsible for the clustering of enteric diseases. Knowledge of these factors will enable PHUs to tailor disease prevention efforts and allocate resources more effectively to improve long-term prevention in high-risk regions over time.

6.0 Conclusion

Foodborne illness is a significant contributor to morbidity and lost productivity in Canada. Food-insecure individuals represent a vulnerable population that is disproportionately affected by infectious diseases, chronic diseases, and injuries. Previous research suggests aggregate-level demographic and economic attributes may influence the incidence of gastrointestinal illness at the population-level. A stepwise exploratory analytical framework was adopted and applied to investigate the magnitude, distribution, and clustering of enteric infections, and to explore whether food insecurity plays a key role on the incidence of enteric disease across PHUs in Ontario, Canada. Several significant spatial, temporal and space-time clusters were detected for eight different enteric pathogens.

The findings from this study suggest that household food insecurity may play a significant role on the incidence of certain enteric pathogens including *Campylobacter* spp., STEC, and *Giardia duodenalis*. Other enteric infections such as *Salmonella* spp., *Listeria monocytogenes*, *Shigella* spp., *Cyclospora cayetanensis*, and hepatitis A did not appear to be influenced by food insecurity, although other socioeconomic variables did influence their infection rates. This study was the first to explore food insecurity as a risk factor for the incidence of enteric infections at an aggregate level.

Future studies need to explore this relationship at different geographical scales to provide further evidence and positively influence knowledge translation about the association between food insecurity and the incidence of foodborne infections. These studies should also account for different levels of food insecurity within food insecure populations to see whether infections rates significantly differ among households experiencing food insecurity without hunger, moderate hunger, or severe hunger. There is also a need for conducting future case-control

studies on food insecure and food secure populations and examining whether these groups have different food safety practices and behaviours that could increase the risk of an infection.

Despite food insecurity and foodborne illness persisting as public health challenges in Canada, both are preventable. This thesis contributes to the growing framework that food safety and food security must be addressed simultaneously to reduce the burden of foodborne illness. There is a critical need for local public health units to collaborate with experts in food safety, food security, as well as partnering with farmers, researchers, consumers in the community to design and tailor effective public health prevention programs for specific enteric pathogens. Adopting and implementing policies that support sustainable agriculture and strengthening resilient public health systems that address micro- and macro-level drivers of food insecurity and food safety is essential to minimize the burden of foodborne illness in the province of Ontario.

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Appendices

Appendix A: Additional Tables from Chapter 3-Methods

Table A1. List of Public Health Unit (PHU) labels (Legend for Figure 1), names, and their respective administrative Health Region in Ontario, Canada.

Label	Public Health Unit (PHU)	Health Region
1	The District of Algoma Health Unit	Northeast
2	Brant County Health Unit	Central West
3	Chatham-Kent Health Unit	Southwest
4	Durham Regional Health Unit	Central East
5	The Eastern Ontario Health Unit	East
6	Grey Bruce Health Unit	Southwest
7	Haldimand-Norfolk Health Unit	Central West
8	Haliburton, Kawartha, Pine Ridge District Health Unit	Central East
9	Halton Regional Health Unit	Central West
10	City of Hamilton Health Unit	Central West
11	Hastings and Prince Edward Counties Health Unit	East
12	Huron Perth Health Unit	Southwest
13	Kingston, Frontenac and Lennox and Addington Health Unit	East
14	Lambton Health Unit	Southwest
15	Leeds, Grenville and Lanark District Health Unit	East
16	Middlesex-London Health Unit	Southwest
17	Niagara Regional Area Health Unit	Central West
18	North Bay Parry Sound District Health Unit	Northeast
19	Northwestern Health Unit	Northwest
20	City of Ottawa Health Unit	East
21	Peel Regional Health Unit	Central East
22	Peterborough County--City Health Unit	Central East
23	Porcupine Health Unit	Northeast
24	Waterloo Health Unit	Central West
25	Renfrew County and District Health Unit	East
26	Simcoe Muskoka District Health Unit	Central East
27	Southwestern Public Health	Southwest
28	Sudbury and District Health Unit	Northeast
29	Thunder Bay District Health Unit	Northwest
30	Timiskaming Health Unit	Northeast
31	City of Toronto Health Unit	Toronto
32	Wellington-Dufferin-Guelph Health Unit	Central West
33	Windsor-Essex County Health Unit	Southwest
34	York Regional Health Unit	Central East

Table A2. Number of reported cases of *Campylobacter* spp. (n=6), *Salmonella* spp. (n=8), STEC (n=1), *Listeria monocytogenes* (n=0), *Shigella* spp. (n=4), *Cyclospora cayetanensis* (n=1), *Giardia duodenalis* (n=2), and hepatitis A (n=3) excluded from the study due to missing age or sex information in Ontario, Canada (2019-2022).

Year	***Campylobacter* spp.**	***Salmonella* spp.**	**STEC**	***Listeria monocytogenes***	***Shigella* spp.**	***Cyclospora cayetanensis***	***Giardia duodenalis***	**Hepatitis A**	**Total Annual**
2019	3	2	0	0	0	1	1	1	8
2020	0	4	1	0	2	0	0	1	8
2021	2	0	0	0	1	0	1	0	4
2022	1	2	0	0	1	0	0	1	5
Total (2019-2022)	6	8	1	0	4	1	2	3	25

Appendix B: Additional Figures from Chapter 4-Results

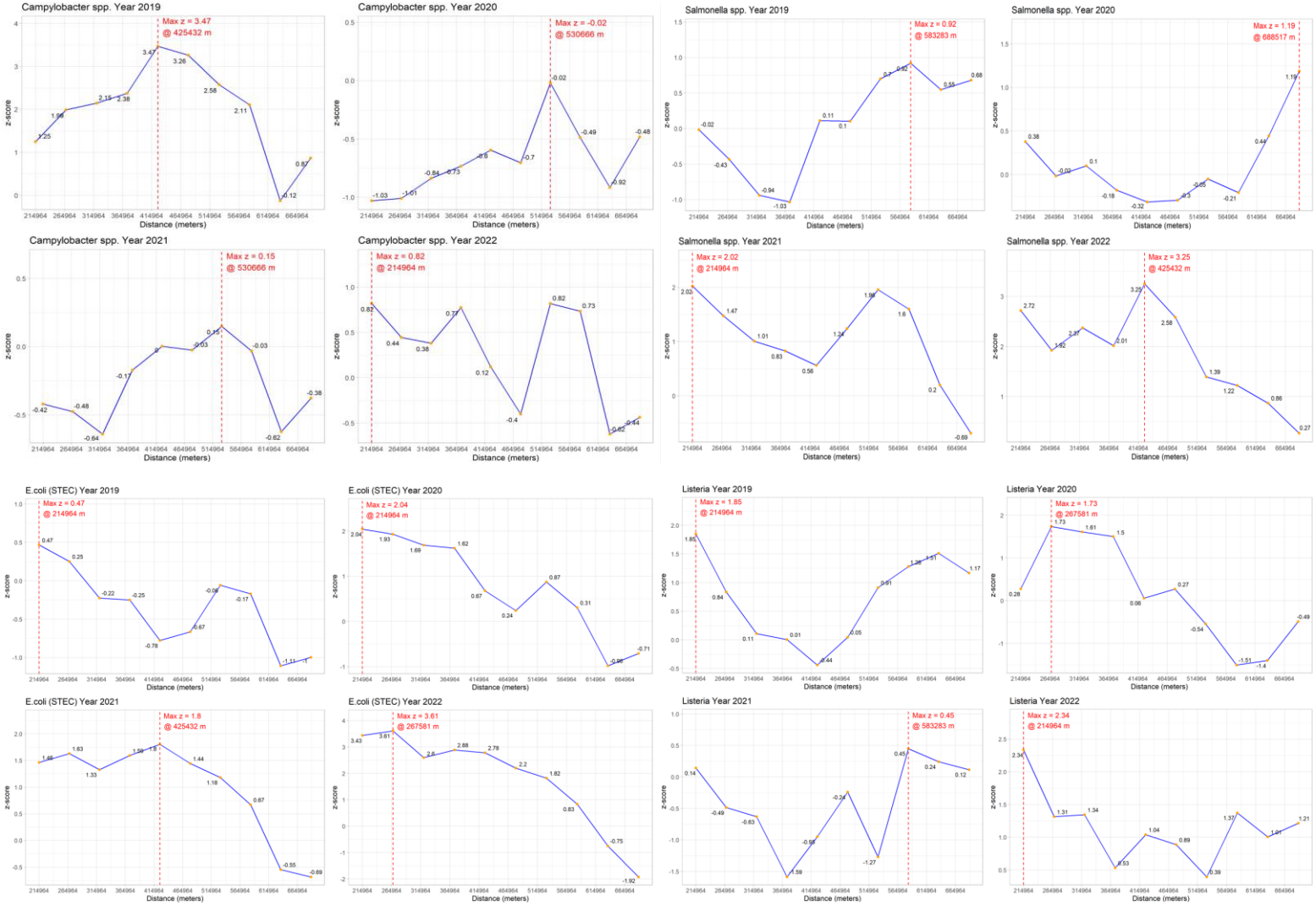


Figure B1. Global spatial autocorrelation of incidence rates for eight enteric pathogens across 31 Public Health Units in Ontario, Canada (2019-2022; continued on the next page).

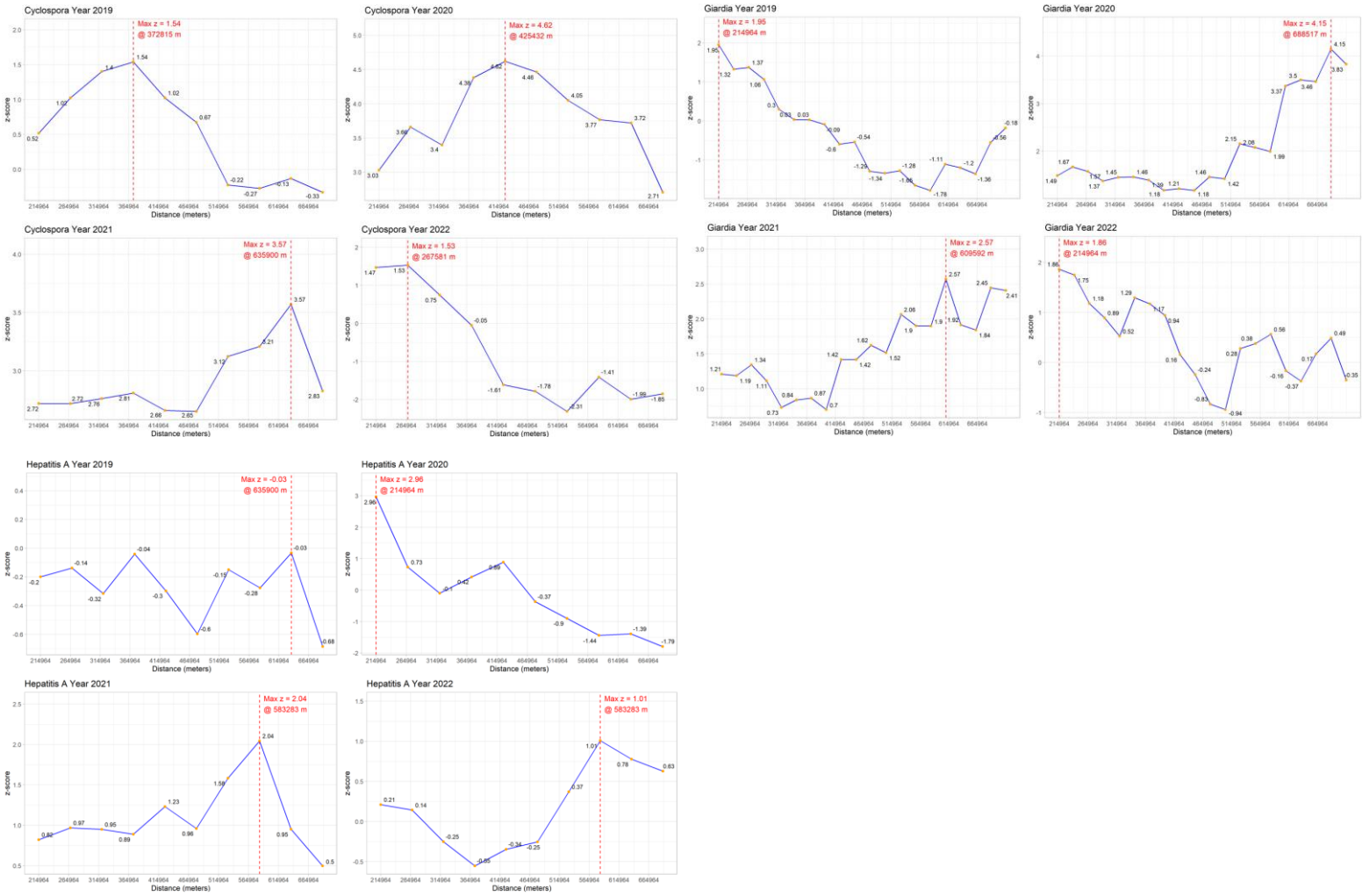


Figure B1. (Continued).

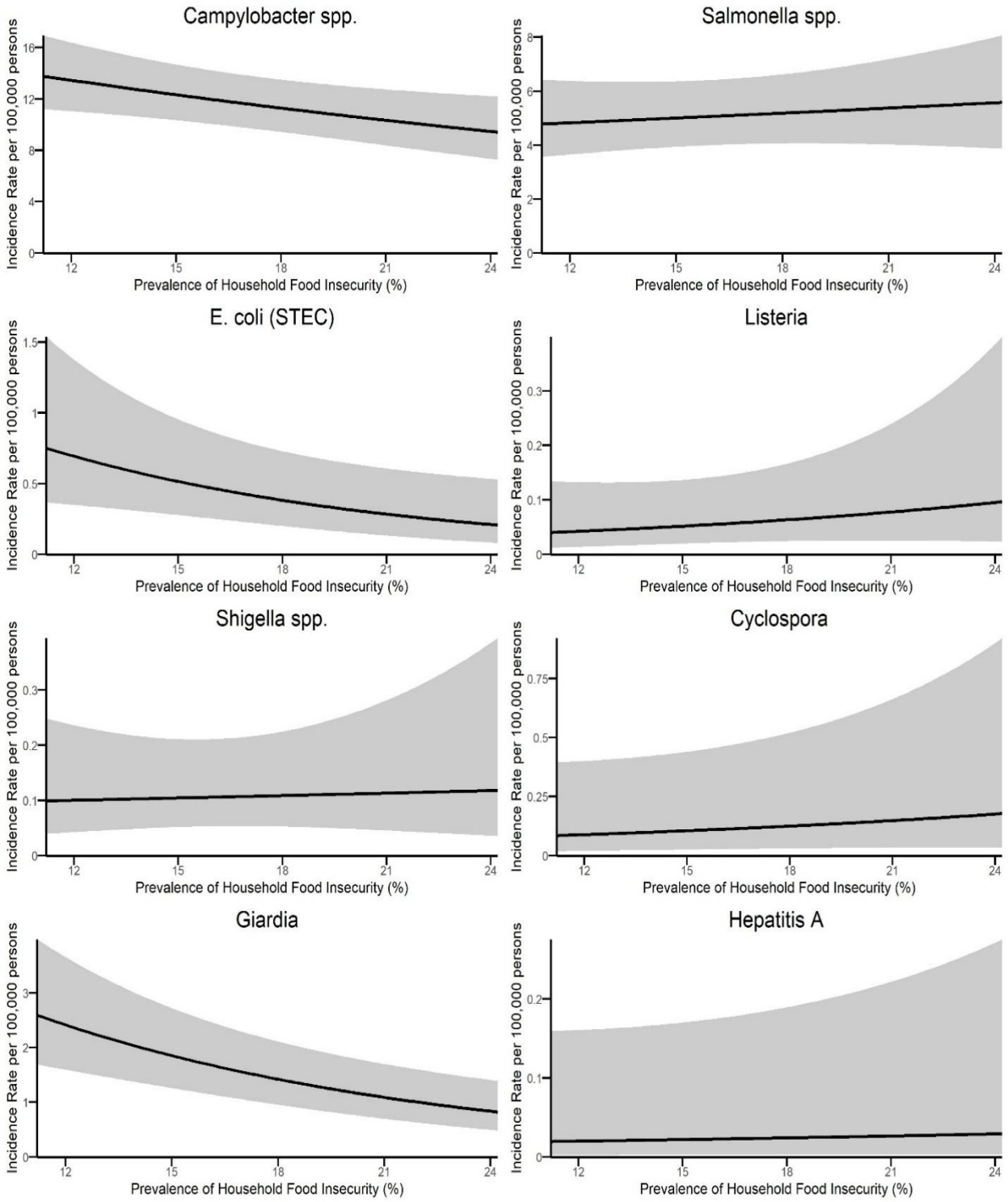


Figure B2. Predicted age- and sex-adjusted incidence rates for eight enteric pathogens at different prevalence estimates of household food insecurity at the Public Health Unit level in Ontario, Canada (2021), holding all variables in the final multivariable model constant. The grey shaded area represents the 95% confidence intervals for the predicted incidence rates.

Appendix C: Additional Tables from Chapter 4-Results

Table C1. Significant purely spatial high-rate clusters (n=20 total clusters) of reported *Campylobacter* spp., *Salmonella* spp., STEC, *Shigella* spp., *Cyclospora cayetanensis, Giardia duodenalis*, and hepatitis A infections across 34 Public Health Units in Ontario, Canada.

Pathogen	Clusters	Public Health Units	Observed cases	Expected Cases	Observed/Expected Cases	Relative Risk	P-value	Log likelihood Ratio
Campylobacter	C1	Grey Bruce, Wellington-Dufferin-Guelph, Huron-Perth	906	417.77	2.17	2.29	<0.001	226.33
	C2	Hastings and Prince Edward Counties, Peterborough County-City, Kingston Frontenac and Lennox and Addington, Haliburton, Kawartha and Pine Ridge District, Leeds, Grenville and Lanark District	770	598.26	1.29	1.31	<0.001	24.23
	C3	Chatham-Kent, Lambton, Windsor-Essex County, Middlesex-London, Southwestern Public Health	1119	925.73	1.21	1.24	<0.001	21.07
	C4	Eastern Ontario Public Health	213	141.82	1.50	1.51	<0.001	15.72
	C5	Niagara Region	417	320.37	1.30	1.32	<0.001	13.80
	C6	Haldimand-Norfolk	118	78.24	1.51	1.51	0.0013	8.81
Salmonella	C1	Lambton	109	62.56	1.74	1.75	<0.001	14.24
	C2	Grey Bruce, Wellington-Dufferin-Guelph, Huron-Perth	372	299.07	1.24	1.26	0.0017	8.65
STEC	C1	Grey Bruce, Wellington-Dufferin-Guelph, Huron-Perth	113	32.4	3.49	3.93	<0.001	65.32
	C2	York Region	104	60.9	1.71	1.82	<0.001	13.95
	C3	Brant County, Haldimand-Norfolk, City of Hamilton, Waterloo, Halton Region, Southwestern Public Health	170	116.51	1.46	1.6	<0.001	13.09
Shigella	C1	City Of Toronto	392	163.03	2.40	3.69	<0.001	160.51
Cyclospora cayetanensis	C1	City of Ottawa	181	98.75	1.83	1.96	<0.001	30.11
	C2	Halton Region	90	57.55	1.56	1.6	0.003	8.19
	C3	City Of Toronto	335	275.36	1.22	1.29	0.005	7.67
Giardia duodenalis	C1	Sudbury and District, The District of Algoma, Timiskaming, North Bay Parry Sound District, Grey Bruce, Simcoe Muskoka District, Renfrew County and District, Haliburton, Kawartha and Pine Ridge District, Wellington-Dufferin-Guelph	781	485.15	1.61	1.77	<0.001	89.83
	C2	City of Toronto	985	745.36	1.32	1.44	<0.001	44.78
	C3	Kingston, Frontenac and Lennox and Addington, Hastings and Prince Edward Counties, Leeds, Grenville and Lanark District, Peterborough County--City	243	184.5	1.32	1.34	0.0018	8.91
Hepatitis A	C1	Middlesex-London	42	14.79	2.84	3.04	<0.001	17.56
	C2	Halton Region, Peel Region	105	60.34	1.74	1.99	<0.001	16.41

Table C2. Significant space-time high-rate clusters (n=50 total clusters) of reported *Campylobacter* spp., *Salmonella* spp., STEC, *Shigella* spp., *Cyclospora cayetanensis, Giardia duodenalis*, and hepatitis A infections across 34 Public ealth Units in Ontario, Canada (2019-2022).

Pathogen	Clusters	Public Health Units	Cluster Time Frame	Observed cases	Expected Cases	Observed/Expected Cases	Relative Risk	P-value
Campylobacter	C1	Lambton, Chatham-Kent, Middlesex-London, Southwestern Public Health, Windsor-Essex County, Huron-Perth, Waterloo, Brant County, Haldimand-Norfolk, Grey Bruce	2019/06 to 2019/10	539	235.29	2.29	2.37	<0.001
	C3	City of Toronto	2019/06 to 2019/10	428	199.12	2.15	2.2	<0.001
	C4	Haliburton, Kawartha and Pine Ridge District, Peterborough County--City, Hastings and Prince Edward Counties, Durham Region, Simcoe Muskoka District, York Region, Renfrew County and District, Kingston, Frontenac and Lennox and Addington	2019/07 to 2019/08	230	91.22	2.52	2.56	<0.001
	C5	Grey Bruce, Wellington-Dufferin-Guelph, Huron-Perth	2020/05 to 2020/10	143	52.11	2.74	2.77	<0.001
	C8	Peterborough County--City, Haliburton, Kawartha and Pine Ridge District, Hastings and Prince Edward Counties, Durham Region, Kingston, Frontenac and Lennox and Addington, Simcoe Muskoka District	2020/06 to 2020/09	186	111.18	1.67	1.69	<0.001
	C11	Niagara Region	2020/06 to 2020/11	78	39.74	1.96	1.97	0.0021
	C7	Haldimand-Norfolk, Brant County, City of Hamilton, Southwestern Public Health, Waterloo, Niagara Region	2021/06 to 2021/08	175	90.06	1.94	1.96	<0.001
	C2	Thunder Bay District, Northwestern Public Health, Porcupine Public Health, The District of Algoma, Sudbury and District, Timiskaming, North Bay and Parry Sound District, Grey Bruce, Simcoe Muskoka District, Renfrew County and District, Huron-Perth, Haliburton, Kawartha and Pine Ridge District, Wellington-Dufferin-Guelph	2021/06 to 2021/10	383	163.03	2.35	2.41	<0.001
	C6	Huron-Perth, Waterloo, Middlesex-London, Wellington-Dufferin-Guelph, Southwestern Public Health, Grey Bruce, Brant County, Lambton	2022/06 to 2022/10	300	160.97	1.86	1.89	<0.001
	C9	Niagara Region	2022/06 to 2022/10	74	34.47	2.15	2.16	<0.001
	C10	Peterborough County--City, Haliburton, Kawartha and Pine Ridge District, Hastings and Prince Edward Counties, Durham Region, Kingston, Frontenac and Lennox and Addington, Simcoe Muskoka District	2022/07 to 2022/07	64	29.49	2.17	2.18	0.0011
Salmonella	C2	Wellington-Dufferin-Guelph, Waterloo, Peel Region, Halton Region, City of Hamilton	2019/01 to 2019/09	496	311.04	1.59	1.64	<0.001
	C3	North Bay Parry Sound District, Simcoe Muskoka District, Renfrew County and District, Haliburton, Kawartha and Pine Ridge District, Timiskaming, Peterborough County--City, Grey Bruce, Sudbury and District, York Region, Durham Region	2019/01 to 2019/11	565	369.05	1.53	1.58	<0.001
	C4	City of Toronto	2019/01 to 2019/11	477	311.17	1.53	1.57	<0.001
	C5	Thunder Bay District, Northwestern Public Health, Porcupine Public Health, The District of Algoma, Sudbury and District, Timiskaming, North Bay Parry Sound District, Grey Bruce, Simcoe Muskoka District, Renfrew County and District, Huron-Perth, Haliburton, Kawartha and Pine Ridge District, Wellington-Dufferin-Guelph, York Region	2020/07 to 2020/08	146	70.46	2.07	2.1	<0.001

	C1	Lambton	2020/10 to 2020/10	42	1.32	31.85	32.04	<0.001
	C6	Wellington-Dufferin-Guelph, Waterloo, Peel Region, Halton Region	2022/04 to 2022/08	220	151.53	1.45	1.47	0.0023
STEC	C6	Haldimand-Norfolk, Brant County, City of Hamilton, Southwestern Public Health, Waterloo, Niagara Region	2019/04 to 2019/08	31	11.27	2.75	2.83	0.012
	C3	Sudbury and District, The District of Algoma, Timiskaming, North Bay Parry Sound District, Grey Bruce, Simcoe Muskoka District, Renfrew County and District, Haliburton, Kawartha and Pine Ridge District, Wellington-Dufferin-Guelph, York Region, Huron-Perth	2019/06 to 2019/12	63	23.59	2.67	2.82	<0.001
	C2	Grey Bruce, Wellington-Dufferin-Guelph, Huron-Perth	2020/06 to 2020/07	19	1.34	14.18	14.53	<0.001
	C1	Grey Bruce, Wellington-Dufferin-Guelph, Huron-Perth	2021/06 to 2021/09	26	2.72	9.55	9.86	<0.001
	C4	Grey Bruce, Wellington-Dufferin-Guelph, Huron-Perth, Waterloo	2022/04 to 2022/11	38	10.91	3.48	3.62	<0.001
	C5	York Region	2022/04 to 2022/11	31	10.31	3.01	3.09	0.0024
Shigella	C3	City Of Toronto	2019/01 to 2019/01	17	3.45	4.93	5.01	0.0028
	C1	City Of Toronto	2019/03 to 2020/02	139	40.74	3.41	3.9	<0.001
	C2	City Of Toronto	2022/02 to 2022/11	100	34.23	2.92	3.19	<0.001
Cyclospora cayetanensis	C4	Renfrew County and District, Haliburton, Kawartha and Pine Ridge District, Hastings and Prince Edward Counties, Peterborough County--City, Kingston, Frontenac and Lennox and Addington, North Bay Parry Sound District, Leeds, Grenville and Lanark District, City of Ottawa, Simcoe Muskoka District	2019/06 to 2019/07	93	10.82	8.60	9.14	<0.001
	C3	Huron-Perth, Waterloo, Middlesex-London, Wellington-Dufferin-Guelph, Southwestern Public Health, Grey Bruce, Brant County, Lambton, Halton Region, City of Hamilton	2019/07 to 2019/07	83	6.77	12.27	12.98	<0.001
	C5	City of Toronto	2019/07 to 2019/07	66	5.82	11.33	11.85	<0.001
	C10	Durham Region, York Region	2019/07 to 2019/07	24	3.75	6.40	6.5	<0.001
	C8	Wellington-Dufferin-Guelph, Waterloo, Peel Region, Halton Region, City of Hamilton	2020/06 to 2020/07	64	14.23	4.50	4.67	<0.001
	C9	City of Toronto	2020/06 to 2020/07	55	11.51	4.78	4.93	<0.001
	C11	York Region	2020/06 to 2020/07	21	4.72	4.45	4.5	<0.001
	C2	City of Ottawa, Leeds, Grenville and Lanark District, Eastern Ontario Public Health, Kingston, Frontenac and Lennox and Addington, Hastings and Prince Edward Counties, Renfrew County and District, Peterborough County--City, Haliburton, Kawartha and Pine Ridge District	2020/06 to 2020/08	114	13.5	8.44	9.11	<0.001
	C6	Wellington-Dufferin-Guelph, Waterloo, Peel Region, Halton Region, City of Hamilton	2022/05 to 2022/07	105	21.92	4.79	5.1	<0.001
	C7	Hastings and Prince Edward Counties, Peterborough County--City, Kingston, Frontenac and Lennox and Addington, Haliburton, Kawartha and Pine Ridge District, Leeds, Grenville and Lanark District, Renfrew County and District, Durham Region, City of Ottawa, Simcoe Muskoka District	2022/05 to 2022/07	101	20.79	4.86	5.16	<0.001

	C1	City of Toronto	2022/06 to 2022/07	122	11.64	10.48	11.4	<0.001
Giardia duodenalis	C4	Grey Bruce, Wellington-Dufferin-Guelph, Huron-Perth, Waterloo, Peel Region, Simcoe Muskoka District	2019/01 to 2019/12	353	210.51	1.68	1.75	<0.001
	C6	Renfrew County and District, Haliburton, Kawartha and Pine Ridge District, Hastings and Prince Edward Counties, Peterborough County--City, Kingston, Frontenac and Lennox and Addington, North Bay Parry Sound District, Leeds, Grenville and Lanark District	2019/02 to 2019/10	99	54.09	1.83	1.85	<0.001
	C1	City of Toronto	2019/03 to 2020/02	437	186.27	2.35	2.52	<0.001
	C7	Kingston, Frontenac and Lennox and Addington, Hastings and Prince Edward Counties, Leeds, Grenville and Lanark District, Peterborough County--City District, Peterborough County--City	2020/06 to 2020/10	43	19.15	2.25	2.26	0.04
	C3	Sudbury and District, The District of Algoma, Timiskaming, North Bay Parry Sound District, Grey Bruce, Simcoe Muskoka District, Renfrew County and District, Haliburton, Kawartha and Pine Ridge District, Wellington-Dufferin-Guelph	2020/06 to 2020/11	145	60.14	2.41	2.47	<0.001
	C2	Porcupine Public Health, Thunder Bay District, The District of Algoma, Sudbury and District, Timiskaming, Northwestern Public Health, North Bay Parry Sound District, Renfrew County and District, Simcoe Muskoka District, Grey Bruce, Haliburton, Kawartha and Pine Ridge District, Peterborough County--City	2021/07 to 2021/12	164	66.59	2.46	2.53	<0.001
	C5	Sudbury and District, The District of Algoma, Timiskaming, North Bay Parry Sound District, Grey Bruce, Simcoe Muskoka District, Renfrew County and District, Haliburton, Kawartha and Pine Ridge District, Wellington-Dufferin-Guelph	2022/06 to 2022/09	99	41.69	2.37	2.41	<0.001
Hepatitis A	C1	Middlesex-London	2019/01 to 2019/04	26	1.18	22.03	23.42	<0.001
	C3	Wellington-Dufferin-Guelph, Waterloo, Peel Region, Halton Region	2019/01 to 2019/09	50	15.92	3.14	3.43	<0.001
	C5	Eastern Ontario Public Health, City of Ottawa	2019/01 to 2019/09	25	6.58	3.80	3.98	<0.001
	C4	City of Toronto	2019/03 to 2020/02	54	20.82	2.59	2.83	<0.001
	C2	Timiskaming, Sudbury and District, North Bay Parry Sound District, The District of Algoma, Renfrew County and District, Simcoe Muskoka District	2019/12 to 2020/05	31	4.29	7.23	7.73	<0.001
	C6	Peel Region	2022/09 to 2022/09	9	0.89	10.15	10.35	0.0041