

Giardiasis in the United States – an epidemiologic and geospatial analysis of county-level drinking water and sanitation data, 1993–2010

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ABSTRACT

Giardiasis is the most commonly reported intestinal parasitic infection in the United States. Outbreak investigations have implicated poorly maintained private wells, and hypothesized a role for wastewater systems in giardiasis transmission. Surveillance data consistently show geographic variability in reported giardiasis incidence. We explored county-level associations between giardiasis cases, household water and sanitation (1990 census), and US Census division. Using 368,847 reported giardiasis cases (1993–2010), we mapped county-level giardiasis incidence rates, private well reliance, and septic system reliance, and assessed spatiotemporal clustering of giardiasis. We used negative binomial regression to evaluate county-level associations between giardiasis rates, region, and well and septic reliance, adjusted for demographics. Adjusted giardiasis incidence rate ratios (aIRRs) were highest (aIRR 1.3; 95% confidence interval 1.2–1.5) in counties with higher private well reliance. There was no significant association between giardiasis and septic system reliance in adjusted models. Consistent with visual geographic distributions, the aIRR of giardiasis was highest in New England (aIRR 3.3; 95% CI 2.9–3.9; reference West South Central region). Our results suggest that, in the USA, private wells are relevant to giardiasis transmission; giardiasis risk factors might vary regionally; and up-to-date, location-specific national data on water sources and sanitation methods are needed.

Key words | drinking water, geographic information systems, giardiasis, public health surveillance, sanitation

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INTRODUCTION

Giardiasis is the most commonly reported intestinal parasitic infection in the United States, with an annual incidence, since 2002, of 7.2–8.7 per 100,000 persons (Yoder *et al.* 2012). Northern states consistently report more cases of giardiasis than southern states (Hlavsa *et al.* 2005; Yoder & Beach 2007; Yoder *et al.* 2010), with reported 2010 incidence rates (IR) ranging from 2.6 per 100,000 persons in Arizona to 29.6 in Vermont (Yoder *et al.* 2012). The

causative organism of giardiasis, *Giardia intestinalis* (also known as *G. lamblia* or *G. duodenalis*), is transmitted primarily through ingestion of infected human waste. This can occur in the setting of exposure to fecally contaminated food or water, and through contact with an infected person or animal (Hill & Nash 2009). The incubation period of giardiasis is 1–2 weeks (Hill & Nash 2009). Infection commonly results in a prolonged diarrhea associated with abdominal cramps, bloating, weight loss, and malabsorption; infection might also be asymptomatic or result in chronic diarrhea (Hill & Nash 2009).

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Water is an important source of *Giardia* transmission in the United States. *Giardia* was the most frequently identified pathogen in drinking water outbreaks in both public and private (e.g. private wells) water systems from 1971–2006 (Craun *et al.* 2010). In public water systems, giardiasis outbreaks have been associated with improper, or absent, filtration of surface water and groundwater under the direct influence of surface water (Herwaldt *et al.* 1991; Blackburn *et al.* 2004; Daly *et al.* 2010; Brunkard *et al.* 2011). Private water system outbreaks have been associated with well contamination with surface water and sewage (Lee *et al.* 2002; Liang *et al.* 2006; Brunkard *et al.* 2011). For reference, the 2011 American Housing Survey found that 88.2% of housing units in the USA rely on a water system serving >5 housing units; 11.4% rely on a private well (United States Census Bureau 2011). For household sewage disposal, 80.6% are connected to a public sewer and 19.3% rely on a septic system, cesspool, or chemical toilet (United States Census Bureau 2011).

Following steady decreases in the incidence of giardiasis in the late 1990s, giardiasis IR stabilized in the 2000s (Furness *et al.* 2000; Hlavsa 2005; Yoder *et al.* 2010). Despite this incidence rate stabilization, the burden and cost of giardiasis remain significant (Collier *et al.* 2012; Yoder *et al.* 2012). For example, hospitalizations resulting from giardiasis cost approximately US\$34 million annually. Ambulatory care visits, which are significantly more common than hospitalizations for giardiasis, cost US\$121–273 per visit (Collier *et al.* 2012). While general prevention mechanisms for giardiasis, such as properly treating drinking water and preventing drinking water contamination with sewage, are well understood, epidemiologic studies are needed to identify interventions effective at preventing current routes of giardiasis transmission (Craun *et al.* 2010; Yoder *et al.* 2012). To target these prevention efforts, common mechanisms of giardiasis transmission in the USA, particularly related to water and sanitation, must be understood.

Most of our current understanding of giardiasis transmission in the USA has been informed by outbreak investigations. However, <1% of reported giardiasis cases in 2009–2010 were associated with known outbreaks, and the extent to which outbreak-associated transmission routes are relevant for the majority of giardiasis cases in the USA is unknown (Yoder *et al.* 2012). Unfiltered surface water, shallow well water, and drinking water from a private

well have been associated with non-outbreak (sporadic) giardiasis (Chute *et al.* 1987; Birkhead & Vogt 1989; Dennis *et al.* 1993; Naumova *et al.* 2000; Odoi *et al.* 2004a). However, these analyses were conducted using data from small geographic regions in North America (Chute *et al.* 1987; Birkhead & Vogt 1989; Dennis *et al.* 1993; Naumova *et al.* 2000; Odoi *et al.* 2004a).

To our knowledge, national giardiasis data have never been analyzed in association with potential giardiasis risk factors, such as water sources and sanitation methods (Yoder *et al.* 2012). Geospatial analyses have proved useful in assessing regional risk factors associated with giardiasis and drinking water contamination in Germany and Canada (Dangendorf *et al.* 2002; Odoi *et al.* 2003, 2004a, 2004b; Uhlmann *et al.* 2009). Traditional epidemiologic multivariable models have been used to assess the epidemiology of giardiasis in Auckland, New Zealand, and within regions of the USA (Chute *et al.* 1987; Hoque *et al.* 2002). A combination of geographic and more traditional epidemiologic methods was effectively used to assess environmental risk factors for *Campylobacter*, a partially waterborne bacterium, in Sweden, and a variety of waterborne pathogens in British Columbia (Nygård *et al.* 2004; Uhlmann *et al.* 2009). Thus, to explore the epidemiology of giardiasis in the United States, we used National Notifiable Disease Surveillance System (NNDSS) data to map giardiasis IR and private well and septic system use; assess spatiotemporal clustering of giardiasis; and model the association between county-level giardiasis rates and well and septic system reliance.

METHODS

Data sources

County-level giardiasis case counts were obtained from the NNDSS, 1993–2010. These were the most recent data available at the time of analysis. While giardiasis has only been nationally notifiable since 2002, cases have been reported through NNDSS since 1993. For each year, giardiasis was not a reportable condition in several states (range 2–13). Texas and North Carolina never officially reported giardiasis; all other states reported for at least 3 years. Of 394,852 giardiasis cases reported to NNDSS from 1993–2010, we

excluded cases from Puerto Rico and states not officially reporting giardiasis (2,387 cases), duplicate entries (3,211), cases with missing or invalid county data (8,224), and cases with missing or invalid (e.g. negative) age data (25,114); 368,847 cases were available for analysis. Some cases were excluded for multiple reasons.

Age-standardized IR were calculated via the direct method, using annual population estimates from the US Census and the 2000 US Standard Population Proportions (Day 1996; SEER a, b). Crude age-based (0–19, 20+, and all ages) giardiasis IR were calculated using annual population estimates from the US Census (United States Census Bureau 2003, 2012). We used data on giardiasis outbreaks reported to the Waterborne Disease and Outbreaks Surveillance System to look for reported giardiasis outbreaks in counties with high NNDSS giardiasis IR (Kramer *et al.* 1996; Levy *et al.* 1998; Barkwick *et al.* 2000; Lee *et al.* 2002; Blackburn *et al.* 2004; Liang *et al.* 2006; Yoder *et al.* 2008; Brunkard *et al.* 2011).

County-level data on household water and sanitation were obtained from the 1990 Census, the most recent Census in which water and sanitation data were collected. Income, education, and housing unit owner occupancy rates were obtained from the 2000 Census (United States Census Bureau 2001, 2002). We selected this iteration of the US Census to best represent county demographics from 1993–2010. Well reliance was quantified as the percentage of households in a county reliant on a private well for household water, septic system reliance as the percentage of households in a county reliant on a septic system for household sewage disposal, income as the percent of individuals in a county living below the poverty line, education as the percent of adults aged 25 years and older with a high school degree, and housing unit owner occupancy as the percent of occupied housing units in a county occupied by the unit owner. All continuous variables were analyzed as quartiles or median split, with quartiles and medians defined by the distribution of the variable in reporting states, weighted for the number of years each state reported.

County region was based on the nine US Census Bureau divisions (United States Census Bureau 2013). County cattle density was defined as the number of cattle per square mile using data from the 2007 US Department of Agriculture (USDA) Census of Agriculture. County rural/urban status

was established using the 2003 USDA Rural-Urban Continuum Codes. We categorized Rural-Urban Continuum Codes 1–5 as urban (county population $\geq 20,000$), and 6–9 as rural (population $< 20,000$) (United States Department of Agriculture 2003).

We linked NNDSS, environmental, and demographic data using county Federal Information Processing Standards (FIPS) codes (National Institute of Standards & Technology). All data were analyzed at the county level.

Spatial and temporal clustering

SaTScan™ version 9.0 (Martin Kulldorff, Boston, MA), a spatial scan statistical software package, was used to test for spatial and spatiotemporal clusters of giardiasis within the 46 contiguous US states that report giardiasis (i.e. excluding Alaska, Hawaii, Texas, and North Carolina). We conducted a discrete Poisson model scanning for space-time clusters with high rates of giardiasis across the entire study period (1993–2010), and before and after giardiasis became officially notifiable (1993–2001 and 2002–2010). With this scan statistic, the ‘most likely’ cluster is the space-time window with the largest maximum (logarithmic) likelihood ratio (i.e. the cluster least likely to have occurred by chance alone). To evaluate whether environmental risk factors for giardiasis varied within and among clusters, we examined the distribution of private well and septic system reliance in each cluster.

Geographic distributions

We developed county-level maps to look at the geographic distribution of giardiasis IR, private well reliance, and septic system reliance.

Modeling

We developed univariable and multivariable negative binomial regression models to assess the relationship between county-level crude giardiasis IR and county-level water sources, sanitation methods, and demographics. Case year was included in the model as a binary variable, 1993–2001 or 2001–2010 (before and after giardiasis became nationally notifiable). Covariates were selected in

a backwards stepwise manner; covariates with a p -value <0.05 were retained in the final model and tested for interactions. Statistical significance and the Bayesian Information Criterion (BIC), a model selection criterion that avoids model overfitting by using a penalty term for the number of parameters in the model, were used to select interaction terms for the final model (Hilbe 2011). Models with a lower BIC were preferred.

Results are presented as crude IR, unadjusted incidence rate ratios (uIRR), and adjusted incidence rate ratios (aIRR). We conducted sensitivity analyses by excluding giardiasis cases associated with known outbreaks and cases known to be associated with travel away from the reporting state (either domestic or international travel). We also ran the final adjusted model separately in the 0–19 and 20+ age groups to assess whether the association between county-level private well and septic system reliance and giardiasis differed by age group. Except where otherwise noted, analyses were conducted in SAS 9.3 (Statistical Analysis Software, Cary, NC).

RESULTS

Considering all years and counties in aggregate, there were 368,847 giardiasis cases in 4,003,958,833 person-years, resulting in a national crude incidence rate of 9.2 per 100,000 person-years. Crude national IRs were higher in persons aged 0–19 years (14.2 per 100,000 person-years) than in persons aged ≥ 20 (7.3 per 100,000 person-years). Visually, counties with high age-standardized rates of giardiasis were concentrated in the northern USA, southeastern USA, and New England (Figure 1).

Spatial and temporal clustering

In all three analyzed time periods, our spatiotemporal cluster analysis revealed significant high rate space-time giardiasis clusters in the northern (Pacific, Mountain, West North Central, East North Central, New England, and Middle Atlantic census divisions) and southeastern (South Atlantic) United States (Figure 2). All of the ‘most likely’

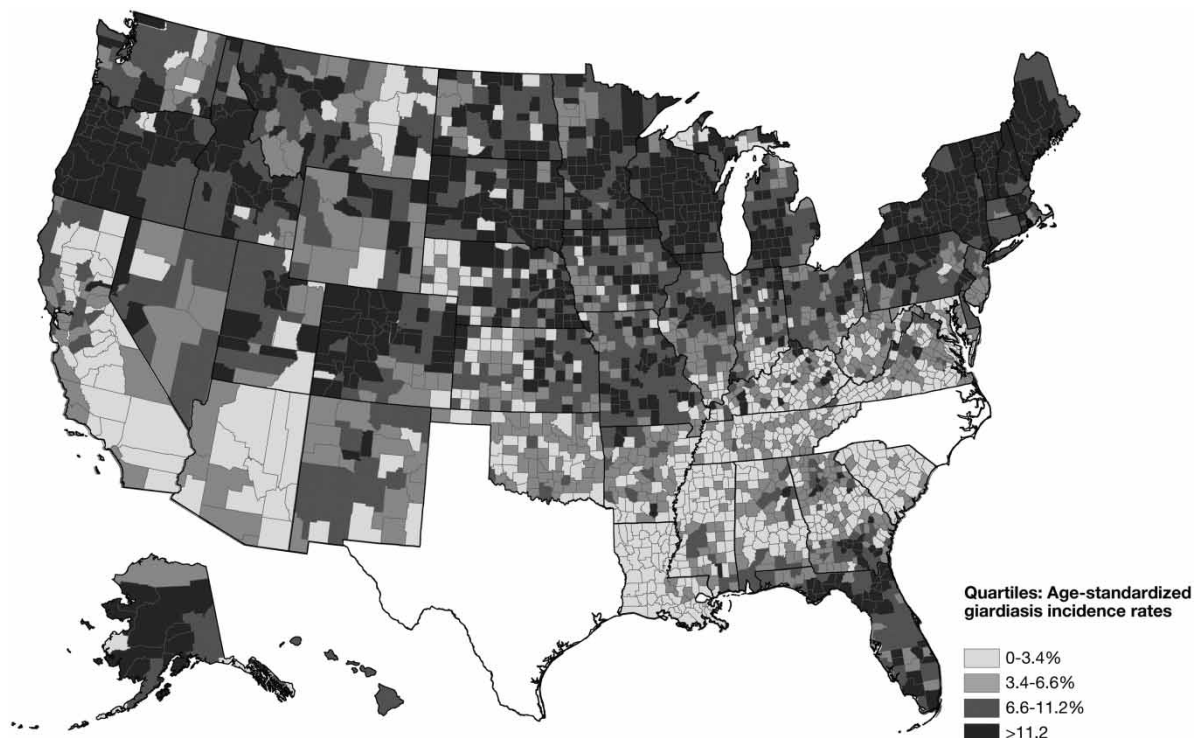


Figure 1 | Age-standardized incidence (per 100,000 population) of giardiasis, by county—National Notifiable Diseases Surveillance System, United States, 1993–2010.

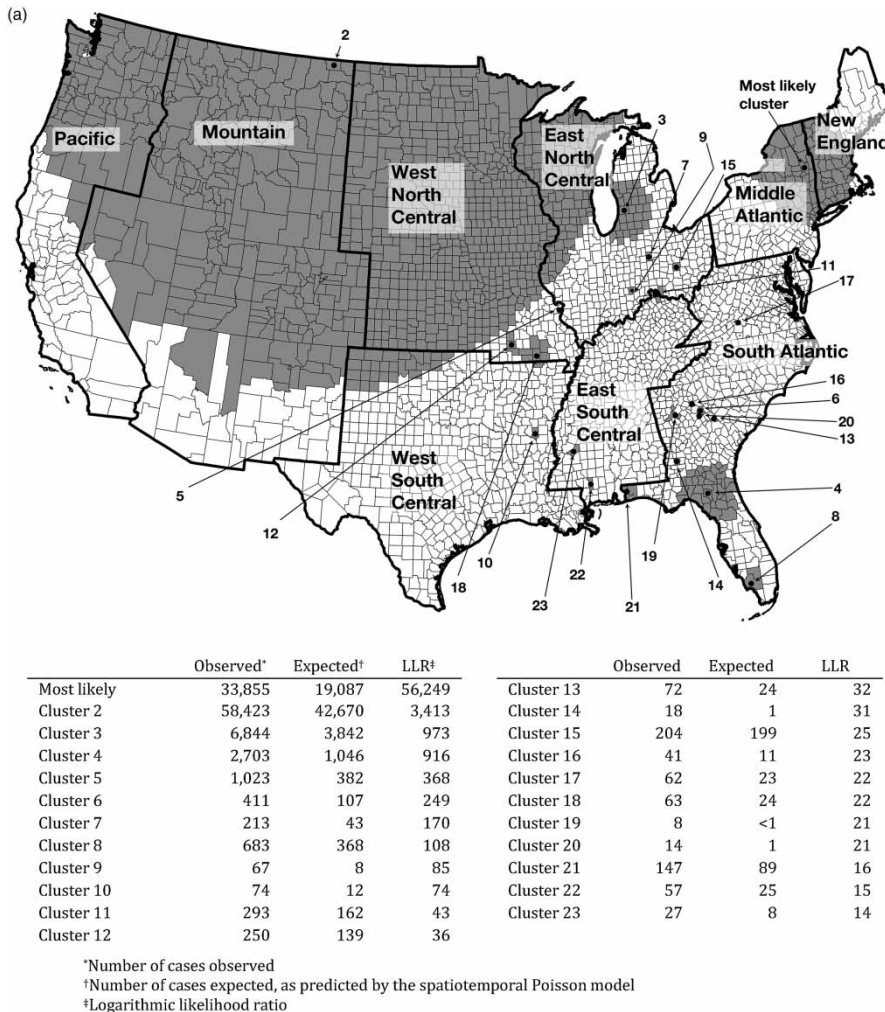


Figure 2 | Spatial distribution of significant high rate space-time giardiasis clusters—National Notifiable Diseases Surveillance System, United States, 1993–2010. Census divisions are labeled. (a) 1993–2001, 23 significant clusters; (b) 2002–2010, 10 significant clusters; and (c) 1993–2010, five significant clusters. (continued)

clusters were located in the north. We identified more significant high rate giardiasis clusters from 1993–2001 (23 clusters) than from 2002–2010 (10 clusters). Proportions of private well reliance and septic system use varied within and among clusters, with private well and septic system reliance ranging from 0 to 100%.

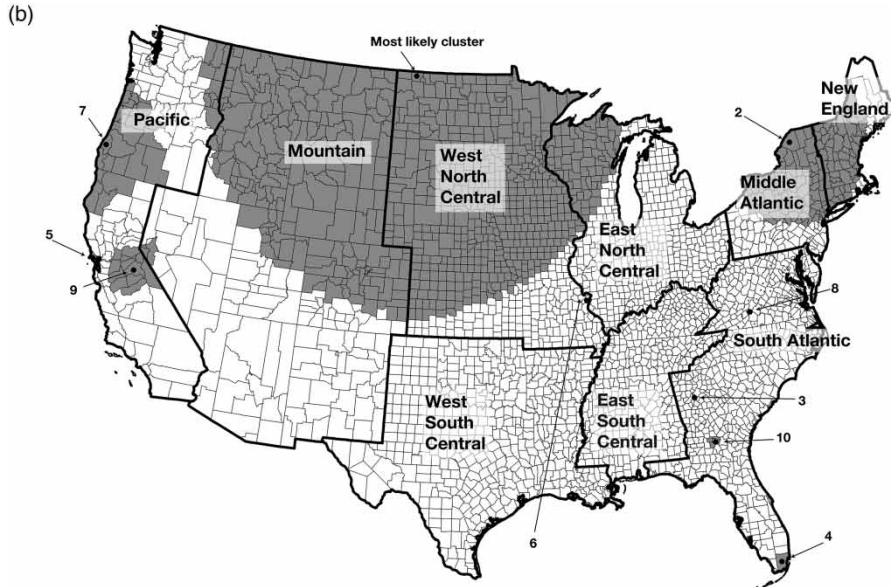
Geographic distributions

Overall, 14.8% of households were reliant on a private well and 24.1% were reliant on a septic system (these estimates include North Carolina and Texas). Visually, counties with high private well reliance were clustered in West and East

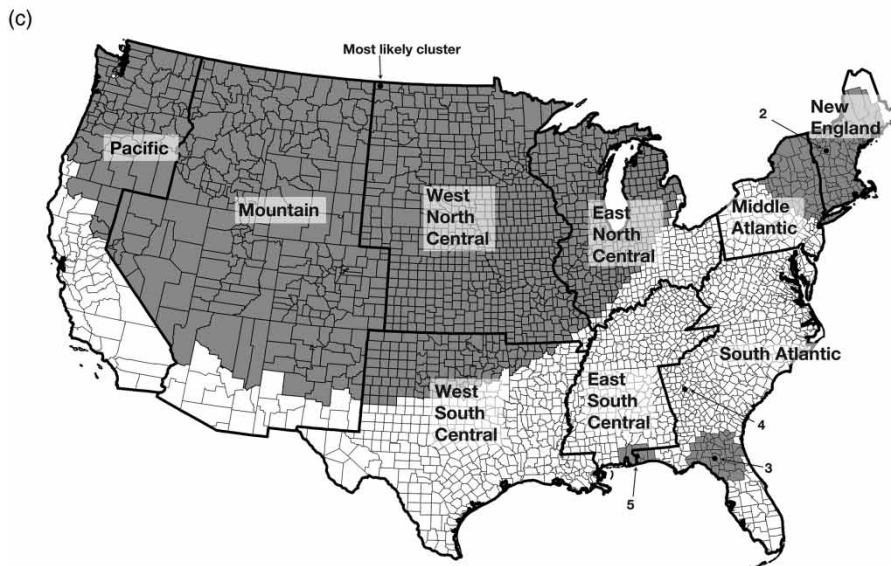
North Central, Middle and South Atlantic, and New England census divisions (Figure 3(a)). These regions of high private well reliance correspond with the locations of most of the high rate giardiasis clusters. Septic system patterns showed fewer geographic associations with giardiasis clusters, with counties with high septic system reliance concentrated in West and East South Central and South Atlantic census divisions (Figure 3(b)).

Modeling

Giardiasis IR and incidence rate ratios, by categories of well reliance, septic reliance, year, and demographics, are shown



	Observed	Expected [†]	LLR [‡]		Observed	Expected	LLR
Most likely	28,288	16,283	4,120	Cluster 6	740	212	399
Cluster 2	29,228	18,118	3,302	Cluster 7	3,501	2,105	391
Cluster 3	1,878	442	1,288	Cluster 8	228	27	283
Cluster 4	1,587	359	1,134	Cluster 9	1,035	489	231
Cluster 5	989	294	507	Cluster 10	82	17	66



	Observed	Expected [†]	LLR [‡]		Observed	Expected	LLR
Most likely	82,426	51,069	9,721	Cluster 4	1,878	561	954
Cluster 2	41,984	20,165	9,674	Cluster 5	533	354	39
Cluster 3	3,677	1,268	1,514				

Figure 2 | continued.

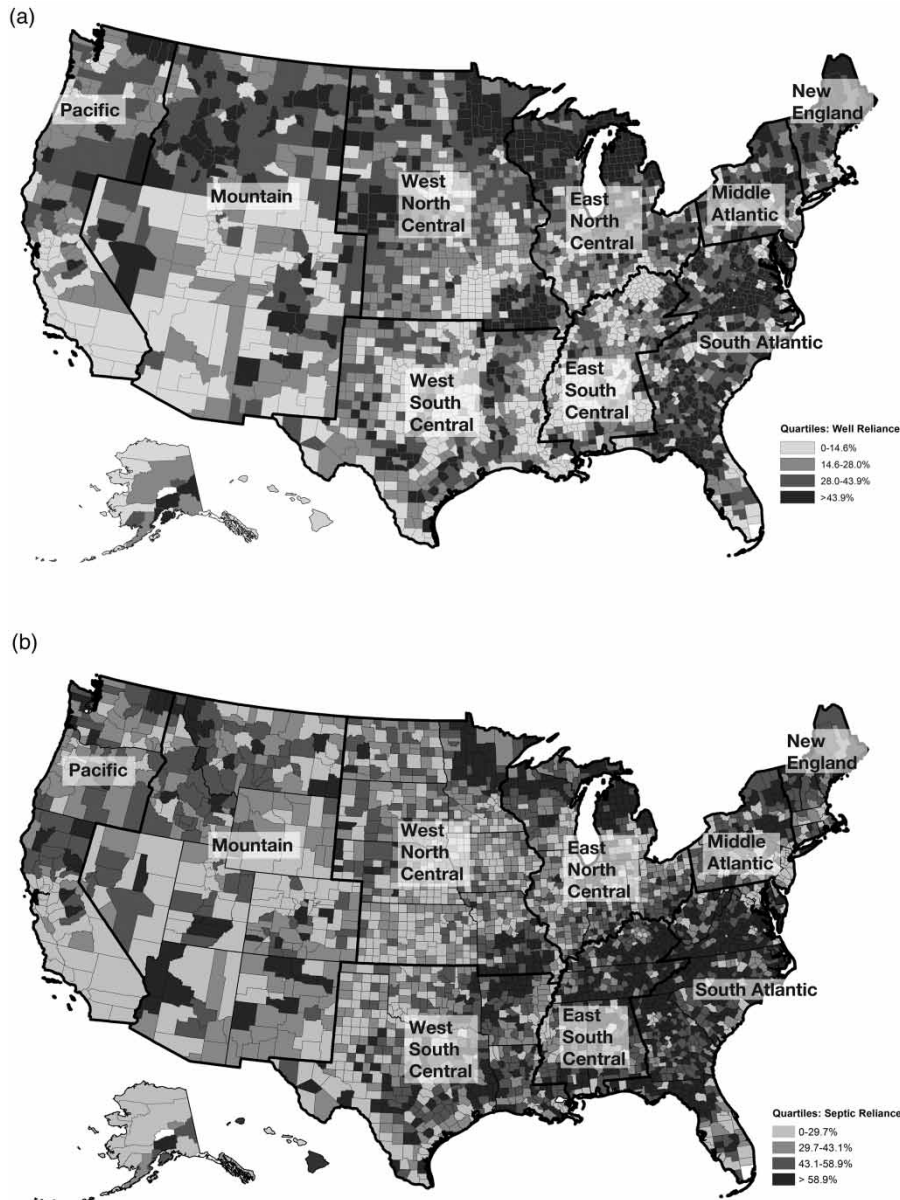


Figure 3 | Private well and septic tank reliance, by county—US Census, 1990. (a) Percent of county reliant on a private well, by quartile and (b) percent of county reliant on a septic tank or cesspool, by quartile.

in [Table 1](#). Giardiasis IRs were similar in rural and urban areas and across all levels of income and cattle density (not shown); therefore, these variables were not considered in the final multivariable model. Although several statistically significant interactions were observed, all had little or no public health significance and were ruled out by consideration of BIC or $<10\%$ differences in the magnitude of effects between strata.

Prior to adjustment, counties with higher private well reliance, lower septic system reliance, higher levels of education, and lower housing unit owner occupancy rates had the highest giardiasis IR ([Table 1](#)). Consistent with the incidence rate maps and SaTScan clusters, the highest unadjusted giardiasis IRs were seen in New England (18.4, CI 16.3–20.8) and the Middle Atlantic (12.4, CI 11.4–13.4),

Table 1 | County-level univariable and multivariable associations between giardiasis IR and private well reliance, septic tank reliance, and demographic data

	Unadjusted incidence rate (95% CI)	Unadjusted incidence rate ratio (95% CI)	Adjusted incidence rate ratio (95% CI)
Private wells			
< 14.6%	7.5 (7.1, 7.8)	1	1
14.6– < 28.0%	7.7 (7.3, 8.1)	1.0 (0.97, 1.1)	1.0 (0.98, 1.1)
28.0– < 43.9%	9.1 (8.7, 9.5)	1.2 (1.1, 1.3)	1.2 (1.1, 1.3)
≥ 43.9%	8.9 (8.5, 9.3)	1.2 (1.1, 1.3)	1.3 (1.2, 1.5)
Septic systems			
< 29.7%	9.2 (8.8, 9.7)	1	1
29.7– < 43.1%	8.6 (8.2, 9.0)	0.93 (0.87, 0.99)	0.95 (0.89, 1.0)
43.1–58.9%	8.0 (7.7, 8.4)	0.87 (0.81, 0.93)	0.94 (0.87, 1.0)
≥ 58.9%	7.2 (6.8, 7.5)	0.77 (0.73, 0.83)	0.96 (0.87, 1.1)
Year			
1993–2001	9.7 (9.4, 10.0)	1	1
2002–2010	6.8 (6.5, 7.0)	0.70 (0.67, 0.73)	0.70 (0.67, 0.73)
High school degree (2000)			
< 76.1%	4.7 (4.5, 4.9)	1	1
76.1– < 81.4%	7.4 (7.1, 7.8)	1.6 (1.5, 1.7)	1.2 (1.1, 1.3)
81.4– < 85.4%	9.6 (9.2, 10.0)	2.1 (1.9, 2.2)	1.4 (1.3, 1.5)
≥ 85.4%	11.3 (10.8, 11.8)	2.4 (2.3, 2.6)	1.5 (1.4, 1.7)
Owner occupancy (2000)			
< 69.2%	9.5 (9.1, 10.0)	1.3 (1.2, 1.4)	1.2 (1.1, 1.3)
69.2– < 74.5%	8.7 (8.3, 9.1)	1.2 (1.1, 1.3)	1.1 (1.0, 1.2)
74.5– < 78.4%	7.6 (7.3, 8.0)	1.1 (0.99, 1.1)	1.0 (0.94, 1.1)
≥ 78.4%	7.2 (6.8, 7.5)	1	1
Census division			
New England	18.4 (16.3, 20.8)	5.5 (4.7, 6.3)	3.3 (2.9, 3.9)
Middle Atlantic	12.4 (11.4, 13.4)	3.7 (3.3, 4.1)	2.5 (2.3, 2.8)
East North Central	9.1 (8.7, 9.5)	2.7 (2.5, 3.0)	1.9 (1.7, 2.0)
West North Central	10.2 (9.7, 10.6)	3.0 (2.8, 3.3)	2.2 (2.0, 2.4)
South Atlantic	5.6 (5.4, 5.9)	1.7 (1.5, 1.8)	1.4 (1.3, 1.5)
East South Central	3.6 (3.4, 3.9)	1.1 (0.96, 1.2)	0.93 (0.84, 1.0)
West South Central	3.4 (3.1, 3.6)	1	1
Mountain	9.7 (9.1, 10.3)	2.9 (2.6, 3.2)	2.0 (1.8, 2.2)
Pacific	10.9 (10.0, 11.9)	3.2 (2.9, 3.6)	2.2 (2.0, 2.5)

with the lowest rates in the East and West South Central divisions.

After multivariable adjustment for all variables shown in Table 1, the association between septic system reliance and giardiasis lost its statistical significance (aIRR ~ 1). The associations between giardiasis and higher private well reliance, higher levels of education, and lower owner

occupancy rates, however, remained significant. Census division results remained consistent with the SaTScan clusters; the census division aIRRs had the same directionality, but lower magnitude, than the corresponding uIRRs.

Examination of standardized deviance residual plots identified several outliers; these were among the highest incidence county/year combinations in the dataset. None of these

corresponded with known giardiasis outbreaks reported to the Waterborne Disease and Outbreaks Surveillance System.

In the sensitivity analyses, 22,825 outbreak-associated cases, 26,371 travel-associated cases, and 47,046 travel and/or outbreak-associated cases were excluded. Excluding these cases resulted in no changes in the direction of associations between predictors and giardiasis, and <10% changes in the incidence rate and incidence rate ratio magnitudes for most variables, with the exception that the IRR for the South Atlantic region vs. West South Central was lower with outbreak-associated cases excluded. When the analyses were stratified by age group, IRRs for most variables (including private well and septic reliance) were similar in both age strata; exceptions included region and education, in which IRRs were smaller in the 0–19 age group than in the 20+ age group (not shown).

DISCUSSION

Results from our novel epidemiologic and geospatial analysis of giardiasis in the United States suggest higher county-level rates of private well reliance are associated with higher rates of giardiasis. County-level septic system reliance was not associated with giardiasis rates. Even in the final model, region was associated with giardiasis rates. To our knowledge, this is the first study in the USA to assess the relationship between giardiasis incidence, water source, sanitation method, and region at the national level. While household water source has been implicated in the transmission of giardiasis in outbreaks, and linked with giardiasis transmission in regional analyses (Chute *et al.* 1987; Birkhead & Vogt 1989; Dennis *et al.* 1993; Naumova *et al.* 2000; Odoi *et al.* 2004a), our study of giardiasis in the entire USA suggests household water sources are broadly relevant to giardiasis transmission in the United States.

In our adjusted analysis, we found 1.3 times higher rates of giardiasis in counties with high (4th quartile) private well reliance than those with low (1st quartile) well reliance. These results are consistent with those from previous studies (Birkhead & Vogt 1989; Dennis *et al.* 1993; Uhlmann *et al.* 2009). For example, a cross-sectional study in British Columbia, Canada, found that persons receiving their drinking

water from private wells had an average giardiasis rate more than four times that of those receiving municipal groundwater (Uhlmann *et al.* 2009). A summary of surveillance data in Vermont found that those with non-municipal residential water supplies had an approximately 30% excess risk of symptomatic giardiasis compared to those receiving public water (Birkhead & Vogt 1989). Using an ecological study design (i.e. county-level exposure and outcome data) (Bhopal 2002), our study expands on these findings by analyzing >15 years of giardiasis surveillance data at a national level.

The timing of implementation of US Environmental Protection Agency (EPA) regulations potentially supports our finding that private wells are an important source of giardiasis transmission in the USA. In the 2000s, the Long Term Surface Water Treatment Rules were implemented. These regulations were designed to target chlorine-tolerant pathogens, such as *Giardia*, in public water systems (United States Environmental Protection Agency 2002, 2006). Since 2002, however, national giardiasis rates have been relatively stable. Assuming the Long Term Surface Water Treatment rules were effective at removing giardiasis from public water supplies, the steady giardiasis rates suggest public water systems are no longer a major route of US giardiasis transmission. Instead, as our results suggest, unregulated water supplies, such as private wells, might be a more important route.

We hypothesized that poorly maintained septic systems might contribute to giardiasis transmission. Each year, 10–20% of septic systems in the USA malfunction, creating the potential for sewage to enter ground and surface water (United States Environmental Protection Agency 2013). In our analysis, however, county-level septic system reliance was not associated with giardiasis rates (IRRs ~ 1). Previous studies linked intestinal pathogens to septic systems. A case-control study in central Wisconsin, for example, identified septic system density as a risk factor for sporadic viral and bacterial diarrhea in children (Borchardt *et al.* 2003). Similarly, a review published in 1985 described several outbreaks of bacterial and viral diarrhea in which septic systems contaminated private wells (Yates 1985). Given the relatively large size of *Giardia* organisms, it is possible the cysts are captured more effectively in septic fields than bacteria and viruses, thus accounting for the lack of association

between septic systems and giardiasis (Perkins 1984; Lipp *et al.* 2001).

There are several other mechanisms by which private wells could become contaminated with *Giardia*. Previous studies have suggested that groundwater contamination with surface water could be a source of giardiasis in private wells (Dennis *et al.* 1993; Odoi *et al.* 2004a). Agricultural run-off, industrial discharge, and sewage have been suggested as potential surface water sources of *Giardia*. For example, a water sample survey conducted in 17 states from 1985–1988 found *Giardia* most commonly in surface water sources receiving sewage and agricultural discharge (Rose *et al.* 1991). Similarly, a cross-sectional study conducted in the USA and Canada from 1989–1990 found an association between higher *Giardia* cyst concentrations and surface water contamination with industrial or sewage discharges (LeChevallier *et al.* 1991). In our study, we found no association between cattle density (a potential marker of agricultural run-off) and giardiasis. Our finding is consistent with research showing that most animals are infected with *Giardia* assemblages (genotypes) that do not cause infection in humans (Olson *et al.* 2004; Oates *et al.* 2012). Thus, groundwater contamination with sewage from public sewers, in contrast to agricultural runoff and well contamination from septic fields, might be particularly important in giardiasis transmission. Notably, the US EPA estimates there are over 9,000 combined sewer overflows and 23,000–75,000 sanitary sewer overflows every year, which can lead to contamination of drinking water supplies (United States Environmental Protection Agency 2001, 2004).

While our results suggest private wells are broadly relevant to giardiasis transmission in the USA, we were not able to fully explain regional differences in giardiasis rates. We attempted to control for other known giardiasis risk factors, such as travel and childcare center exposure (Chute *et al.* 1987; Dennis *et al.* 1993; Hoque *et al.* 2002; Snel *et al.* 2009), using demographic data. However, both county demographics and frequency of private well use varied greatly within our identified space-time giardiasis clusters. Similarly, in an analysis of giardiasis clusters in Southern Ontario, the distribution of clusters coincided with the distribution of livestock/manure risk factors in only one area (Odoi *et al.* 2004b). Thus, our results suggest the importance

of different sources of giardiasis transmission, such as private wells, might vary regionally.

Limitations

Due to our ecological study design, we examined community-level exposures; we were unable to properly control for known giardiasis risk factors more appropriately assessed at the individual level, such as camping, swimming in untreated recreational water venues, exposure to childcare centers, and person-to-person transmission (Birkhead & Vogt 1989; Dennis *et al.* 1993; Hoque *et al.* 2002). We were also unable to assess causation and whether our results represent the sum of individual-level associations or broader associations related to the importance of place in health (Diez Roux 2001). As our outcome was based on passive surveillance data from NNDSS, our data are subject to diagnosis and reporting biases. NNDSS only captures symptomatic cases; as such, the outcome did not include individuals with asymptomatic giardiasis. Misclassification of these asymptomatic cases as uninfected likely diluted the effect of environmental factors on giardiasis rates and biased our results towards the null. NNDSS does include information on case association with known outbreaks; excluding these cases in a sensitivity analysis did not change the direction of any of the associations, and changed the magnitude of most associations by <10%. Despite the lack of association between outliers identified in the residual plots and giardiasis outbreaks reported to the Waterborne Disease and Outbreaks Surveillance System, we think the most likely interpretation of these outliers is that these high incidence observations represent unidentified outbreaks. Thus, we cannot claim our results only represent associations with non-outbreak giardiasis. Finally, location-specific household water and sanitation data has not been systematically collected since 1990. Results from the 2011 American Housing Survey suggest private well (15 to 11%) and septic system (25 to 19%) reliance have decreased since the 1990 Census (United States Census Bureau 2011). However, as the American Housing Survey does not provide geographic information, we do not have data on how the geographic distribution of water source and sanitation system reliance has changed.

Next steps

Our linkage of environmental characteristics with giardiasis rates is a first step towards improving our understanding of the national relationship between water sources, sanitation methods, region, and giardiasis. Including additional hydrogeological, environmental, and climatologic data in future analyses, such as karst hydrogeology; temperature ranges and patterns; and public water system characteristics such as water source filtration and disinfection, might further improve our understanding of waterborne giardiasis transmission in the USA.

Previous exposure to giardiasis confers some protection against reinfection (Istre *et al.* 1984; Isaac-Renton *et al.* 1994). Because of this, we hypothesized the associations between environmental risk factors and giardiasis would be stronger in the younger (0–19) age group, as this group might be less likely to have previous exposure to *Giardia*. While we did observe higher giardiasis rates in younger people, in age-stratified models, the IRRs for private wells and septic system reliance did not vary meaningfully by age group. While the results of this study did not provide support to the hypothesis about greater immunity in older persons, the ecological study design might not be well-suited to address this question. To more precisely assess the impact of immunity on the epidemiology of giardiasis in the USA, serologic studies and stool surveys would be useful (Smith *et al.* 1981; Cedillo-Rivera *et al.* 2009; Moss *et al.* 2014).

CONCLUSIONS

Giardiasis is the most commonly reported intestinal parasitic infection in the USA; yet, non-outbreak routes of transmission are poorly understood. Our results suggest that the importance of specific giardiasis risk factors might vary regionally. In general, however, private well maintenance, including routine microbial testing, is likely an important component of giardiasis prevention.

Our results also highlight the need for up-to-date, location-specific national data on household water sources and sanitation methods. Without ongoing data collection, it is difficult to accurately explain national changes in waterborne disease rate patterns and design, and implement

evidence-based waterborne disease prevention programs. More broadly, it is difficult to assess the population-level health impacts of changes in water and sanitation infrastructure, such as changes in water treatment regulations and an evolving reliance on unregulated water and sanitation systems.

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DISCLAIMER

The findings and conclusions in this report are those of the authors and should not be construed to represent any agency determination or policy.

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