International Journal of Food Microbiology 342 (2021) 109075

Contents lists available at ScienceDirect

International Journal of Food Microbiology

journal homepage: www.elsevier.com/locate/ijfoodmicro

Comparative history of *Campylobacter* contamination on chicken meat and campylobacteriosis cases in the United States: 1994–2018

Michael S. Williams [a,*], Eric D. Ebel [a], Epiphanie Nyirabahizi [b]

[a] Risk Assessment and Analytics Staff, Office of Public Health Science, Food Safety Inspection Service, USDA, 2150 Centre Avenue, Building D, Fort Collins, CO 80526, USA

[b] National Antimicrobial Resistance Monitoring System, Center for Veterinary Medicine, U.S. Food & Drug Administration, 8401 Muirkirk Road, Laurel, MD 20708, USA

ARTICLE INFO

Keywords:
Foodborne pathogens
Surveillance
Poultry
Interventions

ABSTRACT

In many countries campylobacteriosis ranks as one of the most frequently reported foodborne illnesses and poultry is the commodity that is most often associated with these illnesses. Nevertheless, efforts to reduce the occurrence of pathogen contamination on poultry are often more focused on *Salmonella*. While some control measures are pathogen specific, such as pre-harvest vaccination for *Salmonella*, improvements in sanitary dressing and interventions applied during the slaughter process can be effective against all forms of microbial contamination. To investigate the potential effectiveness of these non-specific pathogen reduction strategies in the United States, it is helpful to assess if, and by how much, *Campylobacter* contamination of chicken meat has changed across time. This study assesses change considering data collected in both slaughter and retail establishments and comparing observed trends in contamination with trends in human surveillance data. The results support the assertion that substantial reductions in *Campylobacter* contamination of chicken meat in the late 1990s and early 2000s contributed to a reduction in the human case rate of campylobacteriosis. Further reductions in chicken meat contamination between 2013 and 2018 are more difficult to associate with trends in human illnesses, with one contributing factor being the inclusion of culture independent diagnostic test results in the official case counts during that time. Other contributing factors are discussed.

1. Introduction

Campylobacter is one of the most commonly identified bacterial causes of acute gastroenteritis worldwide (Acheson and Allos, 2001), and second to *Salmonella* as the cause of the most foodborne cases of acute bacterial gastroenteritis in the United States (Scallan et al., 2011). It has also been recognized for decades as one of the top contributors to preventable foodborne illness (National Research Council, 1985). Despite the large annual number of cases in the United States, it has generally been a lower priority pathogen than *Salmonella* and *Escherichia coli* O157:H7 for both the food industry and regulatory agencies. The reduced focus on this pathogen may be due to the small number of annual *Campylobacter*-related foodborne outbreaks and deaths compared to other foodborne pathogens (Taylor et al., 2012). Nevertheless, recent analyses provide estimates as high as nearly one out of every two cases of campylobacteriosis in the United States is associated with chicken (IFSAC, 2018). This high attribution fraction, coupled with the additional concerns regarding the putative link between campylobacteriosis and Guillain-Barré syndrome (Scallan Walter et al., 2020) and campylobacteriosis being the most common form of bacterial foodborne illness detected by the FoodNet surveillance system in the United States (CDC, 2017), provides a justification for focusing regulatory resources on this product-pathogen pair.

In the United States, both processing methods for poultry, and control strategies for microbial pathogens, differ significantly from Europe and other counties. Some of the largest differences are the increased emphasis on reducing pathogens during slaughter and processing (Hwang and Singer, 2020) in the U.S., as compared to an emphasis on pre-harvest interventions in the European Union (EFSA Panel on Biologocal Hazards, 2020) and other countries. Pathogen reduction strategies during slaughter and processing often rely on additional washing steps and the application of antimicrobial interventions, such as peracetic acid, and the water immersion chilling process that is most common in the United States (Ebel et al., 2019a).

In an effort to reduce pathogen contamination of meat and poultry, the Food Safety and Inspection Service (FSIS) implemented the

* Corresponding author.
E-mail address: mike.williams@fsis.usda.gov (M.S. Williams).

https://doi.org/10.1016/j.ijfoodmicro.2021.109075
Received 24 April 2020; Received in revised form 20 October 2020; Accepted 17 January 2021
Available online 26 January 2021

Pathogen Reduction; Hazard Analysis and Critical Control Points (PR; HACCP) System – Final Rule (FSIS, 1996d). In preparation for implementing the PR;HACCP rule, FSIS performed surveys of multiple commodities across the beef, pork and poultry industries between 1993 and 1998. Samples collected during these surveys were tested for up to six different pathogens identified as major contributors to preventable foodborne illness (National Research Council, 1985). FSIS used the results of these surveys to establish 2-class attribute sampling plans for *Salmonella* in beef, pork, and poultry. FSIS refers to these sampling plans as performance standards (FSIS, 1996d).

FSIS announced its first *Campylobacter* performance standards for chicken and turkey carcasses in 2011 (FSIS, 2011). These were followed by *Campylobacter* performance standards for chicken parts and comminuted poultry in 2016 (FSIS, 2016a). The implementation of these five performance standards has been hampered by the following problems.

- Low diagnostic sensitivity of the direct plating of 1 mL of sample rinsate onto Campy Cefex agar resulted in difficulties in correctly classifying establishments as passing or failing the standard (Ebel et al., 2020).
- False-negative test results occurred because of residual antimicrobials that were not neutralized by the buffered peptone water used for the rinse samples of chicken carcasses and parts (Williams et al., 2018).
- Reduced recovery of *Campylobacter* in the revised neutralizing buffered peptone rinsate that FSIS adopted to counter the carry-over of antimicrobials (Bourassa et al., 2018).

FSIS chose to address the possible reduction in sensitivity of its original assay by increasing the aliquot volume of its *Campylobacter* assay from 1 mL to 30 mL, which lowers the concentration at which the sample will be test-positive, and by adding a 24 h enrichment step to resuscitate viable *Campylobacter* cells that may have entered a state of quiescence during transportation to the laboratory.

A historical record of *Salmonella* contamination in meat and poultry has been established by FSIS's ongoing *Salmonella* performance standards (Williams et al., 2014, 2020). Because poultry *Campylobacter* performance standards were published more recently, and those data are based on laboratory methods with a different limit of detection, the historic pattern of *Campylobacter* contamination on poultry is difficult to describe with FSIS data. As FSIS and other food-safety organizations pay increasing attention to *Campylobacter*, it is reasonable to consider all available data sources to understand the current and historical occurrence of this foodborne pathogen. This study combines nearly a quarter century of *Campylobacter*-chicken meat contamination data, collected at both slaughter and retail, and compares changes in chicken contamination with trends in the estimated case rates of human campylobacteriosis in the United States.

2. Data description

We used three data sources to assess changes in *Campylobacter* contamination of chicken and annual occurrence of campylobacteriosis among humans. FSIS provides data from chicken carcasses following slaughter and processing. Another national monitoring system provides data from chicken parts at retail while a public health surveillance system provides human illness data.

Laboratory methods have changed over the nearly quarter century of data collection. Nevertheless, some common features of the assays have remained consistent throughout the study period, particularly for the chicken meat samples. Specifically, all chicken meat samples are obtained by agitating a bag containing a rinsate solution and either a chicken carcass from a slaughter establishment or a chicken meat sample purchased at retail. All tests are performed on the rinsate. Common procedures for the testing of the rinsate are; Double-strength Bolton broth is used as the enrichment media (Bolton and Coates, 1983); incubation is performed at 42C in a microaerobic gas mixture consisting of 85% nitrogen, 10% carbon dioxide, and 5% oxygen; isolation and/or confirmation is performed using colonies grown on Campy Cefex plating media (Stern et al., 1992). Apart from some of the more recent human illness data, all screen test-positive samples were subjected to confirmation. The confirmation step suggests that it is reasonable to assume nearly perfect test specificity. Other changes, such as the replacement of the culture test with a polymerase chain reaction (PCR) test, has led to only modest changes in test sensitivity (Ebel et al., 2016) that would not affect the overall conclusions of the study. The methods for all three surveys are generally appropriate for isolating and identifying *Campylobacter jejuni*, *coli*, and *lari*, though species composition information is only consistently reported for the retail sampling data (FDA, 2011).

2.1. Slaughter data

FSIS has operated two data collection programs relevant to *Campylobacter*. The first program is referred to as the baseline surveys. These surveys are nationwide assessments of the frequency and levels of microbial contamination on various meat and poultry products in the United States. A chicken carcass baseline survey was conducted between July 1994 and July 1995 (FSIS, 1996a). This survey collected 1297 carcass samples from establishments that produced 99% of all broiler carcasses produced in the United States. A sample consisted of a single carcass chosen randomly immediately following removal from the chill tank. Each carcass was shipped to an FSIS laboratory where it was rinsed with 400 mL of buffered peptone water. Each rinse sample was then quantified via a Most Probable Number (MPN) analysis (Cochran, 1950) which had a theoretical limit of quantitation of 0.03 microorganisms/mL.

Another baseline survey was conducted from July 2007 through June 2008. The survey generated 3275 samples, where each sample consisted of a single broiler carcass randomly chosen immediately following removal from the chill tank (FSIS, 2009). The sampling method was identical to the previous baseline survey except that the rinse sampling was performed by FSIS personnel in the slaughter establishment and the rinsate was shipped to one of three FSIS laboratories. Each rinse sample was then subjected to an enrichment-based qualitative screening test with a slightly higher limit of detection than that of the prior baseline (0.033 microorganisms/mL vs 0.030 microorganisms/mL). For the samples that tested *Campylobacter*-positive on the screening test, the concentrations of *Campylobacter* were enumerated by averaging the results of four 0.25 mL direct plating samples grown on Campy Cefex plates.

The second FSIS data collection program began as part of the PR; HACCP verification sampling in production establishments (FSIS, 1996d). Data from this program are used to assess the performance of establishments that produce the majority of all meat and poultry produced in the United States. Only poultry products are tested for *Campylobacter* and these data can be used to assess the contamination status of each establishment regulated by FSIS (FSIS, 2011, 2016a). As mentioned previously, these data were based on direct plating of a 1 mL aliquot of rinsate (i.e., an implied limit of detection of 1 microorganism/mL). This different method limits the comparability of results with the FSIS baseline survey data. In 2018, however, FSIS began testing for *Campylobacter* on poultry carcasses and parts using a 30 mL enrichment-based assay that had similar performance characteristics to the assays employed in the baseline surveys (Ebel et al., 2016). For each sample, FSIS personnel collected a 400 mL rinse sample from a single randomly selected broiler chicken carcass immediately following removal from the chill tank. The sampling methods were similar to those used during the previous baseline studies, except that the rinse solution consisted of a neutralizing buffered peptone water to counteract possible antimicrobial carryover into the rinsate (Bourassa et al., 2018; Gamble et al., 2017). A total of 9043 carcass samples were tested between May 2018

and April 2019. During the first four months of this transition from the 1 mL to 30 mL assay, both assays were used to test 2862 samples for the presence of *Campylobacter*. These samples were used to estimate *Campylobacter* concentrations.

2.2. Retail chicken data

The National Antimicrobial Resistance Monitoring System (NARMS) is a retail meat and poultry surveillance program whose primary goal is to monitor the prevalence and trends of antimicrobial resistance among foodborne isolates of *Salmonella, Campylobacter, Enterococcus* and *Escherichia coli* (FDA, 2011). NARMS is an ongoing collaboration between the U.S. Food and Drug Administration, Center for Veterinary Medicine (FDA/CVM), Centers for Disease Control and Prevention (CDC), United States Department of Agriculture (USDA), and state and local public health departments and universities. The program began in 2002 with sampling in five U.S. states. The geographic coverage expanded to 10 states by 2004 and 14 states by 2012. Samples are tested by one public health laboratory in the state of sample collection using a common laboratory protocol. The participating states are California, Colorado, Connecticut, Georgia, Louisiana, Maryland, Minnesota, Missouri, New Mexico, New York, Oregon, Pennsylvania, Tennessee, and Washington. In each state, 10 packages of retail bone-in, skin-on chicken breasts were randomly sampled from retail grocery stores each month. The date the sample arrived at the laboratory was used to assign the month code. Beginning in 2011, samples of chicken thighs or wings were taken in the rare instance that the appropriate chicken breast samples were not available. Since 2015, each site increased the number of retail chicken packages to 40 per month. Sample collectors were instructed to select different brands or different sell-by dates for each meat commodity during each sampling occasion. In addition to the increase in the number of samples collected at each site, since 2016 NARMS has expanded its sampling coverage to include Iowa, Texas, Oklahoma, North Carolina, South Carolina, Kansas, South and North Dakota. A total 36,067 samples were analyzed from the beginning of 2002 through the end of 2018. A comparison between the fixed geographic locations of the NARMS samples to results from a series of surveys from random locations within the United States found no evidence to suggest a geographic bias (Williams et al., 2020).

For each sample, a single chicken piece was added to a sterile plastic bag with 250 mL of buffered peptone water and the bag was vigorously massaged. Fifty milliliters of double-strength Bolton broth was added to flasks containing 50 mL of rinsate, mixed gently to avoid aeration, and incubated at 42 °C for 24 h in a reduced oxygen atmosphere. The Bolton broth enrichment was inoculated onto Campy Cefex Agar (CCA) to obtain isolated colonies and incubated at 42 °C for 24 to 48 h. When *Campylobacter*-like colonies were observed on the Campy Cefex agar, the confirmation process began by selecting one typical, well-isolated colony for testing to confirm the presence of *Campylobacter*. Confirmation and speciation were performed using PCR, with whole genome sequencing incorporated in 2015. The samples were then tested for resistance to a number of different antimicrobial agents (FDA, 2011; Linton et al., 1997; NARMS, 2016; Williams et al., 2015b). The 50 mL rinsate volume, which is added to the enrichment broth, provides a theoretical limit of detection for the assay of 0.02 microorganisms/mL

2.3. Human illness data

The Foodborne Diseases Active Surveillance Network (FoodNet) surveillance system is a collaborative effort between the CDC, FDA, USDA and State public health laboratories in California, Colorado, Connecticut, Georgia, Maryland, Minnesota, New Mexico, New York, Oregon, and Tennessee (Scallan and Mahon, 2012; Wallace et al., 2000). The number of states participating in FoodNet has evolved, with five states participating in 1996 and expanding to the current 10 states by 2004. The geographical areas covered by the surveillance system do not necessarily cover an entire participating state, but the total area covered represents approximately 15% of the U.S. population. The coverage area within each state is referred to as a FoodNet site.

CDC's FoodNet Fast online database provides the annual number of diagnosed cases of campylobacteriosis within the catchment area (CDC, 2020). From these data, along with information on the population size within the catchment, a reported campylobacteriosis case rate per 100,000 population can be estimated.

General limitations of these data are that not all illnesses are diagnosed because some cases do not seek medical care (thereby escaping surveillance detection), reported illnesses are not necessarily foodborne or domestically acquired, and laboratory procedures may differ across the more than 400 participating laboratories (Hurd et al., 2012). However, it is reasonable to compare FoodNet data to other surveillance systems to understand disease burden as studies have shown that the geographic differences observed in campylobacteriosis rates reflect real differences in risk of illness rather than skewing toward the differences in the source of data (Ailes et al., 2012; Scallan and Mahon, 2012).

More recent complicating factors are the potential effects of increased rates of care-seeking associated with expanded medical coverage (Anderson et al., 2012) in the United States and the increased use of culture independent diagnostic tests (CIDT). The use of these testing methodologies has markedly reduced the number of samples submitted for culture (Cronquist et al., 2012; Iwamoto et al., 2015; Shea et al., 2017). To address this complication, FoodNet began tracking both CIDT and culture-confirmed cases in 2012.

Another complicating factor of CIDTs is that multiple testing methods are in use and each diagnostic test has unique performance characteristics (e.g., sensitivity and specificity). Due to their more frequent use, the ability to test simultaneously for multiple pathogens, the lower specificity relative to culture, and the low prevalence of *Campylobacter*-positive samples, the primary concern is the number of false positive CIDT tests. CDC has developed adjustment techniques that account for the different performance characteristics of the CIDT assays and identified additional data needs (Gu et al., 2018). This technique is novel because it uses the estimated positive predictive value to adjust the number of CIDT-identified cases in the surveillance system.

This study uses the 142,494 campylobacteriosis cases, reported to FoodNet between 1996 and the end of 2018, to provide trend estimates of the annual incidence. Of these, 15,300 were CIDT cases reported in the last seven years (2012–2018). Estimates of the number of true campylobacteriosis cases (i.e., the culture confirmed plus CIDT cases adjusted for false positive and false negative results) are incorporated into the analysis for 2012–2016 (Gu et al., 2018).

3. Methods

This analysis describes temporal changes in *Campylobacter* occurrence (i.e., presence/absence) from the NARMS and FSIS data, as well as *Campylobacter* human illness rates from FoodNet. In addition, we compare the concentrations of *Campylobacter* in FSIS chicken samples collected across three time periods.

3.1. Campylobacter presence/absence statistics

The data for the FSIS baselines were treated as simple random samples despite the fact that FSIS disporportionately samples low-volume producers. The percentages of positive samples and confidence intervals were derived using standard survey methods for proportions (Cochran, 1977).

3.2. Estimation of temporal trends

Given the continuous nature of sample collection of the NARMS and FoodNet programs, the temporal change in the percentage of positive samples (NARMS) or the case rate per 100,000 (FoodNet) can be

modeled. Our trend analysis fits a penalized B-spline regression model to the data using a second-order difference penalty (Powell, 2016; Wood, 2017). This modeling framework has been used to analyze temporal patterns in previous food contamination applications, as well as analyses of the FoodNet surveillance system (Powell et al., 2018; Powell, 2016; Williams et al., 2018).

For the penalized B-spline model, a period in which the 95% confidence band about the estimated curve completely contains a line with slope equal to zero (i.e., a flat line) indicates no significant change across the time period. This visual test, referred to as the horizontal line test, identifies a significant change, or trend over a period of time, when a horizontal line intersects the upper and lower confidence band. The model also provides test statistics for significant temporal trends. A step function can also be added to the model to test for significant changes in the performance characteristics of an assay (Williams et al., 2018, 2020) or change in the surveillance system (Ebel et al., 2019b). The analysis was performed using the mgcv package in R (R Development Core Team, 2018; Wood, 2017).

Confidence bands for the FoodNet data are only provided for the culture-confirmed tests between 1996 and 2011 because the current model cannot account for the uncertainties introduced by the inclusion of the CIDT testing results.

3.3. *Campylobacter* concentration

The FSIS baselines and exploratory study provide evidence for estimation of the concentration of *Campylobacter*. For each baseline study, the concentrations observed for each sample, or the absence of viable *Campylobacter,* were used in conjunction with various censored data methods to fit lognormal distributions that represented concentration on a microorganisms/mL basis (Williams and Ebel, 2012b, 2012c). For the FSIS exploratory samples collected in 2018–2019, there were 2862 samples with 1 mL and 30 mL qualitative sampling results. These results were used in an OpenBUGS model (Lunn et al., 2009) to estimate the underlying concentration distribution (Williams and Ebel, 2012c). The output of these fitting methods were the $\widehat{\mu}_*$ and $\widehat{\sigma}_*$ lognormal parameters for $\log_{10}$ transformed concentration values, where * indicates the year in which each survey was concluded (i.e., 1995, 2008 and 2019). The $\widehat{\mu}_*$ value can be interpreted as the estimated average $\log_{10}$ concentration of *Campylobacter* cells/mL of rinsate in the samples and $\widehat{\sigma}_*$ describes the amount of variability in the $\log_{10}$ transformed concentrations. These parameters, and the normal distribution, describe the range of levels of contamination at each time period. For example, the concentration of about 95% of all concentrations would fall in the range of $\widehat{\mu}_* \pm 2\widehat{\sigma}_*$.

4. Results

In the first FSIS baseline survey (i.e., 1994–1995), 88.2% of chicken carcasses were *Campylobacter*-positive (FSIS, 1996a) (Table 1). During the same time period, the only commodity with a higher *Campylobacter* contamination occurrence was turkey carcasses, with 90% of carcasses testing positive at the end of the slaughter process (FSIS, 1997). The second chicken baseline survey was performed roughly 13 years later (i.e., 2007–2008), by which time the percentage of chicken carcasses that were *Campylobacter*-positive had declined to 46.6%. The percentage of *Campylobacter*-positive chicken carcasses further decreased to 18.2% in the 2019 exploratory survey. The observed percentages of positive samples in the latter two surveys represent overall reductions of 47 and 79% from the first baseline study.

Table 1
Summary statistics for the three FSIS chicken carcass surveys.

Survey	Number of samples	Percent positive (95% confidence interval)	Concentration distribution parameters	
			$\widehat{\mu}_*$	$\widehat{\sigma}_*$
Baseline (1994–1995)	1297	88.2 (86.5, 90.0)	1.08	1.88
Baseline (2007–2008)	3275	46.6 (44.9, 48.3)	−1.92	1.58
Exploratory sampling (2018–2019)	9011	18.3 (17.5, 19.1)	−2.67	0.86

Fig. 1 shows the estimated trend and 95% confidence intervals for the NARMS retail data. The effect of the increase in the number of samples collected each month is demonstrated by the decreasing width of the confidence intervals. The horizontal line test ($\alpha = 0.05$) indicates an initial significant period of increasing *Campylobacter* contamination on retail chicken breasts; from 47% positive in 2002 to a peak of 57% positive in 2004. There was a statistically significant decrease between 2004 and 2006, followed by roughly 7 years where the estimated percentage of positive samples was essentially constant at approximately 43%. There was a nearly 80% reduction in the percentage of positive samples between 2013 and 2016. Between mid-2016 and the end of the available data in 2018, the percentage of positive retail samples was constant at slightly more than 10%. The penalized B-spline model was also used to investigate whether there was evidence that indicated that a change in the laboratory methods or other surveillance system artifacts were affecting the observed trend. No significant changes of this type were detected in the retail data.

Fig. 1 also shows the results of the three FSIS surveys overlaid on the NARMS estimated trend lines. While the first survey was completed prior to the beginning of the NARMS data collection, the magnitude of the observed reductions in the NARMS dataset are generally consistent with the estimated reductions reported by FSIS. Also note that the percentages of positive samples for the FSIS surveys were higher than the NARMS estimates for the most similar time period. This result was expected because an FSIS sample is more likely to be test-positive because the sample consists of an entire chicken carcass, whose total surface area is much greater than that of the individual chicken breast sampled by NARMS.

Fig. 2 provides a visual summary of the concentration of *Campylobacter* on chicken carcasses for the three FSIS surveys. Not only was the mean $\log_{10}$ concentration high for the samples collected during the first baseline survey ($\widehat{\mu}_{1995} = 1.08$ $\log_{10}$ microorganisms/mL), but greater than 30% of the samples had concentrations that exceeded 2 $\log_{10}$ microorganisms/mL, and the highest MPN-estimated $\log_{10}$ concentration exceeded 5 (230,000 microorganisms/mL) (FSIS, 1996a). The concentration distributions estimated from the second baseline (2007–8) and the exploratory sampling (2018–19) surveys represent $\log_{10}$ reductions, relative to the first baseline of roughly $\widehat{\mu}_{1995} - \widehat{\mu}_{2008} \approx -3$ and $\widehat{\mu}_{1995} - \widehat{\mu}_{2019} \approx -3.75$, respectively. In addition to these large reductions in the mean, the variability of the distributions was substantially reduced from that of the first baseline study (Table 1), which demonstrates that the occurrence of heavily contaminated chicken carcasses, relative to the average, has also substantially decreased over time.

At the inception of the FoodNet reporting system, the estimated campylobacteriosis case rate was 23.5 per 100,000 in 1996 (Fig. 3). There was a rapid monotonic reduction in the case rate between 1996 and approximately 2002. An estimated case rate of less than 13 per 100,000 was maintained from 2002 until 2009 when it began to rise. From 2012 to 2018, the trends in culture-confirmed and CIDT cases diverge, with the slopes of the curves indicating that CIDT cases had a larger annual increase in reported cases relative to the annual decrease in culture confirmed cases. After adjusting the CIDT data to account for the differences in the positive predictive value, the annual case rate is roughly 15 per 100,000 during 2012–2016 period. The analysis of adjusted case rates by Gu et al. (2018) concluded there were no statistically significant changes during this period.

Consideration of the human illness and chicken contamination evidence suggests a dramatic reduction in both the case rate of

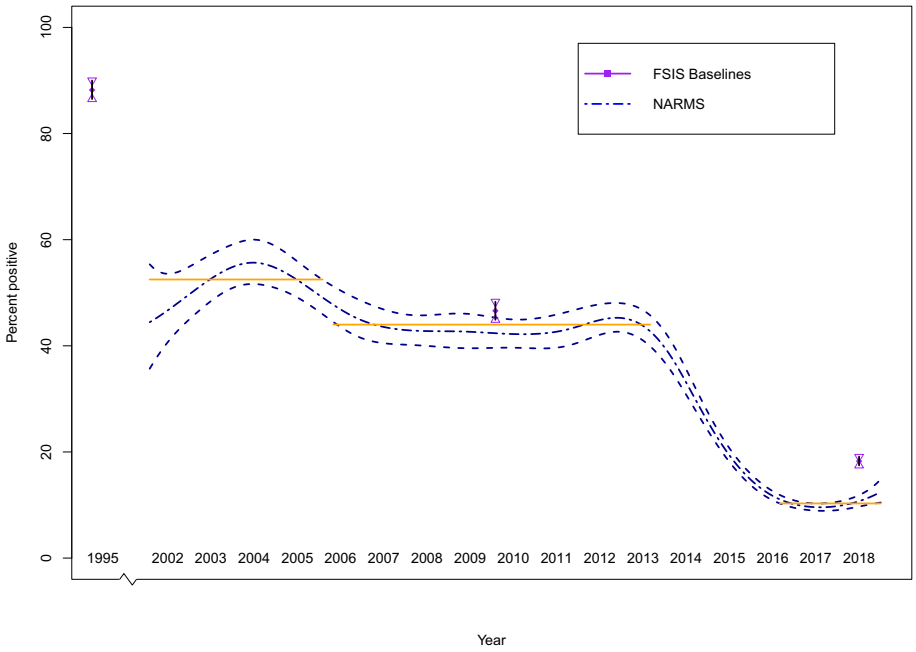

Fig. 1. Trend line and associated 95% confidence intervals for the NARMS retail chicken breast sampling data. Horizontal lines are added to test for significant trends and the point estimates and 95% confidence intervals are overlaid for the three FSIS surveys, though the large sample size for the 2018 survey makes the interval width very narrow.

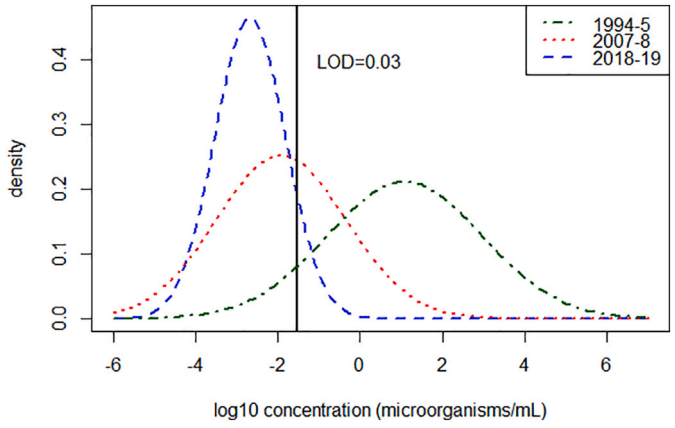

Fig. 2. Lognormal distributions describing the log10 concentration of *Campylobacter* for the three FSIS surveys. The vertical line represents a limit of detection (1/33.3 microorganisms/mL for the first baseline and 1/30 for the second and third surveys).

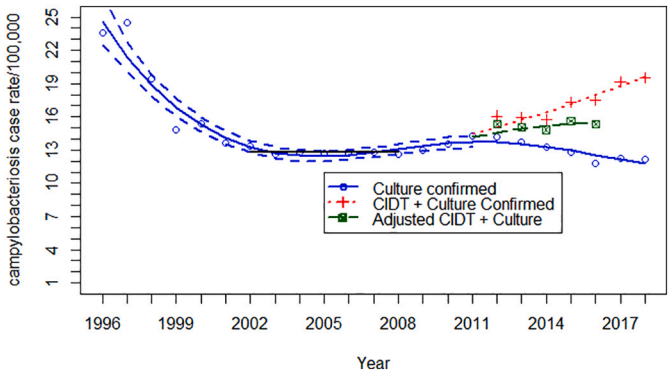

Fig. 3. Campylobacteriosis case rates per 100,000 estimated from the FoodNet surveillance system. The horizontal line represents a period of time (2002–2008) where the case rate did not change significantly. The trend line representing the inclusion of culture independent diagnostic tests (CIDT) increases more rapidly than the reduction in the case rate indicated by culture confirmation. Adjustments for the performance characteristics of the CIDT testing methods demonstrates an approximately constant case rate from 2012 through 2016. Adjusted case rates for 2017–2018 were not available at the time of this study.

campylobacteriosis and the percentage of positive chicken samples between 1996 and 2002. Nevertheless, the reduction in *Campylobacter* contamination on chicken between roughly 2013 and 2018 is not evident in the human illness data. While there is a reduction in culture-confirmed human cases from 2012 to 2018, it is difficult to assess how much, if any, of this change results from the reduction in chicken contamination observed in the NARMS and FSIS data versus the increased use of CIDTs.

The downward chicken contamination trend observed between 2013 and 2018 may be less relevant to the human cases trend during the same period if the overall share of human cases attributed to chicken is small. In contrast, a large attribution of human cases to chicken during the 1996 to 2002 period would be consistent with the similarity in reductions between chicken contamination and human cases observed during that period. If the share of human cases attributed to chicken was substantially reduced after 2002, then the power of the FoodNet surveillance system to detect changes in illnesses contributed by chicken during the 2013–2018 period would also be reduced (Ebel et al., 2017).

5. Discussion

This study focused on *Campylobacter* contamination of chicken because it is the only commodity monitored by FSIS and the NARMS program where this pathogen has been assessed on multiple occasions using roughly comparable laboratory techniques. For example, while FSIS laboratory and sampling methods for *Campylobacter* have changed across time, the sensitivities and limits of detection for the assays remain similar (Ebel et al., 2016).

As part of the original baseline studies, FSIS tested for *Campylobacter*

contamination in other commodities, with *Campylobacter* being isolated from 90% of turkey carcasses (FSIS, 1997), 31.5% of market hogs carcasses (FSIS, 1996c) and 0.2% of ground beef samples (FSIS, 1996b). More recently, FSIS found less than 2 and 1% of 325-g ground turkey and pork samples, respectively, were *Campylobacter*-positive during the 2016–2018 period. Similarly, the NARMS program consistently isolated *Campylobacter* from less than 1% of retail ground turkey, ground beef and pork chops samples. NARMS suspended the testing of ground beef and pork chops for *Campylobacter* after 2007 because the number of positive samples was too small to provide accurate trend information on resistance patterns for the large number of antibiotics monitored.

Since the inception of its PR;HACCP rule, FSIS has placed more emphasis on the reduction of *Salmonella* contamination of meat and poultry. A possible consequence of this focus is less of an emphasis on *Campylobacter* control, especially with regard to pre-harvest interventions which are infrequently employed in the United States (Hwang and Singer, 2020). While the observational data used in the study cannot demonstrate causation, it seems reasonable to assume that FSIS' ongoing focus on improved sanitary dressing (FSIS, 2016b) has led to reductions in both pathogens. Additional interventions, such as the application of organic acids during slaughter and processing, are also likely responsible for reductions in both *Salmonella* and *Campylobacter*, though the effectiveness of an intervention is unlikely to be equivalent for both pathogens (Ebel et al., 2019a; Nagel et al., 2013). Thus, one could describe reductions in *Campylobacter* occurrence and concentration as potentially a fortuitous collateral effect of the poultry slaughter industry's efforts to reduce *Salmonella* (Hwang and Singer, 2020). In fact, it is not unreasonable to conclude that the overall reduction in *Campylobacter* is as large or larger than for *Salmonella* (Nagel et al., 2013). FSIS has already observed that the average log10 reductions in *Campylobacter* concentration between the re-hang and post-chill locations in the chicken slaughter process are nearly double those observed for *Salmonella* (i.e., 2.08 microorganisms/mL for *Salmonella* versus 3.99 microorganisms/mL for *Campylobacter*) (Williams et al., 2015a). Such findings suggest that *Campylobacter* may be more fragile and more easily removed or inactivated during slaughter and processing than *Salmonella*.

Definitively attributing the reductions in *Campylobacter* contamination on chicken meat to specific programs or legislation is not possible, but it is seems likely that the reduction between the first and second baseline studies was due to the industry's reaction to the PR;HACCP legislation (FSIS, 1996d) that set maximums for *Salmonella* and generic *E. coli* contamination. A large fraction of the industry was required to invest in technologies that reduced microbial contamination because meeting the proposed performance standard was a requirement for marketing chicken meat until a successful legal challenge for the PR;HACCP legislation in 2002 (Johnson, 2004). The reductions after 2012 are more difficult to attribute to a single source, but it is seems reasonable to attribute them to a combination of industry's response to FSIS' *Campylobacter* performance standards and additional food safety requirements imposed by major retail chains (FSIS, 2011, 2015; Wal-Mart, 2017).

Relating changes in pathogen contamination in a specific product to reductions in human illness is difficult. FSIS used a risk assessment model to estimate that the implementation of the PR;HACCP rule could explain some early reductions in human salmonellosis observed in FoodNet (Williams and Ebel, 2012a). An alternative interpretation of the FoodNet data for this period attributed much of the reduction in illnesses to better control of *Salmonella* contamination in eggs (CDC, 2002). Nevertheless, concurrent reductions in cases of campylobacteriosis were noted during the same period, despite egg consumption generally not considered a risk factor for campylobacteriosis (Friedman et al., 2004; Samuel et al., 2004). Given the larger reductions in the case rates for both campylobacteriosis and salmonellosis in the early years of FoodNet, and the similar large reduction in the occurrence of these pathogens on meat and poultry, it is possible that a significant fraction of the improvement in public health resulted from pathogen reduction efforts undertaken by the meat and poultry industry.

One factor that contributes to the burden of chicken illnesses is the change in consumption. Chicken meat consumption has increased dramatically over the last 70 years, except for a period of only modest fluctuation between 2002 (36.8 kg/person) and 2012 (36.7 kg/person) (National Chicken Council, 2020) when contamination at retail was relatively stable. Annual chicken consumption grew to exceed 42 kg/person by the end of the study period in 2018, further complicating interpretation of the results.

The attribution of human illnesses to specific commodities is a challenging problem. Many different techniques have been applied (Ebel et al., 2015; Guo et al., 2011; Hald et al., 2007; Hald et al., 2004; Hoffmann et al., 2007; IFSAC, 2019; Painter et al., 2013; Pires et al., 2009) and the epidemiological evidence linking poultry and case rates of campylobacteriosis is often contradictory (CDC, 2015; Cody et al., 2010; David et al., 2017; Nelson and Harris, 2006a; Nelson and Harris, 2006b; Williams et al., 2015b; Wilson et al., 2008). The contradictory evidence of the role of poultry in campylobacteriosis cases has led to estimated attribution fractions for chicken-*Campylobacter* ranging from 7 to 95% (Lowman et al., 2009; Painter et al., 2013). An additional complicating factor for the estimation of the chicken-campylobacteriosis attribution fraction is the influence of infrequently consumed commodities, such as raw milk and chicken livers (Lanier et al., 2018; Mungai et al., 2015), that have a much higher frequency of contamination at the time of consumption and account for a disproportionately large fraction of *Campylobacter*-associated outbreaks for the broad commodity classes of milk and chicken. Another complicating factor is the degree to which environmental factors, such as exposure via contaminated water and fly transmission, may contribute to cases of campylobacteriosis (David et al., 2017; Ekdahl et al., 2005; Nichols, 2005; Pitkänen, 2013). If one accepts that much of the reduction in the campylobacteriosis case rate for the late 1990s was attributed to the reduction in contaminated chicken meat, then this study would suggest that the attribution fraction for chicken would likely have been in the middle- to high-end of the range during that period. Furthermore, the observed reductions in *Campylobacter* occurrence on chicken meat between 2013 and 2018, paired with the lack of a similar reduction in human illness, would suggest that the attribution fraction for this commodity is now on the lower range of the current estimates. Another possible, though less plausible, explanation for the discrepancy in trends between 2013 and 2018 could be that *Campylobacter* cells enter a viable but non-culturable state (Zhao et al., 2017) due to exposure to antimicrobials while still maintaining their pathogenicity after consumption (Ayrapetyan and Oliver, 2016). The difficulties of interpreting the differences between CIDT and culture confirmed cases in FoodNet and the observational nature of all three data sources complicate any interpretation of a change in the attribution fraction for the 2013–2018 period.

Regardless of the magnitude of the reductions in the occurrence and levels of *Campylobacter* contamination on chicken meat, the data for 2018 used in this study suggest that nearly 1 in 5 carcasses were *Campylobacter*-positive at slaughter and approximately 1 in 11 chicken breasts samples were positive at retail. These rates of contamination are roughly 5 and 2 times higher, respectively, than the observed rates on *Salmonella* on the same chicken meat samples (Williams et al., 2020) and are still some of the highest observed pathogen contamination rates for any commodity in the United States. More focused efforts to reduce the occurrence of this pathogen will be necessary to further reduce the burden of illness for this important foodborne pathogen.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Acheson, D., Allos, B.M., 2001. *Campylobacter* jejuni infections: update on emerging issues and trends. Clin. Infect. Dis. 32, 1201–1206.

Ailes, E., Scallan, E., Berkelman, R.L., Kleinbaum, D.G., Tauxe, R.V., Moe, C.L., 2012. Do differences in risk factors, medical care seeking, or medical practices explain the geographic variation in campylobacteriosis in foodborne diseases active surveillance network (FoodNet) sites? Clin. Infect. Dis. 54, S464–S471.

Anderson, M., Dobkin, C., Gross, T., 2012. The effect of health insurance coverage on the use of medical services. Am. Econ. J. Econ. Pol. 4, 1–27.

Ayrapetyan, M., Oliver, J.D., 2016. The viable but non-culturable state and its relevance in food safety. Curr. Opin. Food Sci. 8, 127–133.

Bolton, F.J., Coates, D., 1983. Development of a blood-free *Campylobacter* medium: screening tests on basal media and supplements, and the ability of selected supplements to facilitate aerotolerance. J. Appl. Bacteriol. 54, 115–125.

Bourassa, D.V., Lapidus, J.L., Kennedy-Smith, A.E., Morey, A., 2018. Efficacy of neutralizing buffered peptone water for recovery of *Salmonella*, *Campylobacter*, and *Enterobacteriaceae* from broiler carcasses at various points along a commercial immersion chilling process with peroxyacetic acid. Poult. Sci. 98, 393–397.

CDC, 2002. FoodNet 2000 Surveillance Report. Centers for Disease Control and Prevention. Atlanta, GA.

CDC, 2015. Campylobacteriosis outbreak associated with consuming undercooked chicken liver pâté — Ohio and Oregon, December 2013–January 2014, MMWR Morbidity Mortality Weekly Report, p. 1.

CDC, 2017. Incidence and trends of infection with pathogens transmitted commonly through food and the effect of increasing use of culture-independent diagnostic tests on surveillance—Foodborne Diseases Active Surveillance Network, 10 U.S. Sites, 2013–2016, MMWR Morbidity Mortality Weekly Report.

CDC, 2020. FoodNet Fast. Centers for Disease Control and Prevention. Atlanta, Georgia.

Cochran, W.G., 1950. Estimation of bacterial densities by means of the most probable number Biometrics 6, 105–116.

Cochran, W.G., 1977. Sampling Techniques, 3 ed. John Wiley and Sons, New York.

Cody, A.J., Colles, F.M., Sheppard, S.K., Maiden, M.C.J., 2010. Where does *Campylobacter* come from? A molecular odyssey. Adv. Exp. Med. Biol. 659, 47–56.

Cronquist, A.B., Mody, R.K., Atkinson, R., Besser, J., D'Angelo, M.T., Hurd, S., Robinson, T., Nicholson, C., Mahon, B.E., 2012. Impacts of culture-independent diagnostic practices on public health surveillance for bacterial enteric pathogens. Clin. Infect. Dis. 54, S432–S439.

David, J.M., Pollari, F., Pintar, K.D.M., Nesbitt, A., Butler, A.J., Ravel, A., 2017. Do contamination of and exposure to chicken meat and water drive the temporal dynamics of *Campylobacter* cases? Epidemiol. Infect. 145, 3191–3203.

Ebel, E.D., Williams, M.S., Golden, N.J., Schlosser, W.D., Travis, C., 2015. Time valuation of historical outbreak attribution data. Epidemiology & Infection 144, 396–407.

Ebel, E.D., Williams, M.S., Golden, N.J., Tankson, J., 2016. Bayesian techniques for comparison of the test performance of PCR and culture for the identification of *Campylobacter* in enriched comminuted chicken samples. J. Appl. Microbiol. 120, 1418–1426.

Ebel, E.D., Williams, M.S., Schlosser, W.D., 2017. Estimating the Type II error of detecting changes in foodborne illnesses via public health surveillance. Microbial Risk Analysis 7, 1–7.

Ebel, E.D., Williams, M.S., Tameru, B., 2019a. Relatedness of *Salmonella* contamination frequency on chicken carcasses and parts when processed in the same establishment. Food Control 100, 198–203.

Ebel, E.D., Williams, M.S., Ward-Gokhale, L.A., Kisselburgh, H.M., 2019b. Assessing the maximum size of annual foodborne outbreaks in the United States: an analysis of 1973–2016 outbreaks. Microbial Risk Analysis 12, 20–26.

Ebel, E.D., Williams, M.S., Amann, D.M., 2020. Quantifying the effects of reducing sample size on 2-class attributes sampling plans: implications for United States poultry performance standards. Food Control 111, 107068.

EFSA Panel on Biologocal Hazards, 2020. Update and review of control options for *Campylobacter* in broilers at primary production. EFSA J. 18, e06090.

Ekdahl, K., Normann, B., Andersson, Y., 2005. Could flies explain the elusive epidemiology of campylobacteriosis? BMC Infect. Dis. 5, 11.

FDA, 2011. NARMS Retail Meat Annual Report, 2011. Food and Drug Administration, Health and Human Services, Washington, D.C,.

Friedman, C.R., Hoekstra, R.M., Samuel, M., Marcus, R., Bender, J., Shiferaw, B., Reddy, S., Ahuja, S.D., Helfrick, D.L., Hardnett, F., Carter, M., Anderson, B., Tauxe, R.V., 2004. Risk factors for sporadic *Campylobacter* infection in the United States: a case-control study in FoodNet sites. Clin. Infect. Dis. 38, S285–S296.

FSIS, 1996a. Nationwide Broiler Chicken Microbiological Baseline Data Collection Program (July 1994–June 1995). U. S. Department of Agriculture, Washington D.C.

FSIS, 1996b. Nationwide Federal Plant Raw Groud Beef Survey. In: Auguest 1993 - March 1994 U. Agriculture, Washington, D.C, S. Deparment of.

FSIS, 1996c. Nationwide Pork Microbiological Baseline Data Collection Program: Market Hogs April 1995 - March 1996. U.S. Department of Agriculture, Washington. D.C.

FSIS, 1996d. Pathogen Reduction; Hazard Analysis and Critical Control Point (HACCP) Systems; Final Rule. U. S. Department of Agriculture, Washington D.C.

FSIS, 1997. Nationwide Young Turkey Microbiological Baseline Data Collection Program (August 1996–July 1997). U. S, Department of Agriculture, Washington, D.C.

FSIS, 2009. The Nationwide Microbiological Baseline Data Collection Program: Young Chicken Survey: July 2007– June 2008. U. S, Department of Agriculture, Washington, D.C.

FSIS, 2011. New Performance Standards for *Salmonella* and *Campylobacter* in Young Chicken and Turkey Slaughter Establishments: Response to Comments and Implementation Schedule. United States Department of Agriculture. Washington, D. C.

FSIS, 2015. Public Health Effects of Raw Chicken Parts and Comminuted Chicken and Poultry Performance Standards. United States Department of Agriculture. Washington, D.C.

FSIS, 2016a. New Performance Standards for *Salmonella* and *Campylobacter* in Not-ready-to-eat Comminuted Chicken and Turkey Products and Raw Chicken Parts and Changes to Related Agency Verification Procedures: Response to Comments and Announcement of Implementation Schedule. U. S. Department of Agriculture, Washington D.C., pp. 7285-7300.

FSIS, 2016b. Verifying poultry slaughter establishments maintain adequate procedures for preventing contamination with feces and enteric pathogens, in: Department of Agriculture (Ed.). Food Safety and Inspection Service, Washington, D.C.

Gamble, G.R., Berrang, M.E., Buhr, R.J., Hinton Jr., A., Bourassa, D.V., Ingram, K.D., Adams, E.S., Feldner, P.W., Johnston, J.J., 2017. Neutralization of bactericidal activity related to antimicrobial carryover in broiler carcass rinse samples. J. Food Prot. 80, 685–691.

Gu, W., Dutta, V., Patrick, M., Bruce, B.B., Geissler, A., Huang, J., Fitzgerald, C., Henao, O., 2018. Statistical adjustment of culture-independent diagnostic tests for trend analysis in the Foodborne Diseases Active Surveillance Network (FoodNet), USA. Int. J. Epidemiol. 47, 1613–1622.

Guo, C., Hoekstra, R.M., Schroeder, C.M., Pires, S.M., Ong, K.L., Hartnett, E., Naugle, A., Harman, J., Bennett, P., Cieslak, P., Scallan, E., Rose, B., Holt, K.G., Kissler, B., Mbandi, E., Roodsari, R., Angulo, F.J., Cole, D., 2011. Application of Bayesian techniques to model the burden of human salmonellosis attributable to U.S. food commodities at the point of processing: adaptation of a Danish model. Foodborne Pathog. Dis. 8, 509–516.

Hald, T., Vose, D., Wegener, H.C., Koupeev, T., 2004. A Bayesian approach to quantify the contribution of animal-food sources to human salmonellosis. Risk Anal. 24, 255–269.

Hald, T., Lo Fo Wong, D.M., Aarestrup, F.M., 2007. The attribution of human infections with antimicrobial resistant *Salmonella* bacteria in Denmark to sources of animal origin. Foodborne Pathog. Dis. 4, 313–326.

Hoffmann, S., Fischbeck, P., Krupnick, A., McWilliams, M., 2007. Using expert elicitation to link foodborne illnesses in the United States to foods. J. Food Prot. 70, 1220–1229.

Hurd, S., Patrick, M., Hatch, J., Clogher, P., Wymore, K., Cronquist, A.B., Segler, S., Robinson, T., Hanna, S., Smith, G., 2012. Clinical laboratory practices for the isolation and identification of *Campylobacter* in Foodborne Diseases Active Surveillance Network (FoodNet) sites: baseline information for understanding changes in surveillance data. Clin. Infect. Dis. 54, S440–S445.

Hwang, H., Singer, R.S., 2020. Survey of the US broiler industry regarding pre-and post-harvest interventions targeted to mitigate *Campylobacter* contamination on broiler chicken products Journal of Food Protection 83, 1137–1148.

IFSAC, 2018. Foodborne Illness Source Attribution Estimates for 2016 for *Salmonella, Escherichia coli* O157, *Listeria monocytogenes*, and *Campylobacter* Using Multi-year Outbreak Surveillance Data, United States U.S. Department of Health and Human Services and Department of Agriuclture, Atlanta, Georgia and Washignton. District of Columbia.

IFSAC, 2019. Foodborne Illness Source Attribution Estimates for 2017 for *Salmonella, Escherichia coli* O157, *Listeria monocytogenes*, and *Campylobacter* Using Multi-year Outbreak Surveillance Data, United States U.S. Department of Health and Human Services and Department of Agriuclture, Atlanta, Georgia and Washignton. District of Columbia.

Iwamoto, M., Huang, J.Y., Cronquist, A.B., Medus, C., Hurd, S., Zansky, S., Dunn, J., Woron, A.M., Oosmanally, N., Griffin, P.M., 2015. Bacterial enteric infections detected by culture-independent diagnostic tests—FoodNet, United States, 2012–2014. MMWR Morb. Mortal. Wkly Rep. 64, 252.

Johnson, B.B., 2004. The supreme beef case: an opportunity to rethink federal food safety regulation. Loyola Consumer Law Review 16, 159–174.

Lanier, W.A., Robertson-Hale, K., Geissler, A.L., Dewey-Mattia, D., 2018. Chicken liver–associated outbreaks of campylobacteriosis and salmonellosis, United States, 2000–2016: identifying opportunities for prevention. Foodborne Pathog. Dis. 15, 726–733.

Linton, D., Lawson, A., Owen, R., Stanley, J., 1997. PCR detection, identification to species level, and fingerprinting of *Campylobacter jejuni* and *Campylobacter coli* direct from diarrheic samples. J. Clin. Microbiol. 35, 2568–2572.

Lowman, R., Haroardottir, H., Kristinsson, K., Sigmundsdottir, G., Frioriksdottir, V., Reiersen, J., 2009. Iceland: A review of reduction in human incidence of domestically acquired campylobacteriosis from 2000–2008, concurrent with Iceland's freezing policy. In: Moore, J.E., Matsuda, M. (Eds.), Proceedings of the 15th International Workshop on *Campylobacter*, *Helicobacter* and Related Organisms (CHRO). Niigata, Japan, p. 140.

Lunn, D., Spiegelhalter, D., Thomas, A., Best, N., 2009. The BUGS project: evolution, critique and future directions (with discussion). Stat. Med. 28, 3049–3082.

Mungai, E.A., Behravesh, C.B., Gould, L.H., 2015. Increased outbreaks associated with nonpasteurized milk, United States, 2007–2012. Emerg. Infect. Dis. 21, 119.

Nagel, G.M., Bauermeister, L.J., Bratcher, C.L., Singh, M., McKee, S.R., 2013. *Salmonella* and *Campylobacter* reduction and quality characteristics of poultry carcasses treated with various antimicrobials in a post-chill immersion tank. Int. J. Food Microbiol. 165, 281–286.

NARMS, 2016. The National Antimicrobial Resistance Monitoring System Manual of Laboratory Methods, in: Medicine, C.f.V. (Ed.), 3rd ed. Food and Drug Administration, Laurel, Mariland, USA.

National Chicken Council, 2020. Per Capita Consumption of Poultry and Livestock, 1960 to Estimated 2021, in Pounds. Washington, D.C.

National Research Council, 1985. An Evaluation of the Role of Microbiological Criteria for Foods and Food Ingredients. National Academies Press.

Nelson, W., Harris, B., 2006a. Can we change the hymn sheet? Campylobacteriosis not just from chicken. The New Zealand Medical Journal 119, U2299.
Nelson, W., Harris, B., 2006b. Flies, fingers, fomites, and food. Campylobacteriosis in New Zealand—food-associated rather than food-borne. The New Zealand Medical Journal 119.
Nichols, G.L., 2005. Fly transmission of *Campylobacter*. Emerg. Infect. Dis. 11, 361–364.
Painter, J.A., Hoekstra, R.M., Ayers, T., Tauxe, R.V., Braden, C.R., Angulo, F.J., Griffin, P. M., 2013. Attribution of foodborne illnesses, hospitalizations, and deaths to food commodities, United States, 1998–2008. Emerging Infectous Diseases 19, 407–415.
Pires, S.M., Evers, E.G., van Pelt, W., Ayers, T., Scallan, E., Angulo, F.J., Havelaar, A.H., Hald, T., 2009. Attributing the human disease burden of foodborne infections to specific sources. Foodborne Pathog. Dis. 6, 417–424.
Pitkänen, T., 2013. Review of *Campylobacter spp.* in drinking and environmental waters. J. Microbiol. Methods 95, 39–47.
Powell, M., Crim, S., Hoekstra, R., Williams, M., Gu, W., 2018. Temporal patterns in principal *Salmonella* serotypes in the USA; 1996–2014. Epidemiology & Infection 146, 437–441.
Powell, M.E., 2016. Trends in reported foodborne illness in the United States: 1996-2013. Risk Anal. 36, 1589–1598.
R Development Core Team, 2018. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.
Samuel, M.C., Vugia, D.J., Shallow, S., Marcus, R., Segler, S., McGivern, T., Kassenborg, H., Reilly, K., Kennedy, M., Angulo, F., 2004. Epidemiology of sporadic *Campylobacter* infection in the United States and declining trend in incidence, FoodNet 1996–1999. Clin. Infect. Dis. 38, S165–S174.
Scallan, E., Mahon, B.E., 2012. Foodborne Diseases Active Surveillance Network (FoodNet) in 2012: a foundation for food safety in the United States. Clin. Infect. Dis. 54, S381–S384.
Scallan, E., Hoekstra, R.M., Angulo, F.J., Tauxe, R.V., Widdowson, M.-A., Roy, S.L., Jones, J.L., Griffin, P.M., 2011. Foodborne illness acquired in the United States—major pathogens. Emerg. Infect. Dis. 17, 7–15.
Scallan Walter, E., SM Crim, S., Bruce, B., Griffin, P., 2020. Incidence of *Campylobacter*-associated Guillain-Barré Syndrome estimated from health insurance data. Foodborne Pathog. Dis. 17, 23–28.
Shea, S., Kubota, K.A., Maguire, H., Gladbach, S., Woron, A., Atkinson-Dunn, R., Couturier, M.R., Miller, M.B., 2017. Clinical microbiology laboratories' adoption of culture-independent diagnostic tests is a threat to foodborne-disease surveillance in the United States. J. Clin. Microbiol. 55, 10–19.
Stern, N.J., Wojton, B., Kwiatek, K., 1992. A differential-selective medium and dry ice-generated atmosphere for recovery of *Campylobacter jejuni*. J. Food Prot. 55, 514–517.
Taylor, E.V., Herman, K.M., Ailes, E.C., Fitzgerald, C., Yoder, J.S., Mahon, B.E., Tauxe, R. V., 2012. Common source outbreaks of *Campylobacter* infection in the USA, 1997–2008. Epidemiol. Infect. 141, 987–996.
Wallace, D., Van Gilder, T., Shallow, S., Fiorentino, T., Segler, S., Smith, K., Shiferaw, B., Etzel, R., Garthright, W., Angulo, F., 2000. Incidence of foodborne illnesses reported by the Foodborne Diseases Active Surveillance Network (FoodNet)-1997 Journal of Food Protection 63, 807–809.
Wal-Mart, 2017. Food Safety Requirements for Food and Beverage Suppliers. Wal-Mart Stores, Inc.
Williams, M.S., Ebel, E.D., 2012a. Estimating changes in public health following implementation of hazard analysis and critical control point in the United States broiler slaughter industry. Foodborne Pathog. Dis. 12, 59–67.
Williams, M.S., Ebel, E.D., 2012b. Methods for fitting a parametric probability distribution to most probable number data. Int. J. Food Microbiol. 157, 251–258.
Williams, M.S., Ebel, E.D., 2012c. Methods for fitting the Poisson-lognormal distribution to microbial testing data. Food Control 27, 73–80.
Williams, M.S., Ebel, E.D., Golden, N.J., Schlosser, W.D., 2014. Temporal patterns in the occurrence of *Salmonella* in raw meat and poultry products and their relationship to human illnesses in the United States. Food Control 35, 267–273.
Williams, M.S., Ebel, E.D., Allender, H.D., 2015a. Industry-level changes in microbial contamination on market hog and broiler chicken carcasses between two locations in the slaughter process. Food Control 51, 361–370.
Williams, M.S., Golden, N.J., Ebel, E.D., Crarey, E.T., Tate, H.P., 2015b. Temporal patterns of *Campylobacter* contamination on chicken and their relationship to campylobacteriosis cases in the United States. Int. J. Food Microbiol. 208, 114–121.
Williams, M.S., Ebel, E.D., Hretz, S.A., Golden, N.J., 2018. Adoption of neutralizing buffered peptone water coincides with changes in apparent prevalence of *Salmonella* and *Campylobacter* of broiler rinse samples. J. Food Prot. 81, 1851–1863.
Williams, M.S., Ebel, E.D., Saini, G., Nyirabahizi, E., 2020. Changes in *Salmonella* contamination in meat and poultry since the introduction of the pathogen reduction; hazard analysis and critical control point rule. J. Food Prot. 83, 1707–1717.
Wilson, D.J., Gabriel, E., Leatherbarrow, A.J., Cheesbrough, J., Gee, S., Bolton, E., Fox, A., Fearnhead, P., Hart, C.A., Diggle, P.J., 2008. Tracing the source of campylobacteriosis. PLoS Genet. 4, e1000203.
Wood, S.N., 2017. Generalized Additive Models: An Introduction With R. CRC press.
Zhao, X., Zhong, J., Wei, C., Lin, C.-W., Ding, T., 2017. Current perspectives on viable but non-culturable state in foodborne pathogens. Front. Microbiol. 8, 580.