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Further Analysis for Trends in Burdens of Foodborne Disease: Leafy Greens and Raw Milk

M. M. Stephenson
Syracuse University
Nicholas A. Azzolina
Margaret E. Coleman
peg@colemanscientific.org

Coleman Scientific Consulting

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Manuscript Prepared by:

M.M. Stephenson, Syracuse University, Syracuse NY USA

N.A. Azzolina, independent consultant, Green Bay, WI, USA

M.E. Coleman*, Coleman Scientific Consulting, Groton NY 13703 USA

* corresponding author: peg@colemanscientific.org

ABSTRACT

Background Transdisciplinary collaborations with risk analysis practitioners may enhance epidemiologic investigations and expand public health protections in light of federal and state laws and policies.

Methods US outbreak data for a 16-year period (2005-2020) reported in Microsoft Access® data tables were structured using systematic queries and pivot tables for deeper analysis of foodborne public health burdens associated with leafy greens and milk. Trends were examined using graphical representation with confidence intervals estimated using LOESS smoothing, as well as Kendall's tau, the Mann-Kendall test for trends, and Sen's slope testing. For raw milk outbreaks, confidence intervals were estimated for disease severity (hospitalizations per outbreak).

Results No evidence for increasing trends over time for morbidity and mortality was observed for leafy greens and raw and pasteurized milks. Numbers of outbreaks and hospitalizations were higher for raw milk than pasteurized milk. Overall, for raw milk at the state level, numbers and rates of outbreaks, illnesses, and hospitalizations were heterogeneous, and categories of average hospitalizations per outbreak displayed wide confidence intervals.

Conclusion Refocusing on understanding the factors driving lower public health impact on leafy green and raw dairy farm systems may reduce burdens of both communicable and non-communicable disease, increase transparency and collaboration, and promote wider deliberation that supports dietary health and wellness for humans and ecosystems.

Key Words: CDC NORS; data quality; One-Health

1 Introduction

Burdens of communicable (infectious) diseases and non-communicable diseases (NCDs) both have significant impacts on global health and well-being [1]. In 2019, the World Health Organization (WHO) estimated ~17 million deaths from NCDs worldwide, with 2.5 million of those deaths reported in the US largely associated with NCDs and only 0.4% of US deaths (9,955) attributed to diarrheal diseases. While epidemiologic researchers and policy analysts may focus on the burden of disease infectious disease, for this work, infectious disease is considered along with some context to the burden of NCDs. Acknowledging trends over time for both burdens of infectious and NCDs has relevance for decision-making about risks to human health, as well as for resource allocations to assess and monitor risks.

Time-series analysis for completeness was conducted using United States (US) outbreak data reported in the Centers for Disease Control and Prevention (CDC) National Outbreak Reporting System (NORS) from 1998 to 2019 to model disease outbreaks with greater reliability, accounting for seasonality, to better inform policies and improve public health accountability [2]. However, such observational data lacking information on data quality is

correlative, requiring additional data and analysis to establish causality and account for spatial and temporal dependencies [2–4].

Although observational epidemiologic data commonly inform decisions about public health risks, recent scientific and technological advances of the 21st century offer unprecedented opportunities to incorporate collaborative transdisciplinary evidence into assessing, managing, and communicating about risks more broadly and more mechanistically, using methods that estimate uncertainties as well as risks, for both environmental and public-health decision-making [5].The need to incorporate diverse data sources for 21st-century science, including but not limited to epidemiology (e.g., data from both observational and biological or mechanistic pathway/process approaches for pathogenesis, as well as from sociological, cultural, and ecosystem studies), and powerful and robust statistical techniques (including causality assessment) is critical for improving risk-based decision support [5]. Despite the size and complexity of the CDC NORS database, limitations of the data, as well as gaps in knowledge about causality for complex food systems, impose severe vulnerabilities for misinterpreting this body of evidence without rigorous statistical analysis [2,6]. Otherwise, dietary guidance and policies may harm rather than restore human health.

The WHO's 75th World Health Assembly [7] identified the need to strengthen the 'assessment, management, and communication of food risks' in order to achieve sustainable health and food systems, reduce global health threats, and improve ecosystem management. Methods for quantitative microbial risk assessment (QMRA) are commonly applied for communicable diseases attributed to foods, though often using oversimplified simulation models for enteric pathogen-food pairs, with some attention to estimation of confidence intervals for hypothesis testing and decision support [8,9]. Further, recent papers extended QMRA methods to predict epidemic curves and identify potential root causes for more effective prevention of future outbreaks [4,10]. Methods for benefit-risk assessment [11–13] or risk-risk tradeoffs [14–16] seem to be applied more rarely for foodborne risk analysis.

Based on our perception of the need for greater coherence across disciplinary silos for nuanced bodies of data on burdens of disease, microbial ecology, and root cause analysis for complex systems, the authors had undertaken a detailed trend analysis of US outbreak data for all transmission sources from CDC NORS for the years 2005 through 2020 [6], the most recent 16 years of data available at the time of the request [17]. The current analysis of the CDC NORS dataset extends our previous work to address trends for foods of concern in this decade, leafy greens and raw and pasteurized milks.

Limitations of CDC NORS data documented in the Stephenson study included the small numbers of milkborne outbreaks per state (e.g., ≤2), particularly for raw milk regulated at the state level. Low numbers of outbreaks and severe outcomes (hospitalizations and deaths) per state are unstable estimates that should be interpreted cautiously and with rigorous statistical analysis. Data documented from this 16-year period for milkborne mortality, 4 deaths associated with pasteurized milk, and 1 confirmed death associated with raw milk [6,18], are

too sparse for reliable predictions of the likelihood or relative risks of mortality. Therefore, this study provides a more detailed analysis of hospitalization numbers and rates associated with raw milk by state, in line with the dataset's state-level regulatory structure.

The current work examines CDC NORS data for leafy greens and raw and pasteurized milks for the period 2005-2020 in more detail, given ongoing concerns about the safety and security of these commodities. Although the 2024 Stephenson study documented that milkborne trends in outbreaks, illnesses, and hospitalizations were not increasing over the 16-year period [6], the authors noted higher numbers of hospitalizations for raw milk compared with pasteurized, differences that merit deeper analysis.

2 Methods

2.1 Epidemiological Data

Outbreak data were obtained from the CDC's National Outbreak Reporting System (NORS) for 2005–2020 [17]. Each outbreak record included a unique CDC outbreak identification number, the exposure state, and the date of first illness onset. Counts of outbreaks, illnesses, hospitalizations, and deaths, as well as outbreak etiology, were extracted for all foodborne sources, although the present analyses focus on leafy greens and raw milk. Previous work described the major NORS database tables and their relationships, which also served as the basis for the current analysis. Further details on NORS data are available online (https://www.cdc.gov/nors/index.html).

Temporal trends in leafy green outbreaks, illnesses, and hospitalizations were evaluated graphically using smoothing splines and Locally Weighted Scatterplot Smoothing (LOESS) with 95% confidence intervals. LOESS curves were used for graphical visualization of temporal patterns and were not interpreted as formal hypothesis tests.

Monthly leafy-green outbreak and illness counts were evaluated for monotonic temporal trend using Kendall's tau and Mann-Kendall trend testing [19,20]. Sen's slope was used to estimate the median monthly rate of change and its 95% confidence interval [21]. Pivot-table summaries and exploratory graphics were developed in Microsoft Excel®, while additional statistical analyses and graphical smoothing were conducted in R [22] and Minitab® [23].

2.2 Population-Scaling

State-year population estimates were obtained from three US Census Bureau tables described by Stephenson et al. (Stephenson et al. 2024). Population estimates were matched to outbreak records by state and year, resulting in a combined dataset containing outbreak counts and corresponding population estimates for each state-year combination.

Annual outbreak, illness, and hospitalization counts were standardized as rates per one million persons (outbreaks/1MM, illnesses/1MM, and hospitalizations/1MM, respectively). Supplementary Table S1 from

Stephenson et al. (Stephenson et al. 2024) served as the basis for the present analyses of state-year outbreak, illness, and hospitalization rates associated with raw milk.

2.3 Analysis of Severity

State-level measures of raw milk outbreak severity were calculated while preserving the structure of Stephenson Table S1. Total outbreaks and hospitalizations were aggregated by state across the 2005-2020 study period. For states reporting at least one outbreak, the mean number of hospitalizations per outbreak (H/O) was calculated as a measure of outbreak severity. The number of state-years contributing non-zero outbreak observations was also recorded.

Poisson-based 95% confidence intervals for hospitalization rates per outbreak were calculated using chi-square approximations. Estimates based on small numbers of outbreaks were interpreted cautiously because of increased statistical uncertainty.

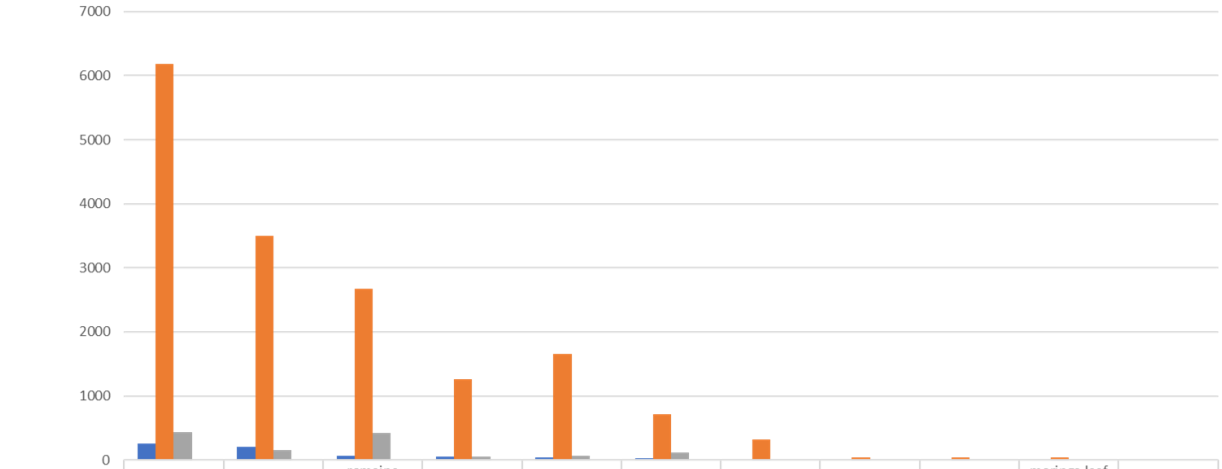
2.4 Estimates of Annual Outbreak Illnesses per Million Raw Milk Servings

Previously reported data on retail raw milk production from a California dairy farm for 2005-2024, cited previously [6,24], were converted from gallons to millions of 250-mL servings. The 83 outbreak-associated illnesses reported during the 16-year study period and 171 outbreak-associated illnesses reported subsequently [25] were expressed as annual statewide illness counts and standardized to annual rates per 100,000 retail raw milk servings.

3 Results

3.1 Trends for Leafy Greens

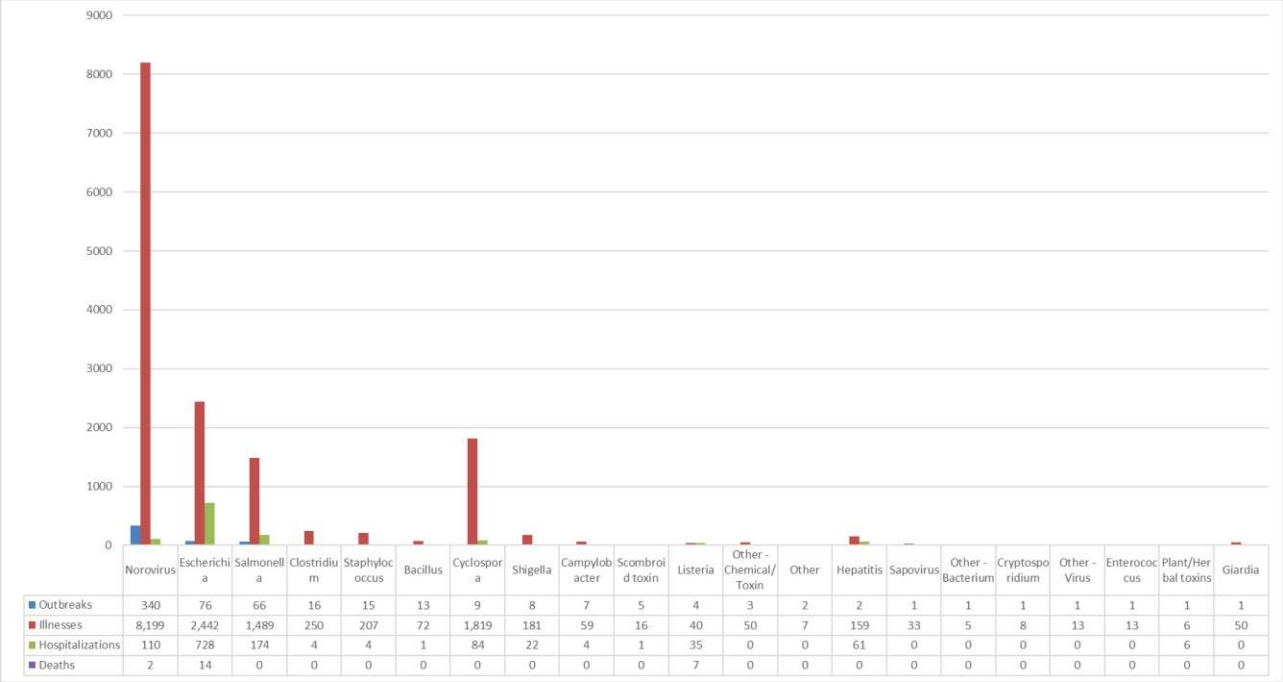
Leafy greens contributed to 671 outbreaks, 16,434 illnesses, 1,250 hospitalizations, and 23 deaths over the 16-year period (Fig. 1). Norovirus contributed to the highest numbers of leafy green outbreaks and illnesses (340 outbreaks and 8,199 illnesses, while pathogenic *E. coli* contributed the highest numbers of hospitalizations and deaths from leafy greens (728 hospitalizations and 14 deaths; Fig. 2). Three bacterial pathogens contributed more than 1,000 illnesses from leafy greens (2,442 illnesses for pathogenic *E. coli*, 1,819 for *Cyclospora*, and 1,489 for *Salmonella*; Fig. 2).



	leafy green	lettuce	romaine lettuce	leaf lettuce	cabbage	spinach	green salad	kale	mesclun mix	moringa leaf powder	salad
Outbreaks	254	206	65	50	41	32	14	5	2	1	1
Illnesses	6,188	3,501	2,673	1,265	1,659	712	323	37	37	35	4
Hospitalizations	434	148	417	49	66	119	6	5	0	6	0
Deaths	10	3	5	0	0	5	0	0	0	0	0

Fig. 1. Leafy green outbreaks by food grouping (CDC, 2021; 2005-2020)

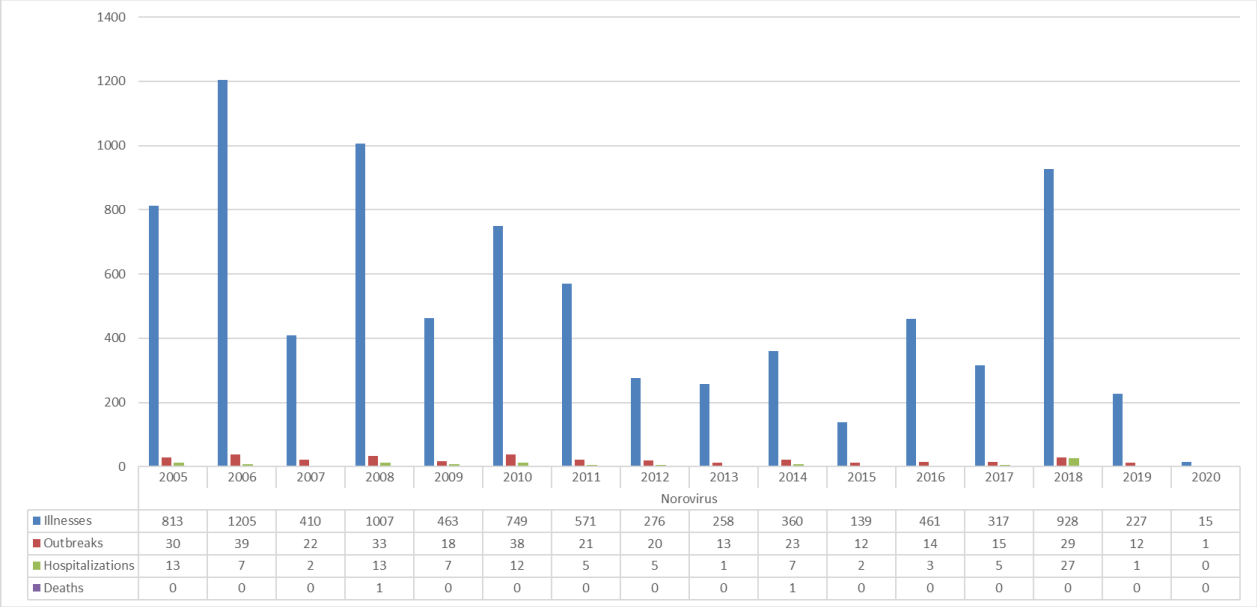
Beyond primary foodborne transmission, leafy greens were also associated with 73 confirmed secondary illnesses across 29 distinct outbreaks. Where a secondary transmission mode was recorded, person-to-person contact was the most common (28 outbreaks), followed by indeterminate or unknown modes (23 outbreaks), and other foods (10 outbreaks). Among confirmed secondary illnesses, Norovirus was the most frequently implicated pathogen (36 cases), followed by *Salmonella* (19 cases), Shiga toxin-producing *E. coli* (12 cases), and Hepatitis A (6 cases). Two outbreaks illustrate the severity of secondary transmission involving leafy greens. The 2006 multistate *E. coli* outbreak associated with spinach included 6 confirmed secondary illnesses among 238 total cases, while the 2016 multistate Hepatitis A outbreak associated with kale and spinach included 6 confirmed secondary illnesses among 144 total cases.



	Norovirus	Escherichia	Salmonella	Clostridium	Staphylococcus	Bacillus	Cyclospora	Shigella	Campylobacter	Scombroid toxin	Listeria	Other - Chemical/ Toxin	Other	Hepatitis	Sapovirus	Other - Bacterium	Cryptosporidium	Other - Virus	Enterococcus	Plant/Herbal toxins	Giardia
Outbreaks	340	76	66	16	15	13	9	8	7	5	4	3	2	2	1	1	1	1	1	1	1
Illnesses	8,199	2,442	1,489	250	207	72	1,819	181	59	16	40	50	7	159	33	5	8	13	13	6	50
Hospitalizations	110	728	174	4	4	1	84	22	4	1	35	0	0	61	0	0	0	0	0	6	0
Deaths	2	14	0	0	0	0	0	0	0	0	7	0	0	0	0	0	0	0	0	0	0

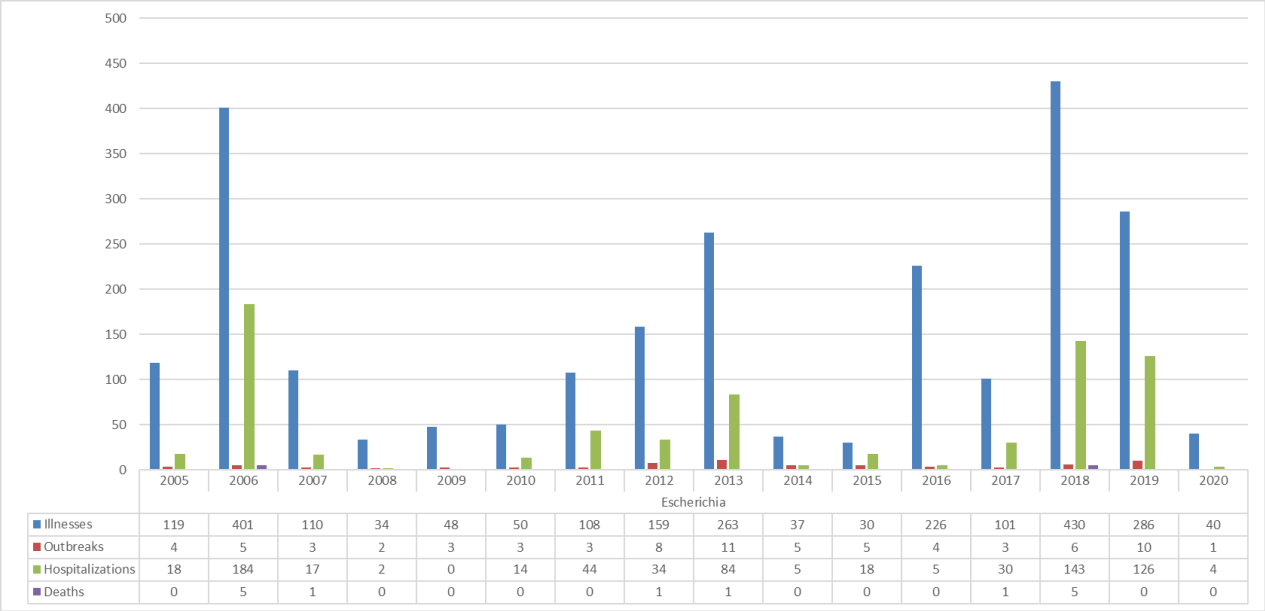
Fig. 2. Leafy green outbreaks by pathogen association (CDC, 2021; 2005-2020).

Norovirus contributes significantly to the burden of illness associated with leafy greens, and the trend does not appear to be decreasing (Fig. 3a). In 2018, 928 illnesses and 27 hospitalizations were attributed to leafy green contamination by Norovirus (Fig. 3a). For *E. coli* O157:H7, the trend may be increasing, with four of the highest burdens of illness occurring from 2013 to 2019 (Fig. 3b). Similarly, the trends may be increasing for salmonellosis (Fig. 3c), with the two highest numbers of annual illnesses recorded in 2015 and 2017, and for *Cyclospora* (Fig. 3d).



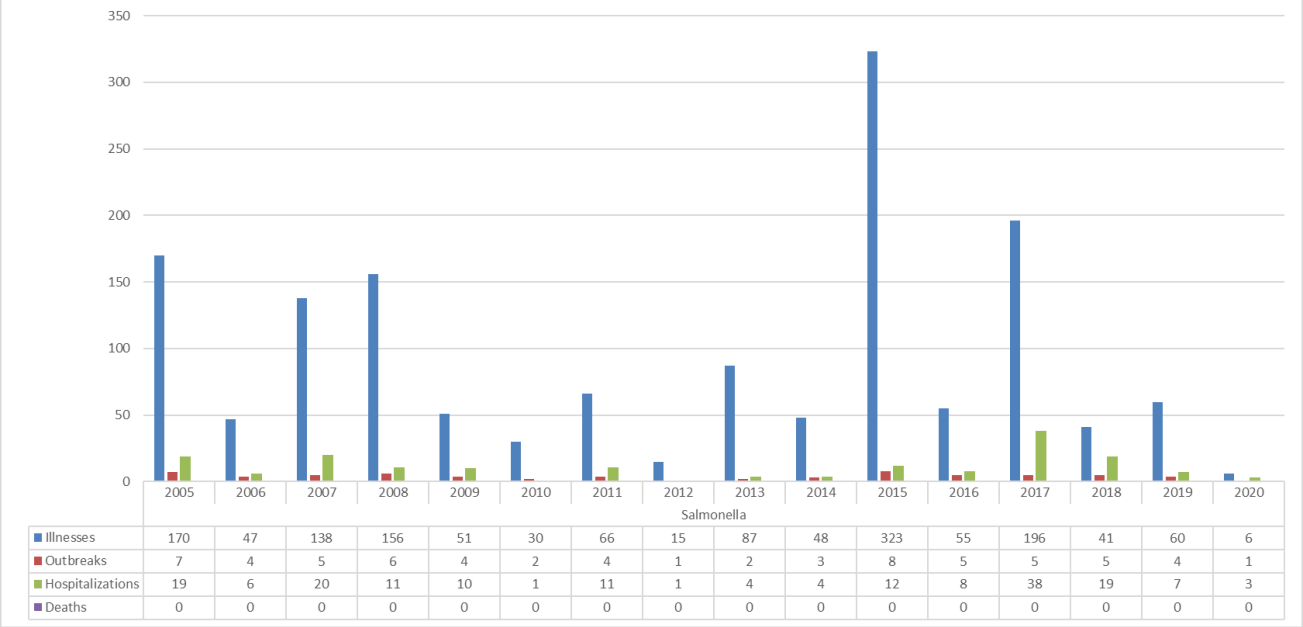
	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
	Norovirus															
Illnesses	813	1205	410	1007	463	749	571	276	258	360	139	461	317	928	227	15
Outbreaks	30	39	22	33	18	38	21	20	13	23	12	14	15	29	12	1
Hospitalizations	13	7	2	13	7	12	5	5	1	7	2	3	5	27	1	0
Deaths	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0

Norovirus



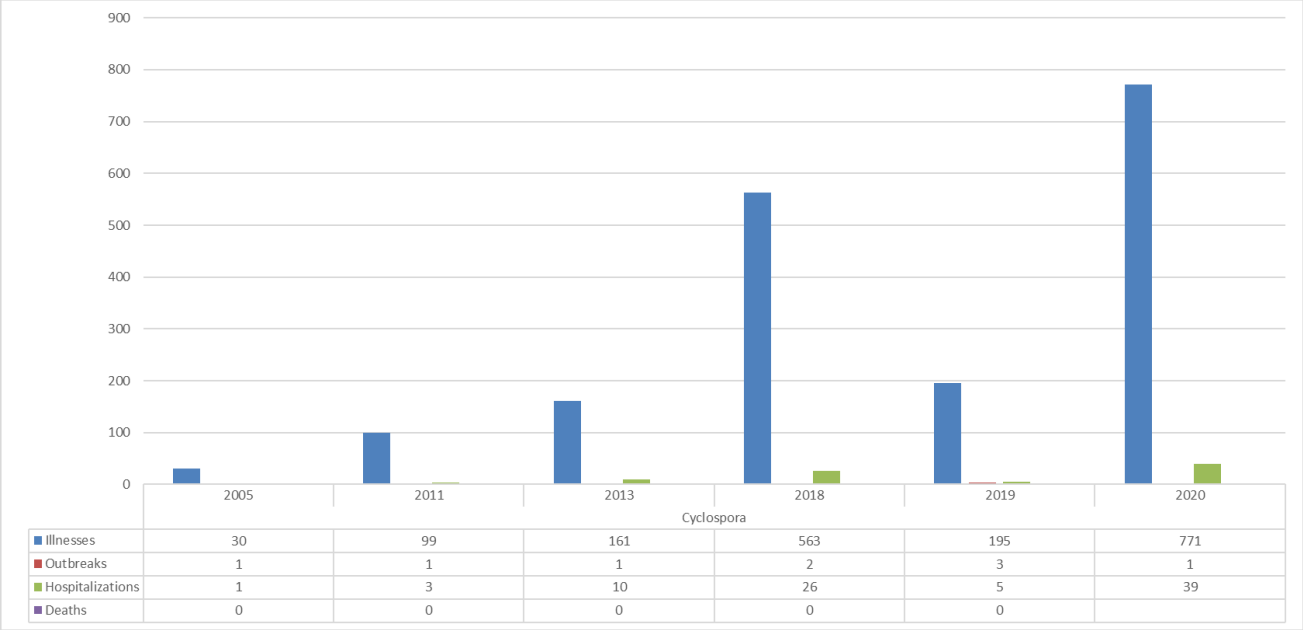
Escherichia	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Illnesses	119	401	110	34	48	50	108	159	263	37	30	226	101	430	286	40
Outbreaks	4	5	3	2	3	3	3	8	11	5	5	4	3	6	10	1
Hospitalizations	18	184	17	2	0	14	44	34	84	5	18	5	30	143	126	4
Deaths	0	5	1	0	0	0	0	1	1	0	0	0	1	5	0	0

***E. coli* O157:H7**



Salmonella	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Illnesses	170	47	138	156	51	30	66	15	87	48	323	55	196	41	60	6
Outbreaks	7	4	5	6	4	2	4	1	2	3	8	5	5	5	4	1
Hospitalizations	19	6	20	11	10	1	11	1	4	4	12	8	38	19	7	3
Deaths	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Salmonella

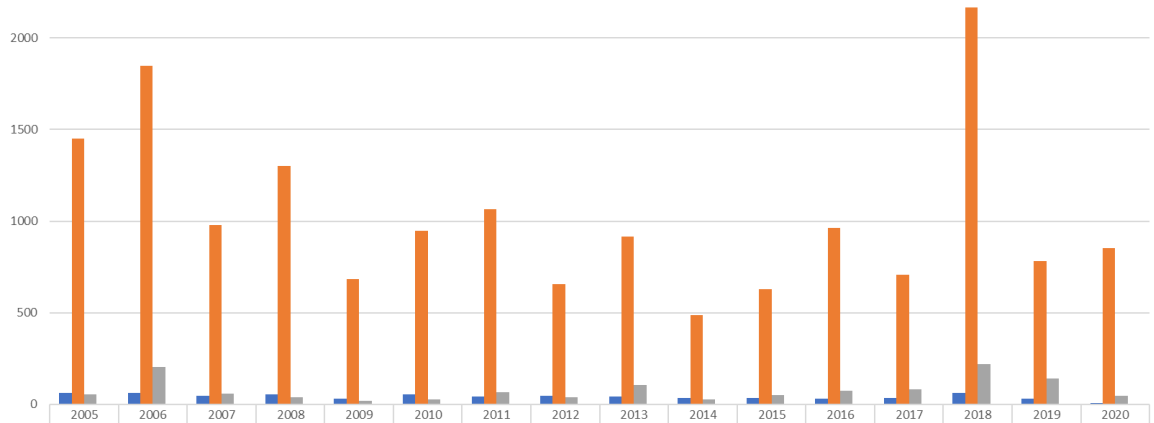


	2005	2011	2013	2018	2019	2020
	Cyclospora					
Illnesses	30	99	161	563	195	771
Outbreaks	1	1	1	2	3	1
Hospitalizations	1	3	10	26	5	39
Deaths	0	0	0	0	0	

Cyclospora

Fig. 3. Leafy green outbreaks by pathogen and year for top 4 pathogens (CDC, 2021; 2005-2020)

Graphical analysis of trends for illnesses, outbreaks, hospitalizations, and deaths associated with leafy greens is provided in Fig. 4. More detailed analysis is provided in Figures 5 and 6, reporting illnesses and outbreaks from date of first illness, along with 95% confidence intervals. No evidence of trends in numbers of illnesses were apparent in this period (Fig. 5), with suggestive but weak evidence of decreasing trends for leafy green outbreaks for 2020 (Fig. 6).



	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Outbreaks	62	64	45	53	30	54	41	45	44	36	34	32	33	61	30	7
Illnesses	1,450	1,848	979	1,302	684	949	1,064	657	917	486	628	961	709	2,165	781	854
Hospitalizations	55	204	57	40	18	27	68	40	106	25	51	73	82	219	139	46
Deaths	0	5	1	1	0	0	0	1	1	4	1	0	4	5	0	0

Fig. 4. Leafy green outbreaks, illnesses, hospitalizations, and deaths by year (CDC, 2021; 2005-2020)

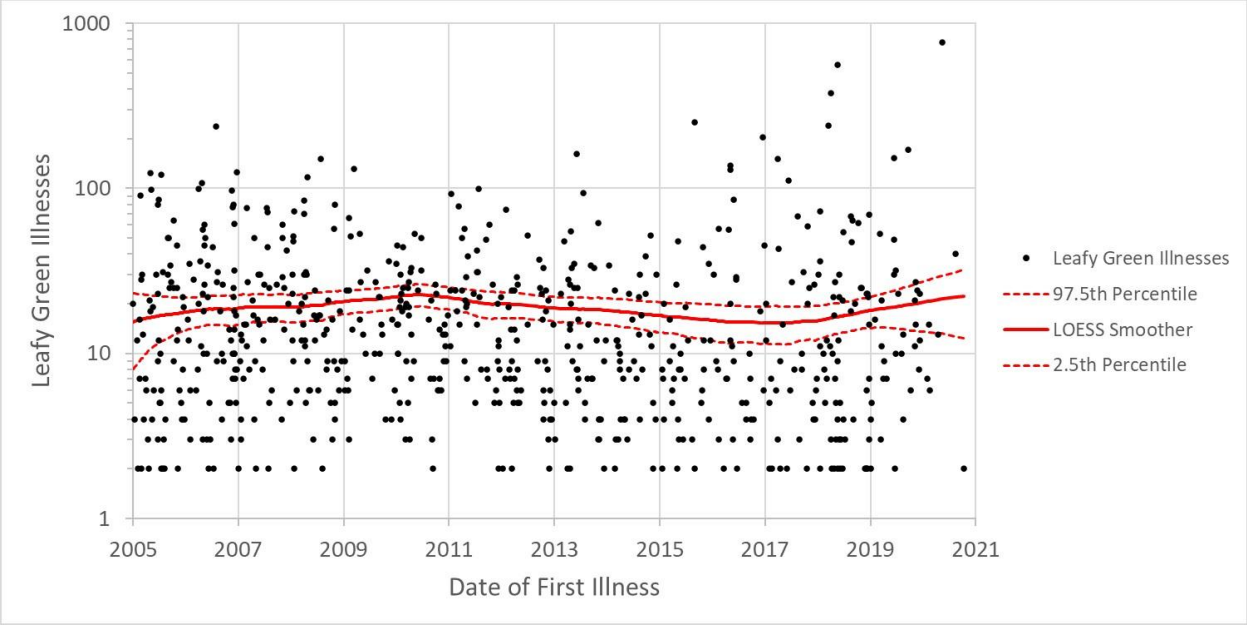


Fig. 5. Leafy green illnesses by date first ill (CDC, 2021; 2005-2020) depicted using LOESS Smother (red lines) and 95% confidence intervals (red dashed lines)

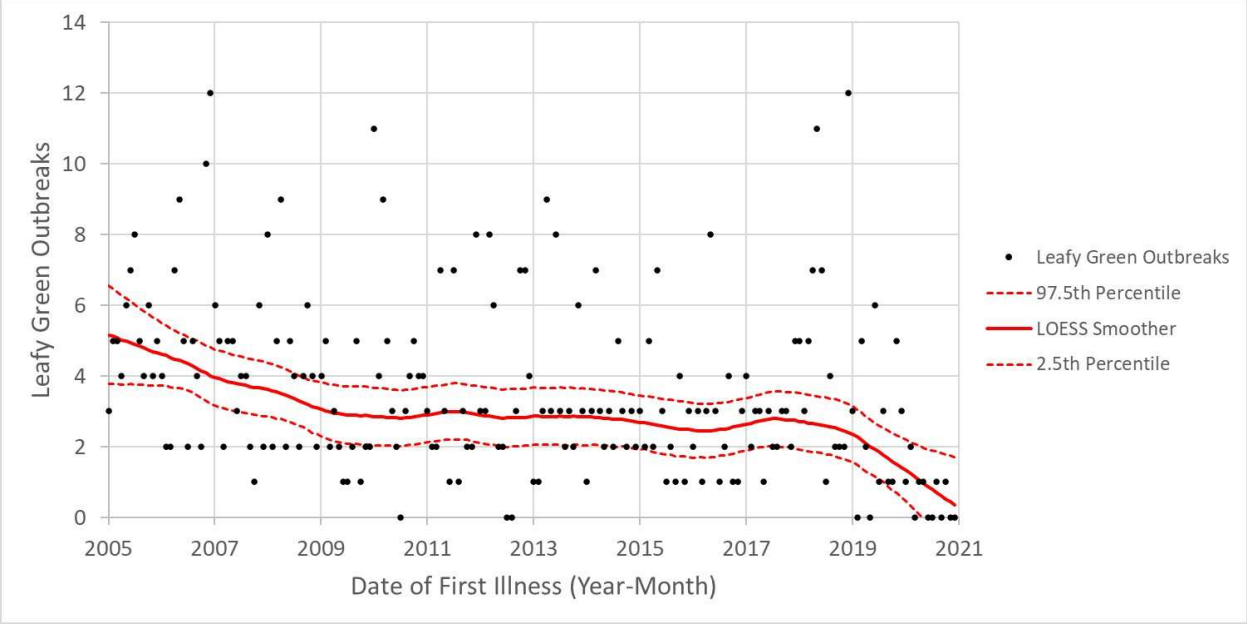


Fig. 6. Leafy green outbreaks by date first ill (CDC, 2021; 2005-2020) depicted using LOESS Smoother (red lines) and 95% confidence intervals (red dashed lines)

For testing of seasonal trends for monthly leafy-green outbreak and illness counts, a non-significant Mann–Kendall test, together with a Sen slope confidence interval that included zero, was interpreted as indicating no detectable monotonic trend over the study period. Monthly leafy-green illnesses exhibited a weak but statistically significant

downward monotonic trend over the study period (Kendall's $\tau = -0.145$, $p = 0.0038$). Sen's slope estimated an average decline of approximately 2.4 illnesses per year, although substantial month-to-month variability remained evident.

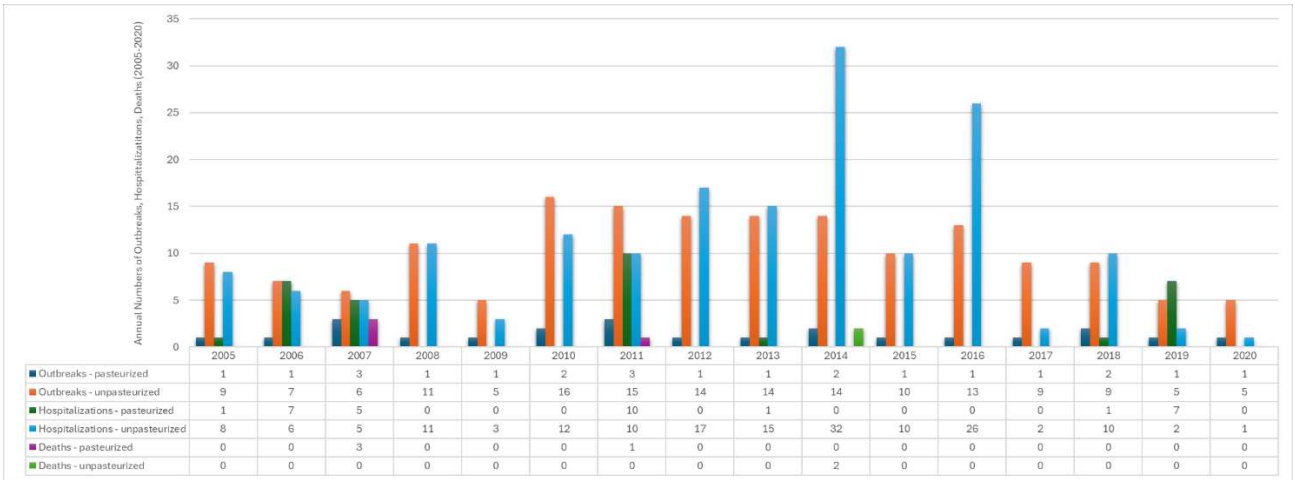
Monthly leafy-green outbreaks also demonstrated a statistically significant downward monotonic trend (Kendall's $\tau = -0.273$, $p < 0.001$). Sen's slope estimated an average reduction of approximately 0.16 outbreaks per year. LOESS smoothing suggested that temporal patterns were nonlinear and characterized by periods of relative stability and fluctuation rather than a uniform decline.

The pronounced decline near the end of the series should be interpreted cautiously, as reporting and surveillance practices may have been affected during the COVID-19 pandemic.

3.2 Trends and Deeper Analysis for Milkborne Disease Severity

Results on the numbers of annual milkborne outbreaks, hospitalizations, and deaths over the 16-year period reported in Figure 10 of the 2024 Stephenson study were rescaled in Figure 7 below, with the numbers of illnesses removed to increase visual clarity. Note that secondary cases were reported for 10 of 162 raw milk outbreaks (7 STEC cases; 4 campylobacteriosis cases), but none were reported for pasteurized milk in this period. One to 3 outbreaks per year were reported for pasteurized milk, with 5-16 outbreaks per year for raw milk. Annual numbers of hospitalizations varied from 0 to 10 for pasteurized milk and from 1 to 32 for raw milk. For 12 of 16 years, the number of hospitalizations was higher in raw milk. Over time, the annual numbers of raw milk outbreaks and hospitalizations appeared to be on the decline since 2010 and 2014, respectively. However, additional scrutiny of the data structure is required due to state-specific regulatory factors and other potential confounders.

Note that 4 deaths were reported for pasteurized milk (3 in 2007 and 1 in 2011), and a single death was confirmed for raw milk consumers in 2014 [6,18]. As previously noted, data for milkborne deaths is too sparse for reliable prediction of future milkborne mortality.



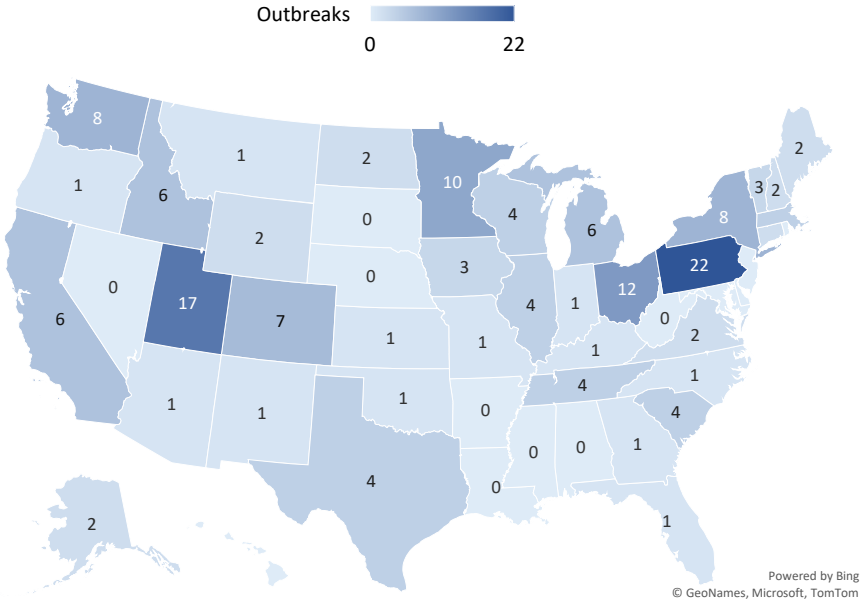
	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Outbreaks - pasteurized	1	1	3	1	1	2	3	1	1	2	1	1	1	2	1	1
Outbreaks - unpasteurized	9	7	6	11	5	16	15	14	14	14	10	13	9	9	5	5
Hospitalizations - pasteurized	1	7	5	0	0	0	10	0	1	0	0	0	0	1	7	0
Hospitalizations - unpasteurized	8	6	5	11	3	12	10	17	15	32	10	26	2	10	2	1
Deaths - pasteurized	0	0	3	0	0	0	1	0	0	0	0	0	0	0	0	0
Deaths - unpasteurized	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0

Fig. 7. Annual trends for numbers of milkborne outbreaks, hospitalizations, and deaths reported from 2005-2020 (rescaled from Figure 10, [6]). Note that a single death in 2014 was confirmed for raw milk consumers.

3.2.1 State-Level Analysis

As previously reported for this dataset [6], no temporal trend was detected for raw milk outbreaks or outbreak rates at either the state or national level ((Stephenson et al. 2024), Figures 9 and 13-15). State-level patterns in outbreak counts and population-adjusted outbreak rates (Figure 8) were heterogeneous, as might be expected given the relative sparsity of raw milk outbreaks, differences in state populations, and variation in state regulatory frameworks.

The upper panel of Figure 8 shows that most states (35/51 jurisdictions, including the District of Columbia) reported fewer than three outbreaks during the 2005-2020 study period, whereas two states reported notably higher totals (UT, 17 outbreaks; PA, 22 outbreaks). The lower panel similarly demonstrates that most states (30/51 jurisdictions) reported outbreak rates below 0.03 outbreaks per million person-years, whereas UT and VT reported higher population-adjusted outbreak rates (0.37 and 0.30 outbreaks per million person-years, respectively).



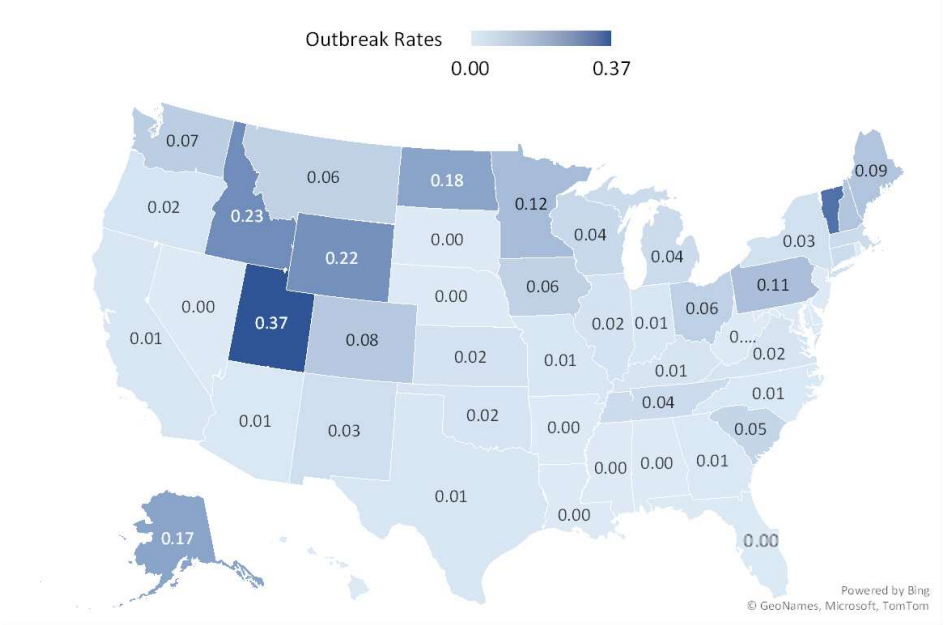


Figure 8. Upper panel: number of raw milk outbreaks by state (Figure 9, [6]); lower panel: rates of raw milk outbreaks by state adjusted for state populations expressed in numbers of outbreaks per million person-years, as reported in Supplemental Table S1 [6].

Figure 9 provides an integrated visualization of state-level outbreak, illness, and hospitalization burdens, along with corresponding population-adjusted rates. Overall, the predominance of low counts and low rates across most states is consistent with the relatively limited reported public health impacts of raw milk outbreaks during the study period. However, substantial heterogeneity among states was evident.

State	Outbreaks	Illnesses	Hospitalizations	Outbreak Rate per One Million People	Illness Rate per One Million People	Hospitalization Rate per One Million People
Alabama	0	0	0	0.00	0.00	0.00
Alaska	2	47	2	0.17	4.10	0.17
Arizona	1	13	1	0.01	0.12	0.01
Arkansas	0	0	0	0.00	0.00	0.00
California	6	83	11	0.01	0.14	0.02
Colorado	7	164	7	0.08	1.96	0.08
Connecticut	2	21	6	0.04	0.37	0.11
Delaware	0	0	0	0.00	0.00	0.00
District of Columbia	0	0	0	0.00	0.00	0.00
Florida	1	3	0	0.00	0.01	0.00
Georgia	1	8	0	0.01	0.05	0.00
Hawaii	0	0	0	0.00	0.00	0.00
Idaho	6	32	4	0.23	1.23	0.15
Illinois	4	38	2	0.02	0.19	0.01
Indiana	1	25	0	0.01	0.24	0.00
Iowa	3	47	0	0.06	0.95	0.00
Kansas	1	4	0	0.02	0.09	0.00
Kentucky	1	4	4	0.01	0.06	0.06
Louisiana	0	0	0	0.00	0.00	0.00
Maine	2	8	0	0.09	0.38	0.00
Maryland	0	0	0	0.00	0.00	0.00
Massachusetts	4	14	3	0.04	0.13	0.03
Michigan	6	30	4	0.04	0.19	0.03
Minnesota	10	51	11	0.12	0.59	0.13
Mississippi	0	0	0	0.00	0.00	0.00
Missouri	1	13	0	0.01	0.14	0.00
Montana	1	7	3	0.06	0.43	0.19
Nebraska	0	0	0	0.00	0.00	0.00
Nevada	0	0	0	0.00	0.00	0.00
New Hampshire	2	5	1	0.09	0.23	0.05
New Jersey	0	0	0	0.00	0.00	0.00
New Mexico	1	6	0	0.03	0.18	0.00
New York	8	58	4	0.03	0.19	0.01
North Carolina	1	3	0	0.01	0.02	0.00
North Dakota	2	10	0	0.18	0.88	0.00
Ohio	12	50	7	0.06	0.27	0.04
Oklahoma	1	8	0	0.02	0.13	0.00
Oregon	1	4	1	0.02	0.06	0.02
Pennsylvania	22	286	20	0.11	1.40	0.10
Rhode Island	0	0	0	0.00	0.00	0.00
South Carolina	4	51	7	0.05	0.67	0.09
South Dakota	0	0	0	0.00	0.00	0.00
Tennessee	4	31	12	0.04	0.30	0.12
Texas	4	15	1	0.01	0.04	0.00
Utah	17	249	17	0.37	5.41	0.37
Vermont	3	23	3	0.30	2.30	0.30
Virginia	2	23	7	0.02	0.18	0.05
Washington	8	38	5	0.07	0.34	0.04
West Virginia	0	0	0	0.00	0.00	0.00
Wisconsin	4	109	13	0.04	1.19	0.14
Wyoming	2	14	2	0.22	1.55	0.22

Figure 9. Summary of raw milk outbreaks, illnesses, and hospitalizations from 2005 to 2020, as reported in Supplemental Table S1, [6]. Conditional formatting was used to show bar lengths proportional to the total counts or rates within each column.

Several large-population states, particularly CA and PA, reported comparatively larger absolute numbers of illnesses and hospitalizations while maintaining relatively modest population-adjusted rates. In contrast, smaller-population states, including AK, ID, MT, VT, and WY, exhibited comparatively elevated population-adjusted illness or hospitalization rates despite relatively few reported outbreaks. UT and WI demonstrated elevated burdens, as

indicated by both absolute counts and population-adjusted rates, suggesting comparatively greater outbreak-associated impacts during the study period.

These findings should be interpreted cautiously because outbreak surveillance data are sparse and may be influenced by differences in reporting practices, outbreak detection, healthcare utilization, and regulatory oversight across states.

3.2.2 Analysis of Severity

State-level measures of outbreak severity exhibited substantial variability when the state-year structure of Stephenson Table S1 was preserved (Figure 10). Severity was summarized as the mean number of hospitalizations per outbreak (H/O) aggregated across the 2005-2020 study period. Additional information is provided using color coding corresponding to year-2020 legal access mode classifications (green, retail; blue, on-farm sales; purple, herdshare; orange, pet food; gray, prohibited/illegal) to provide visual context for potential differences in severity and legal access mode among states.

Categories for severity across states:

- 16 states had ≥1 hospitalization/outbreak on average over the 16 years period (range 1-4 hospitalization/outbreak (AK, AZ, CA, CO, CT, KY, MN, MT, OR, SC, TN, UT, VA, VT, WI, WY);
- 11 states had <1 hospitalization/outbreak on average (ID, IL, MA, MI, MN, NH, NY, OH, PA, TX, WA);
- 10 states reported outbreaks, but no hospitalizations (FL, GA, IN, IO, KS, ME, MO, NM, NC, ND, OK); and
- 14 states reported no outbreaks during the study period (AL, AR, DE, DC, HI, LA, MD, MS, NE, NV, NJ, RI, SD, WV).

No clear clustering of outbreak severity by legal access mode was evident based on the visual distribution of state classifications, although, as expected, states prohibiting access were represented in the lower two severity groupings. However, interpretation should be cautious because the CDC NORS database does not identify whether outbreaks originated from licensed or unlicensed producers and does not capture legal access mode or changes over time. Between 2005 and 2020, 15 state-level legal changes increasing raw milk access were identified.

Because many states reported relatively few outbreaks, several severity estimates had wide confidence intervals and should be interpreted cautiously.

State	N Outbreaks	N Hospitalizations	Average: # Hospitalizations per Outbreak	Lower 95% CI	Upper 95% CI
Alabama	0	0			
Alaska	2	2	1.00	0.12	3.61
Arizona	1	1	1.00	0.03	5.57
Arkansas	0	0			
California	6	11	1.83	0.92	3.28
Colorado	7	7	1.00	0.40	2.06
Connecticut	2	6	3.00	1.10	6.53
Delaware	0	0			
District of Columbia	0	0			
Florida	1	0	0.00	0.00	3.69
Georgia	1	0	0.00	0.00	3.69
Hawaii	0	0			
Idaho	6	4	0.67	0.18	1.71
Illinois	4	2	0.50	0.06	1.81
Indiana	1	0	0.00	0.00	3.69
Iowa	3	0	0.00	0.00	1.23
Kansas	1	0	0.00	0.00	3.69
Kentucky	1	4	4.00	1.09	10.24
Louisiana	0	0			
Maine	2	0	0.00	0.00	1.84
Maryland	0	0			
Massachusetts	4	3	0.75	0.15	2.19
Michigan	6	4	0.67	0.18	1.71
Minnesota	10	11	1.10	0.55	1.97
Mississippi	0	0			
Missouri	1	0	0.00	0.00	3.69
Montana	1	3	3.00	0.62	8.77
Nebraska	0	0			
Nevada	0	0			
New Hampshire	2	1	0.50	0.01	2.79
New Jersey	0	0			
New Mexico	1	0	0.00	0.00	3.69
New York	8	4	0.50	0.14	1.28
North Carolina	1	0	0.00	0.00	3.69
North Dakota	2	0	0.00	0.00	1.84
Ohio	12	7	0.58	0.23	1.20
Oklahoma	1	0	0.00	0.00	3.69
Oregon	1	1	1.00	0.03	5.57
Pennsylvania	22	20	0.91	0.56	1.40
Rhode Island	0	0			
South Carolina	4	7	1.75	0.70	3.61
South Dakota	0	0			
Tennessee	4	12	3.00	1.55	5.24
Texas	4	1	0.25	0.01	1.39
Utah	17	17	1.00	0.58	1.60
Vermont	3	3	1.00	0.21	2.92
Virginia	2	7	3.50	1.41	7.21
Washington	8	5	0.63	0.20	1.46
West Virginia	0	0			
Wisconsin	4	13	3.25	1.73	5.56
Wyoming	2	2	1.00	0.12	3.61

Figure 10. Distribution of raw milk outbreaks, hospitalizations, and average hospitalizations per outbreak, and confidence intervals by state from 2005 to 2020. Conditional formatting was used to show bar lengths proportional to the total counts within each column.

3.2.3 Estimates of Annual Outbreak Illnesses per Raw Milk Serving

While adjusting outbreak data for ingested servings per consumer is a desirable metric for assessing public health burdens in addition to numbers and population-adjusted rates of outbreak metrics, reliable national data for numbers of US consumers actually exposed to raw milk over time do not exist. One dataset for California (CA) retail raw milk production cited previously (Fig. 14 in the Stephenson study) depicted increasing production over this period from approximately 0.6 million gallons in 2005 to 1.7 million gallons in 2020. Figure 11 below extends the production and outbreaks data through 2024 with gallons converted to millions of 240 mL servings. Annual retail production data for this CA farm was annotated with numbers of raw milk illnesses for the entire state per 100,000 servings.

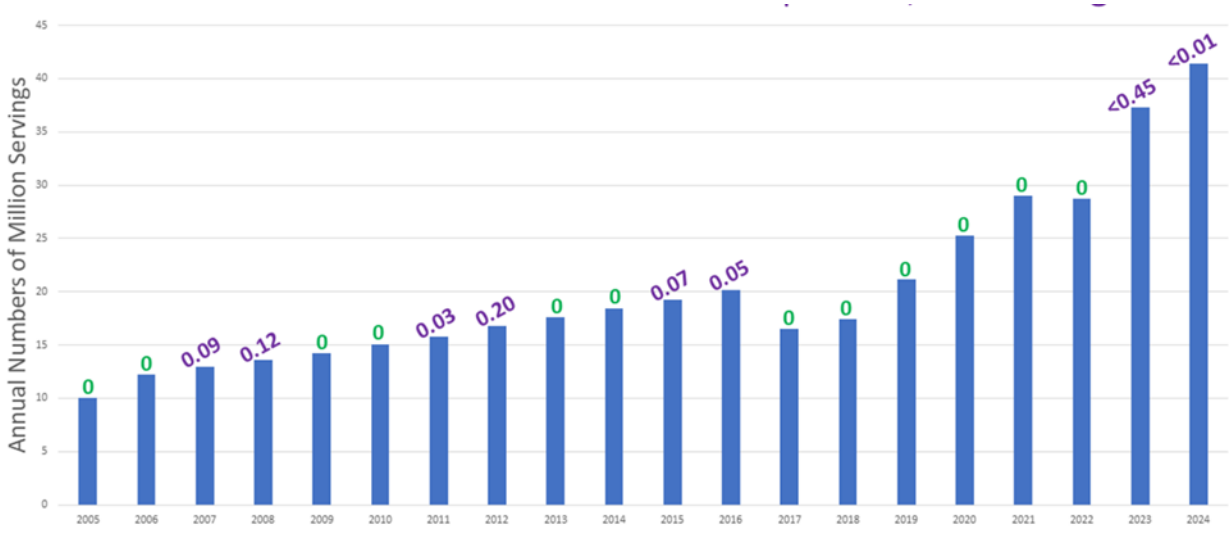


Figure 11. Annual millions of servings of retail raw milk from one California farm, with annotations of the number of illnesses reported in the state per 100,000 servings from one producer [17,25].

The number of illnesses per 100,000 servings incorporated data from the 6 CA outbreaks in the CDC dataset [17] and a subsequent outbreak [25]. In 12 of 20 years, no outbreaks were reported (green text annotations in Figure 11). In 8 years, when outbreaks were reported in CA, illness rates ranged from <0.01 illnesses per 100,000 servings to <0.45 illnesses per 100,000 servings (purple text annotations in Figure 11). Note that adjusting for production of other licensed CA dairies would likely reduce these estimates.

4 DISCUSSION

Researchers around the world [26–28] acknowledged the need for multisector and transdisciplinary collaborations consistent with One-Health approaches for safe and sustainable food systems that promote human, animal, and ecosystem health in the 21st century. Replacing fragmented, simplistic analyses within traditional disciplinary silos with transdisciplinary collaborations is essential to optimize food safety and food security in complex ecosystems. Though trends for leafy greens and raw milk are not increasing, weak evidence suggesting potential declines may indicate that a more multidisciplinary systems focus of risk management, not only on farms with observed

outbreaks (failures in food production, processing, storage, and/or distribution systems), but on farms without outbreaks (or with low numbers or rates of illness and hospitalization), could contribute to more effective public health protection.

Context is needed to put the trends for the burdens of infectious diseases in the US discussed herein in broader perspective. Infectious diseases including diarrhea were not listed among the top ten causes of mortality in the US for 2019 by the WHO [1]. Rather, the major burdens of disease (heart disease, pulmonary disease, stroke, and diabetes) are potentially linked to unhealthy diet [29]. Further, scientific and social or cultural advances are needed to transform food systems to meet Sustainable Development Goals, reducing malnutrition (stunting, wasting, overweight, and obesity) and enhancing availability, accessibility, affordability, and resilience of safe, biodiverse, and nutritious foods [30]. Consideration of minimally processed fruits and vegetables from small, local family farmers described in the FAO report are also relevant for local dairies raising pastured cows, with potential to foster economic, social, and environmental sustainability. Moving the world towards more affordable, healthy diets that enhance human health, reduce the burden of both infectious and non-communicable diseases, and lower rates of decline in land, water, and environmental resources is critically important in these times of conflict and unrest. A similar urgent need for holistic reforms to food systems was identified in a US report by the National Academies [31], highlighting the complex interrelationships of science, economics, and cultural or social science studies for more effective policy making, in the US and globally, in light of damages to ecological systems degrading land, water, and biodiversity.

The US CDC NORS data analyzed herein were generated from voluntary passive surveillance systems at local, state, and territorial levels and are subject to limitations in data quality and completeness, as documented previously [2,6]. Variability in reporting by site and transmission mode may introduce biases in NORS data [32]. NORS data are incomplete for many variables relevant to assessing risk, including: attack rate (numbers ill/numbers exposed), age range of cases, signs and symptoms, point of contamination in the food chain from production to consumption, identification of the outbreak strain in suspect foods or other sources, and contributing factors to illness and its severity. Other confounding factors may include immune status of cases and underlying health conditions, predisposing factors (diet, malnutrition, pharmaceuticals, polluted environments, poverty, cultural stressors), and doses of pathogens ingested, inhaled, or contacted. NORS is unlikely to include key factors from a risk analysis perspective: data quality, attack rates, and information on doses or levels of pathogens ingested by consumers, stratified by health outcome. In summary, the NORS data may not be generalizable to future outbreaks or illnesses, and caution is warranted for making predictions based on these data, particularly in the absence of rigorous statistical analysis.

This section focuses on aspects of trends in infectious disease associated with leafy greens and milk that intersect with the need to incorporate systems analysis and quality of risk- and risk-benefit analysis, consistent with One-Health approaches, to more transparently and effectively balance risks to human health and the planet.

4.2.1 Annual and Seasonal Trends for Leafy Greens

Leafy greens were associated with a substantial public health burden (16,434 illnesses and 73 secondary illnesses), as well as a high public health burden of severe disease (1,250 hospitalizations and 23 deaths) over the recent 16-year period ([17]; Figures 1-6). Despite nearly two decades of government and industry collaborations after the 2006 outbreak that sickened 238 people, 5 fatally [33], leafy greens continue to cause significant human morbidity and mortality (Fig. 4). Although Norovirus dominated numbers of illnesses and outbreaks for leafy greens (8,199 illnesses and 340 outbreaks, as well as 110 hospitalizations and 2 deaths), Shiga toxigenic *E. coli* (STEC) dominated severe effects in leafy greens (728 hospitalizations and 14 deaths, as well as 76 leafy green outbreaks and 2,442 illnesses) in this period (Fig. 3). Also, *Cyclospora* and *Salmonella* contamination of leafy greens accounted for more than 1,000 illnesses each and 84 and 174 hospitalizations, respectively, though no deaths.

It is possible that the greater severity of STEC outbreaks prompted more studies of causal analysis and interventions to reduce STEC outbreaks than for other pathogens, even though Norovirus accounts for the majority of outbreaks and illness among leafy greens. A recent overview reported 49 leafy green outbreak investigations linked to contamination of STEC in the US between 2009 and 2021, with traceback information available on 25 outbreaks [34]. Since 2018, more diverse sample collection has been observed in addition to leafy green sampling (air, agricultural and drainage waters, feces from birds, rodents, and wildlife, sediment, soil, swabs). The outbreak strain was detected in 6 of 17 farm investigations reviewed; 7 of these outbreaks were traced back to a single farm, while 10 were traced back to multiple farms [34]. Farm practices for irrigation and fertilizer and pesticide applications, as well as adjacent and nearby land uses, were examined. Outbreak strains were recovered throughout the lifespan of the leafy green products, from agricultural waters, sediments, manure on nearby land, and in retail products, requiring systems-based risk management. However, the authors note that such a comprehensive traceback requires substantial resources and collaboration to identify and mitigate risks across leafy green producers in the US in a timely manner for control and prevention of future outbreaks. Research to identify the root causes of outbreaks associated with different pathogens by season, weather, irrigation sources, and transmission from workers throughout the supply chain may be needed to reduce the burden of illness associated with leafy greens. Certainly, practices from farms not associated with outbreaks or associated with lower burdens of illness or severity merit deeper analysis.

Some findings of a recent analysis of the 2006 outbreak of STEC illness associated with leafy greens [33] merit consideration herein, particularly the 'social' or cultural construction of the outbreak with limited interventions that favored the dominant 'food regime', industrialized agriculture largely on irrigated lands in AZ and CA. Unfortunately, in 2006, consumers were warned to avoid eating fresh spinach from any source, unnecessarily causing market collapse, even though the contaminated product was quickly traced to one California grower. Evidence of failures at processing facilities was disregarded, and technical interventions on farms were pursued rather than holistic structural reforms of both production and processing industries.

Risk management policies appear to have further consolidated the US industry to large producers in two states, Arizona and California. For the years 2017 through 2019, these two states accounted for 100% of the US production of head lettuce, leaf lettuce, and romaine lettuce [35]. Meagher [33] reported that an alternative intervention not considered by regulators was the reduction of the scale or speed of production (e.g., hand harvesting, decentralizing processing, lower sprouting temperatures). Notably, farming leafy greens in these two states impacts consumers and the environment (e.g., costs of irrigation, refrigerated transportation, food waste due to spoilage and recalls, continuing burdens of human disease, and pollution of air, land, and water). Further, the root causes of the 2006 outbreak do not appear to have been identified and controlled, since public health impacts associated with leafy green outbreaks continue, peaking at 2,165 illnesses, 61 outbreaks, 219 hospitalizations, and 5 deaths associated with leafy greens in 2018 (Fig. 4; [17]).

Other researchers considered the recent decade of leafy green outbreaks in the US and Canada [36], reporting romaine lettuce as the most common cause and October and April as the most common months for outbreaks. These were months when US growers use California's Central Valley rather than the desert regions of California and Arizona (winter months from November to March). Limited environmental assessments cited by the authors note possible links between leafy green contamination and adjacent concentrated animal feeding operations (CAFOs), and between soil and water contamination and animals, including feral pigs and cattle. Restoring depleted soils and agricultural ecosystems will require attention to rebuilding healthy soils with dense and diverse soil microbiota essential for ecosystem resilience and functionality [37–39]. Researchers have raised concerns about ecological, economic, animal welfare, and social detriments for CAFOs or conventional industrialized 'factory' farms, compared to sustainable and regenerative agriculture practices that build healthy ecosystems and soils [37–39], warranting a more holistic analysis of the impacts of the safety and security policies for food systems, including leafy greens.

A largely unexplored opportunity for holistic research on leafy green safety, quality, affordability, and sustainability involves the natural microbiota of leafy greens. Mogren and colleagues [40] noted dense and diverse microbiota of leafy greens ($8x10^3$ to $6x10^8$ colony-forming units/g) that differed under field-grown and hydroponic/laboratory media conditions. Bacterial genera present in leafy greens included: *Pseudomonas, Rhodococcus, Chryseobacterium, Pantoea, Flavobacterium, Ralstonia, Stenotrophomonas, Erwinia, Xanthomonas, Serratia, Enterobacter, Bacillus, Staphylococcus, Acinetobacter, Alkanindiges, Comamonas, Limnobacter,* and *Pelomonas* [40,41]. Inoculation of these commensal microbes [42] or traditional probiotic strains could provide synergy in multiple hurdle systems to outcompete potential pathogens that might be present in or on leafy greens.

Some seasonal patterns were observed in two published studies [36,41], though no strong evidence of seasonality was detected herein. In the current study, the highest numbers of leafy green outbreaks and illnesses were observed in April and December, and the lowest in February, July, August, September, and October. Marshall and colleagues [36] reported romaine lettuce as the most common cause of leafy green outbreaks, and October and

April as the most common months for romaine lettuce outbreaks. In comparison, Leonard and colleagues [41] reported some differential effects for seasonality (spring and fall crops) and physiology of interactions of the soil microbiota and the inoculated pathogen *E. coli* O157:H7 for romaine grown in coastal California stored at cold (6°C) and warm (24°C) temperatures. It may be that further study will reveal seasonal patterns for leafy greens that could influence the development of alternative risk management strategies to reduce the burden of illness.

While exploring seasonal effects may be of great interest and importance for reducing the likelihood and severity of illnesses associated with leafy greens, concerns about the quality and completeness of the data and its adequacy for time-series analyses [2,43,44] may limit the utility of such methods to support the development of more effective risk management interventions for leafy greens.

4.2.2 State-Level Analysis of Milkborne Disease Severity

The numbers of outbreaks and hospitalizations were higher in raw milk than pasteurized milk, especially considering that consumption of pasteurized milk is likely orders of magnitude higher. Overall, no increasing trends in numbers and rates of outbreaks, illnesses, and hospitalizations by state were detected (Figures 8-10). Over the 16-year period, ≥80% of states reported fewer than 4 outbreaks, 38 illnesses, and 5 hospitalizations (Figure 9), suggestive evidence that raw dairy operations can be well managed at the state level. However, factors beyond the type of legal access affect the severity of raw milk outbreaks. Unfortunately, CDC NORS provides no information on the source of raw milk causing outbreaks (e.g., from licensed state operations, unlicensed state operations, buyers clubs, other states) or the type of legal access associated with the outbreaks (retail, on-farm, herdshare, prohibited/illegal), particularly problematic for states that allow multiple legal access types. Claims from previous studies [45–47] that retail legal status was associated with more outbreaks or illnesses appear misleading without proper statistical analysis of confounding effects, including adjusting for greater consumption in retail states than other states. Such claims are inconsistent with state-level analyses of numbers and rates of outbreaks, illnesses, and hospitalizations described herein.

The sensitivity of estimates from epidemiologic evidence, including CDC NORS, to assumptions for which reliable verification data do not exist merits careful scrutiny, including estimation of the impacts of alternative assumptions. The critical data gap on consumption of raw milk and raw dairy across all 50 states and DC, and over time, merits such scrutiny. Available survey data used are sparse, indirect, and ambiguous. Extrapolating from poor-quality evidence from small convenience samples of the surveyed population from 2006-2007 [48] to estimate consumption of raw and pasteurized milks without accounting for trends over time is problematic. Multiple studies [47,49] have applied a point estimate of 3.2% of the US population to estimate numbers of raw milk consumers for risk-risk comparisons between pasteurized and raw milks, without accounting for variability or uncertainty in this extrapolation. This assumption does not account for opposing trends observed in the US over time (decreasing consumption of pasteurized milk and increasing consumption of raw milk).

435 Pasteurized milk consumption has steadily decreased from 2006 to 2019, from 185 to 141 pounds per capita (~21
436 gallons to 16 gallons), representing a substantial loss in per capita consumption over this period [50]. In contrast,
437 multiple sources document rising consumption of raw milk. Raw milk consumption for one CA farm increased from
438 810,000 gallons in 2006 to 1.7 million gallons in 2020 (Fig. 11), representing a 10% increase in production for one
439 farm. Increased raw milk consumption likely paralleled increased production, since farmers report that supply
440 barely kept up with demand in these years. Other sources documented surges in the consumption of raw milk in
441 the US [6,24,51–59]. In New York State, the number of licenses for raw dairies increased from 10 in 2005 to 82 in
442 2022 [6], without increasing numbers or rates of illnesses or hospitalizations. In the past decade, only 4 cases of
443 campylobacteriosis were associated with raw milk in New York State, with no hospitalizations or deaths during that
444 period.

445 Growing US populations that have chosen raw milk for centuries also merit consideration. The current Amish
446 population in the US is estimated at ~411,00 people [60], and the Mennonite population is currently estimated at
447 ~500,000 people [61]. A recent clinical study [62] reported that >94% of the 4,200 Amish and Old Order
448 Mennonites responding to a survey consumed raw milk and had considerably lower allergenic disease than the
449 general US population. These data for Amish and Mennonite populations are consistent with evidence maps
450 documenting evidence of benefits and risks of pasteurizing human donor breastmilk [63] and bovine milk [13],
451 spanning human clinical studies, mechanistic studies, epidemiologic evidence, and risk assessments.

452 Although it is unclear what order-of-magnitude corrections are needed to extrapolate the assumption that 3.2% of
453 the 2006 survey populations can be applied for every state across the US over time, statistical analysis is
454 warranted. If extrapolations from survey data are made, estimation of confidence intervals and the use of
455 alternative assumptions are warranted, acknowledging variability between states and uncertainty about
456 representativeness over time and across sampling sites. More reliable data on US raw milk consumers could be
457 obtained from bar code data on sales collected for the 16 states that permit their residents and visitors legal
458 access in retail stores (AK, AR, AZ, CA, CT, DE, ID, ME, NH, NM, OR, PA, SC, WA, WY, UT).

459 The data in Figure 11 put epidemiologic observations from 7 outbreaks over 20 years in context regarding safety by
460 considering the volume of retail production and years with no outbreaks and few illnesses, as well as the outbreak
461 years. The effectiveness of training through the Raw Milk Institute was noted in a previous study of the CDC NORS
462 data [64]. Practical knowledge of pasture-based dairy production, commitment to continual monitoring and
463 improvement, and systematic practices consistent with Hazard Analysis and Critical Control Points (HACCP)
464 analysis in raw dairy management all contribute to the quality and safety of raw milk produced for direct human
465 consumption for RAWMI-listed farms. Such practices include: i) stringent production and process controls; ii)
466 regular veterinary health inspections and herd testing for and culling of pathogen ‘superspreaders’; iii) farmer
467 training; iv) sanitation checks; and v) monitoring bulk-tank milk and dairy products for indicator and pathogenic
468 microbes in a sophisticated test-and-hold system incorporating an on-farm laboratory. Further, RAWMI supported

a challenge study, conducted by an independent laboratory certified to analyze for bacterial pathogens. The study documented the effectiveness of pathogen suppression in inoculated raw milk stored and maintained at the recommended temperature (4.4°C/39.9°F) for at least one week [65]. Claims in the media (raw milk is inherently dangerous and always will be; raw milk is unsafe to transport due to cold chain issues) are not supported by the current body of evidence. As pointed out for leafy greens, shifting policy and risk management focus to building knowledge of farms and states with lower public health impacts on raw milk consumers, as well as examining synergies in multiple hurdle systems that include farmer and consumer training, monitoring, and cold-chain verification, may positively impact public health protections for consumers choosing raw milk.

5 CONCLUSIONS

Leafy greens and raw milk account for significant public health burdens in the US. The trends in foodborne disease burden and disease severity for leafy greens and raw milk were not increasing over this 16-year period, but neither were the public health burdens strongly decreasing.

For leafy greens, Norovirus accounted for the majority of morbidity and secondary transmission, while STEC accounted for the majority of severe outbreaks. *Salmonella*, STECs, and Hepatitis A were associated with fewer secondary cases in leafy green outbreaks and more severe outcomes than Norovirus. Policy implications for these findings suggest that different policy strategies may be needed to reduce both the likelihood and severity of the public health burden for leafy greens. The benefits and risks of small-scale operations merit additional research, particularly in regard to supporting more holistic research at all scales that might inform policies promoting the safety, quality, affordability, and sustainability of leafy green operations that incorporate soil ecology and plant-microbial-human interactions to reduce morbidity and mortality.

For raw milk, public health impacts of severe disease vary by U.S. state, as might be expected given the relative sparsity of outbreaks, differences in state populations, and variation in state-level regulatory frameworks. State-level patterns in numbers and rates of outbreaks, illnesses, and hospitalizations were heterogeneous. The state-level measure of disease severity, average hospitalizations per outbreak, was also highly variable when the state-year structure of the underlying data was preserved. No clear clustering of outbreak severity by legal access type was evident from the wide confidence intervals estimated. No trends were observed for outbreak illnesses per 100,000 raw milk servings produced by one CA farm for the retail market, despite substantial increases in production in this period. Milkborne secondary cases were reported for 10 of 162 raw milk outbreaks (7 STEC cases; 4 campylobacteriosis cases), but none were reported for pasteurized milk in this period.

An overarching implication for this analysis of CDC NORS data for leafy greens and raw milk suggests that refocusing on farms linked with lower public health impacts may reveal driving factors that might more effectively contribute to public health protections in the future. More holistic analysis and transparent collaborations consistent with One-Health approaches, incorporating not only epidemiologic observations, but also risk analysis

methodologies and data on food safety, food security, food waste, sustainability, and economic, cultural, social, and political factors, may facilitate the development of more evidence-based policies for leafy greens and raw milk farming systems in the future.

DECLARATIONS

Abbreviations

CDC: U.S. Centers for Disease Control and Prevention

H/O hospitalizations per outbreak

LOESS Locally Weighted Scatterplot Smoothing

NCDs non-communicable diseases

NORS: National Outbreak Reporting System

QMRA quantitative microbial risk assessment

US United States of America

WHO World Health Organization

US State Abbreviations

AK	**Alaska**	**KY**	**Kentucky**	**NY**	**New York**
AL	**Alabama**	**LA**	**Louisiana**	**OH**	**Ohio**
AR	**Arkansas**	**MA**	**Massachusetts**	**OK**	**Oklahoma**
AZ	**Arizona**	**MD**	**Maryland**	**OR**	**Oregon**
CA	**California**	**ME**	**Maine**	**PA**	**Pennsylvania**
CO	**Colorado**	**MI**	**Michigan**	**RI**	**Rhode Island**
CT	**Connecticut**	**MN**	**Minnesota**	**SC**	**South Carolina**
DC	**District of Columbia**	**MO**	**Missouri**	**SD**	**South Dakota**
DE	**Delaware**	**MS**	**Mississippi**	**TN**	**Tennessee**
FL	**Florida**	**MT**	**Montana**	**TX**	**Texas**

527	**GA**	**Georgia**	**NC**	**North Carolina**	**UT**	**Utah**
528	**HI**	**Hawaii**	**ND**	**North Dakota**	**VA**	**Virginia**
529	**IA**	**Iowa**	**NE**	**Nebraska**	**VT**	**Vermont**
530	**ID**	**Idaho**	**NH**	**New Hampshire**	**WA**	**Washington**
531	**IL**	**Illinois**	**NJ**	**New Jersey**	**WI**	**Wisconsin**
532	**IN**	**Indiana**	**NM**	**New Mexico**	**WV**	**West Virginia**
533	**KS**	**Kansas**	**NV**	**Nevada**	**WY**	**Wyoming**

534

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6. REFERENCES

1. World Health Organization (WHO) Global Health Estimates 2020: Disease Burden by Cause, Age, Sex, by Country and by Region, 2000-2019 Available online: https://www.who.int/data/gho/data/themes/mortality-and-global-health-estimates/global-health-estimates-leading-causes-of-dalys.
2. Zhang, Y.; Simpson, R.B.; Sallade, L.E.; Sanchez, E.; Monahan, K.M.; Naumova, E.N. Evaluating Completeness of Foodborne Outbreak Reporting in the United States, 1998–2019. *International Journal of Environmental Research and Public Health* **2022**, *19*, 2898.
3. Cox, L.A. Shapes and Definitions of Exposure-Response Curves: A Comment on "A Matrix for Bridging the Epidemiology and Risk Assessment Gap." *Global Epidemiology* **2019**, *1*, 100006, doi:10.1016/j.gloepi.2019.100006.
4. Mokhtari, A.; Pang, H.; Santillana Farakos, S.; McKenna, C.; Crowley, C.; Cranford, V.; Bowen, A.; Phillips, S.; Madad, A.; Obenhuber, D.; et al. Leveraging Risk Assessment for Foodborne Outbreak Investigations: The Quantitative Risk Assessment-Epidemic Curve Prediction Model. *Risk Analysis* **2023**, *43*, 324–338, doi:10.1111/risa.13896.
5. National Academies of Sciences, Engineering, and Medicine (NAS) *Using 21st Century Science to Improve Risk-Related Evaluations*; National Academies Press: Washington, DC, 2017; ISBN 978-0-309-45351-6.
6. Stephenson, M.M.; Coleman, M.E.; Azzolina, N.A. Trends in Burdens of Disease by Transmission Source (USA, 2005-2020) and Hazard Identification for Foods: Focus on Milkborne Disease. *J Epidemiol Glob Health* **2024**, *14*, 787–816, doi:10.1007/s44197-024-00216-6.
7. World Health Organization (WHO) Strengthening WHO Preparedness for and Response to Health Emergencies 2022.
8. Bouwknegt, M.; Knol, A.B.; van der Sluijs, J.P.; Evers, E.G. Uncertainty of Population Risk Estimates for Pathogens Based on QMRA or Epidemiology: A Case Study of Campylobacter in the Netherlands. *Risk Analysis* **2014**, *34*, 847–864, doi:10.1111/risa.12153.
9. Capone, D.; Bivins, A.; Brown, J. Producing Ratio Measures of Effect with Quantitative Microbial Risk Assessment. *Risk Analysis* **2023**, *43*, 917–927, doi:10.1111/risa.13972.
10. Pang, H.; Pouillot, R.; Van Doren, J.M. Quantitative Risk Assessment-epidemic Curve Prediction Model for Leafy Green Outbreak Investigation. *Risk Analysis* **2023**, *43*, 1713–1732, doi:10.1111/risa.14073.

11. Fischhoff, B.; Brewer, N.T.; Downs, J.S. Communicating Risks and Benefits: An Evidence-Based User's Guide 2011.
12. Tumlison, C.; Song, G. Cultural Values, Trust, and Benefit-Risk Perceptions of Hydraulic Fracturing: A Comparative Analysis of Policy Elites and the General Public. *Risk Analysis* **2019**, *39*, 511–534, doi:10.1111/risa.13197.
13. Dietert, R.R.; Coleman, M.E.; North, D.W.; Stephenson, M.M. Nourishing the Human Holobiont to Reduce the Risk of Non-Communicable Diseases: A Cow's Milk Evidence Map Example. *Applied Microbiology* **2022**, *2*, 25–52, doi:10.3390/applmicrobiol2010003.
14. Hayashi, M.A.L.; Eisenberg, M.C.; Eisenberg, J.N.S. Linking Decision Theory and Quantitative Microbial Risk Assessment: Tradeoffs Between Compliance and Efficacy for Waterborne Disease Interventions. *Risk Analysis* **2019**, *39*, 2214–2226, doi:10.1111/risa.13381.
15. Duret, S.; Hoang, H.-M.; Derens-Bertheau, E.; Delahaye, A.; Laguerre, O.; Guillier, L. Combining Quantitative Risk Assessment of Human Health, Food Waste, and Energy Consumption: The next Step in the Development of the Food Cold Chain? *Risk Analysis* **2019**, *39*, 906–925.
16. Smith, D.W.; Islam, M.; Furst, K.E.; Mustaree, S.; Crider, Y.S.; Akter, N.; Islam, S.A.; Sultana, S.; Mahmud, Z.H.; Rahman, M.; et al. Chlorine Taste Can Increase Simulated Exposure to Both Fecal Contamination and Disinfection Byproducts in Water Supplies. *Water Research* **2021**, *207*, 117806, doi:10.1016/j.watres.2021.117806.
17. CDC Microsoft Access® Data Set Including All Transmission Sources (Food, Water, Animal Contact, Environmental, Person-to-Person) for Years 2005 – 2020. Provided to MEC by Hannah Lawinger, NORS Data Request Manager, on July 20, 2021. **2021**.
18. Nichols, M.; Conrad, A.; Whitlock, L.; Stroika, S.; Strain, E.; Weltman, A.; Johnson, L.; DeMent, J.; Reporter, R.; Williams, I. Multistate Outbreak of Listeria Monocytogenes Infections Retrospectively Linked to Unpasteurized Milk Using Whole-Genome Sequencing. *Journal of Dairy Science* **2020**, *103*, 176–178.
19. Kendall, M.G. A New Measure of Rank Correlation. *Biometrika* **1938**, *30*, 81–93, doi:10.1093/biomet/30.1-2.81.
20. Mann, H.B. Non-Parametric Tests Against Trend. *Econometrica* **1945**, *13*, 245–259, doi:10.2307/1907187.
21. Sen, P.K. Estimates of the Regression Coefficient Based on Kendall's Tau. *Journal of the American Statistical Association* **1968**, *63*, 1379–1389, doi:10.1080/01621459.1968.10480934.
22. R Core Team R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing. 2022.
23. Minitab Minitab®17 Statistical Software 2022.
24. Coleman, M.E. Deliberating the Scientific Evidence Base for Influenza Transmission to Raw Milk Consumers. *Risk Analysis* **2025**, doi:10.1111/risa.70077.
25. Weinstein, E. Outbreak of Salmonella Typhimurium Infections Linked to Commercially Distributed Raw Milk — California and Four Other States, September 2023–March 2024. *MMWR Morb Mortal Wkly Rep* **2025**, *74*, doi:10.15585/mmwr.mm7427a1.
26. World Health Organization (WHO); Food and Agriculture Organization (FAO)of the United Nations *Taking a Multisectoral, One Health Approach: A Tripartite Guide to Addressing Zoonotic Diseases in Countries*; World Health Organization: Geneva, 2019; ISBN 978-92-4-151493-4.
27. Bronzwaer, S.; Catchpole, M.; de Coen, W.; Dingwall, Z.; Fabbri, K.; Foltz, C.; Ganzleben, C.; van Gorcom, R.; Humphreys, A.; Jokelainen, P.; et al. One Health Collaboration with and among EU Agencies – Bridging Research and Policy. *One Health* **2022**, *15*, 100464, doi:10.1016/j.onehlt.2022.100464.
28. Bronzwaer, S.; Alves, F.; das Neves, C.G.; Byrne, P.; Url, B. EFSA's Second Risk Assessment Research Assembly (RARA) Delivered on Its Objectives. *Trends in Food Science & Technology* **2023**.

29. World Health Organization (WHO) One Health Available online: https://www.who.int/health-topics/one-health.
30. FAO; IFAD; UNICEF; WFP; WHO *The State of Food Security and Nutrition in the World 2022: Repurposing Food and Agricultural Policies to Make Healthy Diets More Affordable*; The State of Food Security and Nutrition in the World (SOFI); FAO, IFAD, UNICEF, WFP, WHO: Rome, Italy, 2022; ISBN 978-92-5-136499-4.
31. *Operationalizing Sustainable Development to Benefit People and the Planet*; National Academies Press: Washington, D.C., 2022;
32. Wikswo, M.E.; Roberts, V.; Marsh, Z.; Manikonda, K.; Gleason, B.; Kambhampati, A.; Mattison, C.; Calderwood, L.; Balachandran, N.; Cardemil, C. Enteric Illness Outbreaks Reported through the National Outbreak Reporting System—United States, 2009–2019. *Clinical Infectious Diseases* **2022**, *74*, 1906–1913.
33. Meagher, K.D. Policy Responses to Foodborne Disease Outbreaks in the United States and Germany. *Agriculture and Human Values* **2022**, *39*, 233–248.
34. Viazis, S.; Bazaco, M.C.; Blessington, T.; Seelman Federman, S.L.; Lindsay, M.; Minor, T.; Nork, B.; Mattioli, M.C.; Marshall, K.E.; Wise, M.E.; et al. An Overview of Farm Investigation Findings Associated with Outbreaks of Shiga Toxin-Producing *Escherichia Coli* Infections Linked to Leafy Greens: 2009–2021. *Journal of Food Protection* **2025**, *88*, 100542, doi:10.1016/j.jfp.2025.100542.
35. NASS *Census of Agriculture 2022*; 2024;
36. Marshall, K.E.; Hexemer, A.; Seelman, S.L.; Fatica, M.K.; Blessington, T.; Hajmeer, M.; Kisselburgh, H.; Atkinson, R.; Hill, K.; Sharma, D. Lessons Learned from a Decade of Investigations of Shiga Toxin–Producing Escherichia Coli Outbreaks Linked to Leafy Greens, United States and Canada. *Emerging infectious diseases* **2020**, *26*, 2319.
37. Kaufmann, T. Sustainable Livestock Production: Low Emission Farm–The Innovative Combination of Nutrient, Emission and Waste Management with Special Emphasis on Chinese Pig Production. *Animal Nutrition* **2015**, *1*, 104–112.
38. Heckman, J.R. Securing Fresh Food from Fertile Soil, Challenges to the Organic and Raw Milk Movements. *Renew. Agric. Food Syst.* **2017**, *34*, 472–485, doi:10.1017/S1742170517000618.
39. Hermans, S.M.; Lear, G.; Case, B.S.; Buckley, H.L. The Soil Microbiome: An Essential, but Neglected, Component of Regenerative Agroecosystems. *Iscience* **2023**.
40. Mogren, L.; Windstam, S.; Boqvist, S.; Vågsholm, I.; Söderqvist, K.; Rosberg, A.K.; Lindén, J.; Mulaosmanovic, E.; Karlsson, M.; Uhlig, E. The Hurdle Approach–A Holistic Concept for Controlling Food Safety Risks Associated With Pathogenic Bacterial Contamination of Leafy Green Vegetables. A Review. **2018**.
41. Leonard, S.R.; Simko, I.; Mammel, M.K.; Richter, T.K.S.; Brandl, M.T. Seasonality, Shelf Life and Storage Atmosphere Are Main Drivers of the Microbiome and E. Coli O157:H7 Colonization of Post-Harvest Lettuce Cultivated in a Major Production Area in California. *Environmental Microbiome* **2021**, *16*, 25, doi:10.1186/s40793-021-00393-y.
42. Karlsson, M.E.; Uhlig, E.; Håkansson, Å.; Alsanius, B.W. Seed Inoculation with Antagonistic Bacteria Limits Occurrence of E. Coli O157:H7gfp + on Baby Spinach Leaves. *BMC Microbiol* **2022**, *22*, 131, doi:10.1186/s12866-022-02550-w.
43. Simpson, R.B.; Zhou, B.; Naumova, E.N. Seasonal Synchronization of Foodborne Outbreaks in the United States, 1996–2017. *Sci Rep* **2020**, *10*, 17500, doi:10.1038/s41598-020-74435-9.
44. Simpson, R.B.; Kulinkina, A.V.; Naumova, E.N. Investigating Seasonal Patterns in Enteric Infections: A Systematic Review of Time Series Methods. *Epidemiology & Infection* **2022**, *150*, e50, doi:10.1017/S0950268822000243.
45. Mungai, E.A.; Behravesh, C.B.; Gould, L.H. Increased Outbreaks Associated with Nonpasteurized Milk, United States, 2007–2012. *Emerging infectious diseases* **2015**, *21*, 119.

46. Koski, L.; Kisselburgh, H.; Landsman, L.; Hulkower, R.; Howard-Williams, M.; Salah, Z.; Kim, S.; Bruce, B.B.; Bazaco, M.C.; Batz, M.B. Foodborne Illness Outbreaks Linked to Unpasteurised Milk and Relationship to Changes in State Laws–United States, 1998–2018. *Epidemiology & Infection* **2022**, *150*, e183.
47. Hsu, P.; Wu, F. The Unseen Risks of Dairyborne Disease: Disease Burden, Economic Impact, and Regulatory Trends in Raw Milk and Cheese in the US, 2000-2020. *Trends in Food Science & Technology* **2026**, 105712, doi:10.1016/j.tifs.2026.105712.
48. CDC *Foodborne Diseases Active Surveillance Network (FoodNet) Population Survey Atlas of Exposures, 2006-2007*; 2008;
49. Costard, S.; Espejo, L.; Groenendaal, H.; Zagmutt, F.J. Outbreak-Related Disease Burden Associated with Consumption of Unpasteurized Cow's Milk and Cheese, United States, 2009–2014. *Emerging infectious diseases* **2017**, *23*, 957.
50. USDA ERS Dairy Data: Per Capita Consumption 2020.
51. Aleccia, J. Raw Milk Sales Are up despite Bird Flu Outbreak in Dairy Cows Available online: https://www.fastcompany.com/91124899/raw-milk-sales-rise-bird-flu-outbreak-dairy-cows (accessed on 6 June 2024).
52. Doan, L. Influencers Promote Raw Milk despite FDA Health Warnings as Bird Flu Spreads in Dairy Cows - CBS News Available online: https://www.cbsnews.com/news/bird-flu-raw-milk-influencers-fda-warning/ (accessed on 22 October 2024).
53. Flynn, D. Risk Warnings Are Not Pausing Raw Milk Consumption Available online: https://www.foodsafetynews.com/2024/07/risk-warnings-are-not-pausing-raw-milk-consumption/ (accessed on 18 July 2024).
54. Kernodle, R. Bird-Flu Fear Mongering and Disease Mongering. *Robert Kernodle's Substack* 2024.
55. Kernodle, R. Bird Flu: To Fear or Not to Fear ? That Is the Question Available online: https://mail.google.com/mail/u/0/?shva=1#inbox/FMfcgzQVxblkDMsgfVTqJzTfjkRxBRJH (accessed on 14 July 2024).
56. Leake, J. Bird Flu: Separating Fact from Fiction and True Danger from Fear-Mongering. *Courageous Discourse™ with Dr. Peter McCullough & John Leake* 2024.
57. Makis, W. Influenza H5N1 Fear-Mongering Is Flooding the News. Perfect Candidate for "Disease X"? How to Protect Against H5N1. **2024**.
58. Tin, A. Bird Flu Risk Prompts Warnings against Raw Milk, Unpasteurized Dairy Products - CBS News Available online: https://www.cbsnews.com/news/bird-flu-raw-milk-unpasteurized-dairy/ (accessed on 24 July 2024).
59. Lyubomirova, T. Bird Flu Latest: FDA Raises Raw Milk Risks Awareness, Studies Pasteurization Effectiveness Available online: https://www.dairyreporter.com/Article/2024/06/26/FDA-tells-consumers-to-know-the-risks-of-raw-milk (accessed on 14 November 2024).
60. The Young Center *Amish Population, 2024*; Elizabethtown College: Elizabethtown, PA, 2026;
61. ARDA *Mennonite/Amish Membership Study 2020*; Association of Religion Data Archieves, 2026;
62. Tantoco, J.C.; Bontrager, J.E.; Zhao, Q.; DeLine, J.; Seroogy, C.M. The Amish Have Decreased Asthma and Allergic Diseases Compared to Old Order Mennonites. *Ann Allergy Asthma Immunol* **2018**, *121*, 252-253.e1, doi:10.1016/j.anai.2018.05.016.
63. Coleman, M.E.; North, D.W.; Dietert, R.R.; Stephenson, M.M. Examining Evidence of Benefits and Risks for Pasteurizing Donor Breastmilk. *Applied Microbiology* **2021**, *1*, 408–425, doi:10.3390/applmicrobiol1030027.
64. Whitehead, J.; Lake, B. Recent Trends in Unpasteurized Fluid Milk Outbreaks, Legalization, and Consumption in the United States. *PLoS Curr* **2018**, *10*, ecurrents.outbreaks.bae5a0fd685616839c9cf857792730d1, doi:10.1371/currents.outbreaks.bae5a0fd685616839c9cf857792730d1.

65. Coleman, M.E.; Oscar, T.P.; Negley, T.L.; Stephenson, M.M. Suppression of Pathogens in Properly Refrigerated Raw Milk. *PLOS ONE* **2023**, *18*, e0289249, doi:10.1371/journal.pone.0289249.