Exposure to Industrial Hog and Poultry Operations and Urinary Tract Infections in North Carolina, USA: Supplementary Material

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This supplement contains 22 pages, 2 figures, and 6 tables.

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S1. Covariate Selection

We considered known urinary tract infection (UTI) risk factors and available Census variables to assemble a set of covariates for inclusion in this analysis (Foxman, 2010). We used directed acyclic graphs (DAG) to identify the potential confounders of the livestock density and UTI emergency department (ED) visit relationship (Fleischer and Roux, 2008; Tennant et al., 2020). The minimally sufficient adjustment set (Figure S1) was determined using the **R** package *daggity* to specify and evaluate the DAGs (Textor et al., 2017).

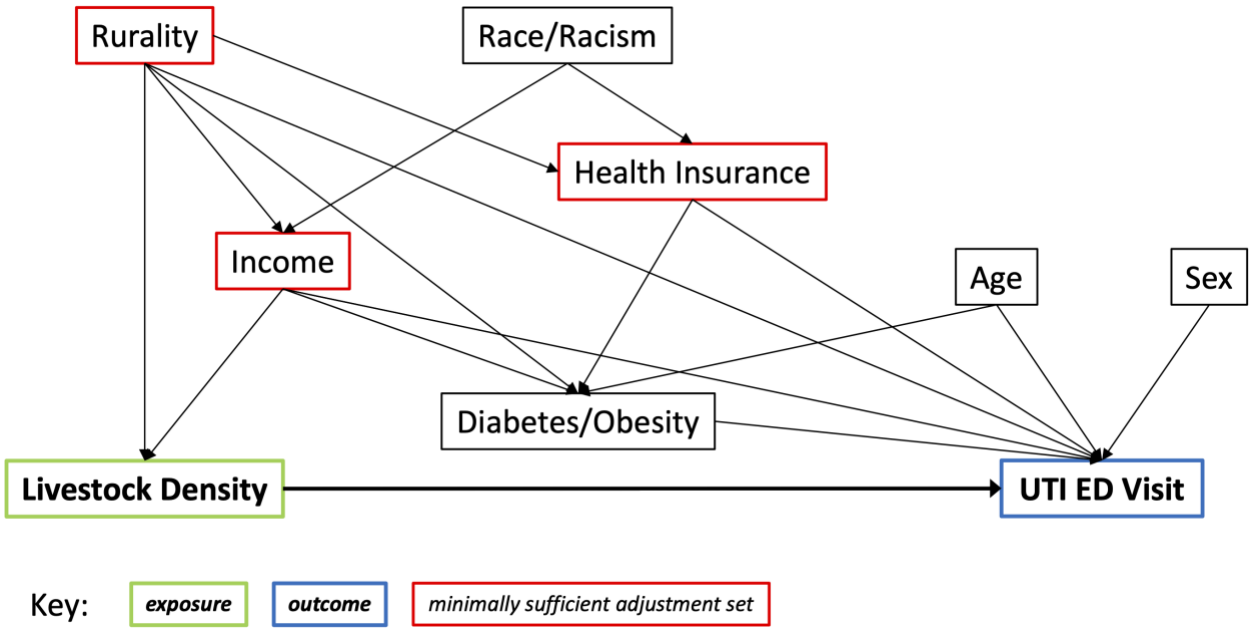

Figure S1. Directed acyclic graph.

S2. Density Calculation Buffer Distance

Exposure variables were derived from counts of hogs and poultry housed in confined animal feeding operations (CAFOs), for which the point locations were known. However, the outcome and many other covariates of interest were available only in aggregate by ZIP codes (which correspond to postal delivery routes), requiring aggregation of the livestock counts over the same areal units in order to express exposures on the same spatial scale as the outcomes (Best et al., 2000; Briant et al., 2010; Parenteau and Sawada, 2011). The simplest aggregation approach, summing the animal counts for all CAFOs located in a given ZIP code and dividing by ZIP code area to obtain the animal spatial density for each ZIP code, carries the implicit assumption that the population is uniformly spatially distributed across the ZIP code and also ignores any contributions from CAFOs located near ZIP code residents but outside of the ZIP code boundaries. A buffer distance may be extended around the boundary of each ZIP code to incorporate nearby CAFO locations, but doing so increases the area over which uniform population distribution is assumed, potentially exacerbating exposure assessment error in the presence of population clustering within the ZIP code.

To partially address concerns about population clustering, we instead estimated animal exposures at a finer spatial resolution by aggregating animal counts within census blocks and assigning census blocks to ZIP codes on the basis of the block geographic centroid. We applied buffers to the block boundaries to capture nearby CAFOs, calculated spatial densities using the combined area of the block and its buffer region as the denominator, and used the block population to estimate a population-weighted mean density across all the blocks in the ZIP code. This approach produces a single animal exposure estimate per ZIP code that is weighted by the ZIP code population that may be exposed to CAFOs through residential proximity, including

CAFOs outside the ZIP code boundary but within the selected buffer distance of populated census blocks. Previous studies of CAFO-related pollution have considered proximity to CAFO locations ranging from approximately 0.5 km to 20 km (Casey et al., 2015; Christenson et al., 2022; de Rooij et al., 2019; Quist et al., 2022; Son et al., 2021a, 2021b; Wiesner-Friedman et al., 2022). We assessed the impact of buffer distance on the distribution of exposures and estimated associations with UTI incidence as a sensitivity analysis. Exposures were estimated using buffer distances of 0 (no buffer), 1, 3, 5, 10, and 15 km around census blocks and compared to the unweighted spatial density obtained using only CAFOs located within ZIP code boundaries. Buffer distances greater than 15 km resulted in substantial overlap between large numbers of blocks and CAFOs that required performing a computationally infeasible number of spatial intersection calculations.

Increasing the buffer distance increased the number of ZIP codes considered exposed (>0 density) and reduced the number of ZIP codes considered unexposed (Table S1). This was particularly notable with poultry, for which the 15 km buffer resulted in only 122 unexposed ZIP codes compared with 498 exposed ZIP codes. Increasing buffer distance also compressed the distribution of exposures, reducing the maximum estimated spatial density and the range of densities in each category of exposure. While the estimated UTI rate ratios generally increased with increasing buffer distance for hog exposures (Figure S2), the pattern for poultry exposure was far less consistent and the effects on model predictive performance were minimal for both animals (Table S2). We therefore selected a buffer distance of 5 km (~3 miles), which provided reasonable exposure distributions and aligns with many literature reports of elevated risks of various contaminants and health outcomes for residents within ~1 – 8 km of CAFOs, with risks

diminishing after ~5 – 8 km (Anker et al., 2018; Casey et al., 2013; Kravchenko et al., 2018; Quist et al., 2022; Williams et al., 2011).

Table S1. Exposure characteristics by buffer distance used to calculate livestock spatial density

		Hog				Poultry			
Exposure Category	**Buffer**	**Density (count/km^2)**	**ZIP codes**	**UTI episodes**	**Person-years**	**Density (count/km^2)**	**ZIP codes**	**UTI episodes**	**Person-years**
unexposed	unweighted	0	423	338980	18352834	0	268	155756	9203441
	no buffer	0	428	338919	18339512	0	270	156880	9265701
	1km buffer	0	391	309033	16827178	0	241	123986	7711641
	3km buffer	0	359	283077	15480500	0	206	99020	6314277
	5km buffer	0	324	253202	14016758	0	184	85070	5375900
	10km buffer	0	282	214411	12040725	0	152	67158	4215480
	15km buffer	0	248	188165	10283557	0	122	42938	2745625
low	unweighted	>0 - 21	66	69239	2911012	>0 - 2245	118	160453	7263712
	no buffer	>0 - 8	64	80263	3246316	>0 - 1208	117	174662	7978015
	1km buffer	>0 - 6	77	94823	4190070	>0 - 1093	126	181419	8335648
	3km buffer	>0 - 4	87	98029	4683170	>0 - 922	138	173300	8342258
	5km buffer	>0 - 4	99	109814	5375323	>0 - 887	145	172628	8531930
	10km buffer	>0 - 5	113	118259	5897359	>0 - 1055	156	152204	8117585
	15km buffer	>0 - 5	124	121479	6646375	>0 - 1001	166	152207	8238083
medium	unweighted	21 - 100	66	62034	2635169	2245 - 6630	117	120724	5599231
	no buffer	8 - 53	64	64956	2735456	1208 - 5414	117	129480	5788891
	1km buffer	6 - 46	76	64711	2698387	1093 - 5078	126	141339	6413814
	3km buffer	4 - 44	87	76686	3142937	922 - 4722	138	163845	7345921
	5km buffer	4 - 36	99	89350	3648783	887 - 4833	146	169125	7716740
	10km buffer	5 - 32	113	104180	4609025	1055 - 4721	156	180238	8259216
	15km buffer	5 - 32	124	101904	4719901	1001 - 4591	166	178570	8634591
high	unweighted	100 - 1931	65	57814	2157828	6630 - 47011	118	91134	3990459
	no buffer	53 - 1392	64	43929	1735559	5414 - 45384	116	67045	3024236
	1km buffer	46 - 1268	76	59500	2341208	5078 - 47267	126	81323	3595740
	3km buffer	44 - 1140	87	70275	2750236	4722 - 40611	138	91902	4054387
	5km buffer	36 - 1099	98	75701	3015979	4833 - 39499	145	101244	4432273
	10km buffer	32 - 1155	112	91217	3509734	4721 - 32130	156	128467	5464562
	15km buffer	32 - 1043	124	116519	4407010	4591 - 29092	166	154352	6438544

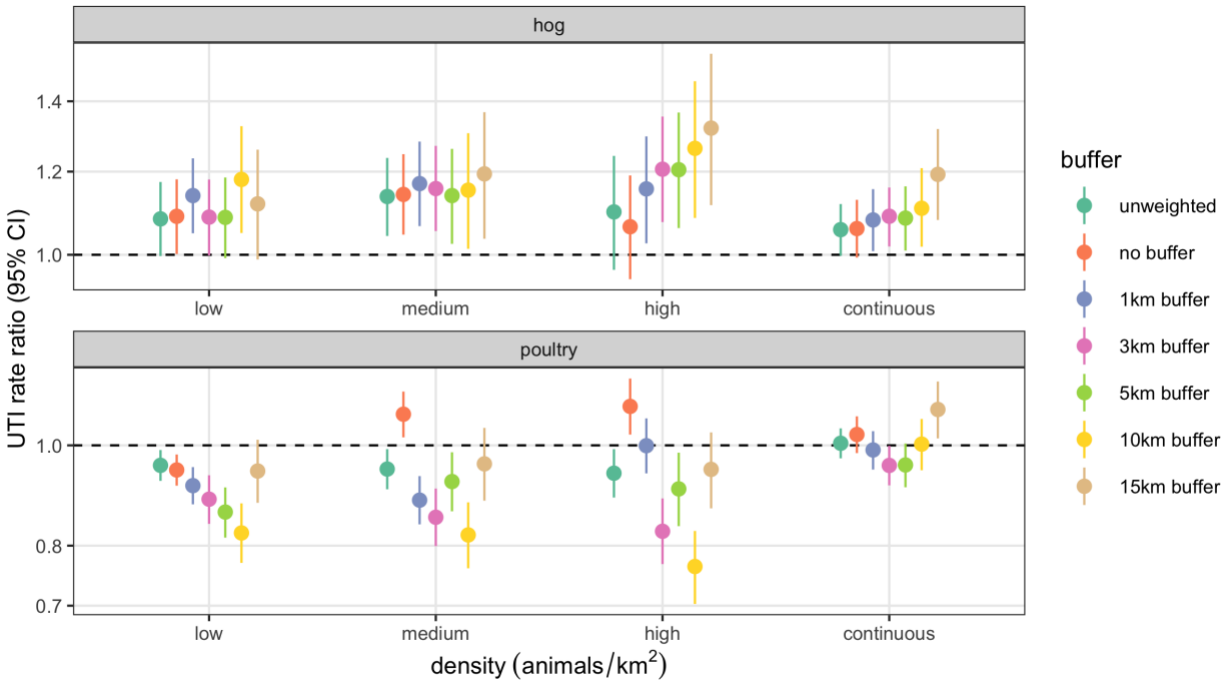

Figure S2. UTI rate ratio estimates for exposure to hogs and poultry buffer distance used to define livestock density exposure. Unweighted buffer distance indicates the ZIP code boundary alone was used to calculate livestock spatial density. All other distances refer to the buffer around each census block used to determine block-specific livestock spatial density, from which population-weighted mean ZIP code density was calculated using 2010 block population.

Table S2. In-sample prediction error by buffer distance used to define livestock spatial density. Unweighted buffer distance indicates the ZIP code boundary alone was used to calculate livestock spatial density. All other distances refer to the buffer around each census block used to determine block-specific livestock spatial density, from which population-weighted mean ZIP code density was calculated using 2010 block population.

	Median Prediction RMSE[a] (UTI episodes)			
	Hog		**Poultry**	
Buffer	**Categorical**	**Continuous**	**Categorical**	**Continuous**
unweighted	31.95	31.94	31.9	31.96
no buffer	31.94	31.96	31.57	31.94
1km buffer	31.96	31.95	31.4	31.95
3km buffer	31.95	31.94	31.78	31.94
5km buffer	31.95	31.96	31.75	31.91
10km buffer	31.95	31.95	31.74	31.95
15km buffer	31.94	31.95	31.95	31.96

[a] RMSE: root mean square error, calculated at the median of the posterior predictive distribution of UTI episodes for each observation.

S3. Spatial Variance

A combined random effect, comprising both spatially structured and heterogenous (unstructured) components, was estimated for each ZIP code to account for overdispersion of UTI incidence rates. The magnitude of overdispersion was estimated as the overall variance of the combined random effects, which describes the extent to which rates vary between ZIP codes after accounting for the effect of the exposure and other covariates included in the model as fixed effects. Estimates of the residual variance and the proportion of the residual variance that was explained by spatial autocorrelation in rates between neighboring ZIP codes are presented in Table S3 for each model specification that we fit, including models assessing joint exposures and effect measure modification (EMM).

Table S3. Variance of the combined random effect and the spatial variance proportion estimates for all BYM2 models of UTI rate conducted for the main analysis

model	exposure	animal	residual variance (95% CI)	spatial variance proportion ρ (95% CI)
intercept only	continuous	null	1.37 (1.31, 1.43)	0.96 (0.92, 0.99)
single exposure	categorical	hog	1.32 (1.27, 1.37)	0.96 (0.92, 0.99)
single exposure	categorical	poultry	1.32 (1.28, 1.38)	0.96 (0.92, 0.99)
single exposure	continuous	hog	1.32 (1.27, 1.37)	0.96 (0.92, 0.99)
single exposure	continuous	poultry	1.33 (1.28, 1.38)	0.96 (0.93, 0.99)
mutually adjusted	categorical	hog & poultry	1.32 (1.27, 1.37)	0.96 (0.92, 0.99)
mutually adjusted	continuous	hog & poultry	1.32 (1.28, 1.38)	0.96 (0.93, 0.99)
joint exposure	categorical	hog & poultry	1.31 (1.26, 1.36)	0.96 (0.92, 0.99)
joint exposure	continuous	hog & poultry	1.34 (1.28, 1.39)	0.96 (0.93, 0.99)
EMM by year	categorical	hog	1.35 (1.29, 1.41)	0.96 (0.92, 0.99)
EMM by year	categorical	poultry	1.35 (1.30, 1.42)	0.96 (0.92, 0.99)
EMM by year	continuous	hog	1.35 (1.29, 1.41)	0.96 (0.92, 0.99)
EMM by year	continuous	poultry	1.35 (1.30, 1.42)	0.96 (0.93, 0.99)
EMM by sex	categorical	hog	1.30 (1.25, 1.36)	0.96 (0.91, 0.99)
EMM by sex	categorical	poultry	1.31 (1.26, 1.36)	0.96 (0.92, 0.99)
EMM by sex	continuous	hog	1.30 (1.26, 1.36)	0.96 (0.92, 0.99)
EMM by sex	continuous	poultry	1.31 (1.26, 1.37)	0.96 (0.93, 0.99)
EMM by age	categorical	hog	1.30 (1.25, 1.36)	0.96 (0.91, 0.99)
EMM by age	categorical	poultry	1.31 (1.26, 1.37)	0.96 (0.92, 0.99)
EMM by age	continuous	hog	1.30 (1.26, 1.36)	0.96 (0.92, 0.99)
EMM by age	continuous	poultry	1.32 (1.27, 1.37)	0.96 (0.92, 0.99)
EMM by race/ethnicity	categorical	hog	1.41 (1.35, 1.48)	0.96 (0.92, 0.99)
EMM by race/ethnicity	categorical	poultry	1.42 (1.35, 1.50)	0.96 (0.92, 0.99)
EMM by race/ethnicity	continuous	hog	1.41 (1.35, 1.49)	0.96 (0.92, 0.99)
EMM by race/ethnicity	continuous	poultry	1.42 (1.36, 1.50)	0.96 (0.93, 0.99)
EMM by rurality	categorical	hog	1.32 (1.27, 1.37)	0.96 (0.91, 0.98)
EMM by rurality	categorical	poultry	1.33 (1.28, 1.39)	0.96 (0.92, 0.99)
EMM by rurality	continuous	hog	1.32 (1.27, 1.38)	0.96 (0.92, 0.99)
EMM by rurality	continuous	poultry	1.33 (1.28, 1.39)	0.96 (0.93, 0.99)
EMM by insurance	categorical	hog	1.29 (1.24, 1.34)	0.95 (0.89, 0.98)
EMM by insurance	categorical	poultry	1.29 (1.25, 1.34)	0.95 (0.91, 0.98)
EMM by insurance	continuous	hog	1.29 (1.24, 1.34)	0.95 (0.90, 0.98)

S4. Effect Estimates

Estimates of the RR and 95% CI for each joint hog and poultry exposure category on UTI incidence rates, as depicted in Figure 4 of the main text, are presented in Table S4. Likewise, Table S5 presents the RR estimates for each stratum of potential effect measure modifier shown in Figure 3 of the main text, separately for hogs and poultry. Table S6. provides additional detail on the population fraction and crude rates of UTI episodes and ED visits by combined race/ethnicity and hog exposure category.

Table S4. UTI rate ratio estimates for joint categorical exposure to hogs and poultry relative to areas with no exposure to either animal. Low, medium, and high exposure categories correspond to tertiles of non-zero density values. Models were adjusted for ZIP code isolation score, median household income, and percent lacking health insurance.

Hog density (count/km2)	Poultry density (count/km2)	ZIP codes[a] (observations)	UTI episodes (outcome)	Person-years (offset)	RR (95% CI)
Unexposed (0)	Unexposed (0)	154	64004	4352470	(ref)
	Low (>0 - 887)	78	87623	4708425	0.97 (0.89, 1.05)
	Medium (887 - 4833)	56	76812	3762531	1.06 (0.96, 1.16)
	High (4833 - 39499)	35	24763	1193332	0.99 (0.85, 1.15)
Low (>0 - 4)	Unexposed (0)	20	15808	820874	1.33 (1.17, 1.52)
	Low (>0 - 887)	29	44859	2140262	1.06 (0.93, 1.20)
	Medium (887 - 4833)	26	34240	1635517	1.04 (0.91, 1.18)
	High (4833 - 39499)	23	14907	778670	1.06 (0.91, 1.22)
Medium (4 - 36)	Unexposed (0)	7	4013	148164	1.44 (1.10, 1.83)
	Low (>0 - 887)	25	35719	1420455	1.19 (1.03, 1.37)
	Medium (887 - 4833)	32	28025	1168889	1.13 (0.98, 1.29)
	High (4833 - 39499)	35	21593	911275	1.09 (0.94, 1.25)
High (36 - 1099)	Unexposed (0)	2	1245	54392	1.51 (1.19, 1.89)
	Low (>0 - 887)	12	4427	262788	1.05 (0.88, 1.24)
	Medium (887 - 4833)	31	30048	1149803	1.28 (1.10, 1.48)
	High (4833 - 39499)	52	39981	1548996	1.25 (1.07, 1.45)

[a] average number of ZIP codes in each hog/poultry joint exposure category 2016-2019

Table S5. Analysis of effect measure modification of the association between hog or poultry exposure and UTI incidence by calendar year, sex, age group, race/ethnicity, health insurance, and rurality. Modification was assessed on the multiplicative scale in single-animal models using product-term interactions between exposure group and the effect measure modifier and rate ratios as the measure of effect. Low, medium, and high exposure categories correspond to tertiles of non-zero density values, with zero-density ZIP codes as the reference group. Models were adjusted for ZIP code isolation score, median household income, and percent lacking health insurance.

		Hog				Poultry			
Group	**Density (count/km^2)**	**ZIP codes[a]**	**UTI episodes**	**Person-years**	**RR (95% CI)**	**ZIP codes[a]**	**UTI episodes**	**Person-years**	**RR (95% CI)**
Main analysis									
All	unexposed	324	253202	14016758	(ref)	184	85070	5375900	(ref)
	low	99	109814	5375323	1.09 (0.99, 1.19)	145	172628	8531930	0.86 (0.81, 0.91)
	medium	99	89350	3648783	1.14 (1.02, 1.27)	146	169125	7716740	0.92 (0.86, 0.98)
	high	98	75701	3015979	1.21 (1.06, 1.37)	145	101244	4432273	0.91 (0.84, 0.98)
	continuous	620	528067	26056843	1.08 (1.01, 1.16)	620	528067	26056843	0.96 (0.91, 1.00)
Year									
2016	unexposed	81	64704	3452532	(ref)	46	21496	1345050	(ref)
	low	25	27484	1325006	1.06 (0.97, 1.16)	37	44133	2118496	0.89 (0.84, 0.94)
	medium	25	22195	904947	1.12 (1.00, 1.25)	36	42691	1889938	0.97 (0.90, 1.04)
	high	24	18498	752283	1.17 (1.02, 1.33)	35	24561	1081284	0.93 (0.85, 1.01)
	continuous	155	132881	6434768	1.06 (0.98, 1.14)	155	132881	6434768	0.96 (0.91, 1.01)
2017	unexposed	81	65271	3485235	(ref)	46	22797	1362961	(ref)
	low	25	27861	1335261	1.07 (0.97, 1.17)	37	44271	2128046	0.85 (0.80, 0.90)
	medium	25	22632	908928	1.14 (1.01, 1.27)	36	42010	1891114	0.91 (0.85, 0.98)
	high	24	19195	756000	1.20 (1.06, 1.37)	36	25881	1103303	0.92 (0.84, 1.00)
	continuous	155	134959	6485424	1.09 (1.01, 1.17)	155	134959	6485424	0.97 (0.92, 1.02)
2018	unexposed	81	63129	3521530	(ref)	46	20497	1327010	(ref)
	low	25	27554	1351872	1.09 (0.99, 1.20)	36	42296	2132255	0.89 (0.83, 0.94)
	medium	25	22048	912642	1.15 (1.03, 1.28)	37	43625	1967395	0.98 (0.91, 1.05)
	high	24	19274	754224	1.26 (1.11, 1.44)	37	25587	1113608	0.97 (0.89, 1.06)
	continuous	155	132005	6540268	1.11 (1.03, 1.19)	155	132005	6540268	0.98 (0.94, 1.03)
2019	unexposed	81	60098	3557461	(ref)	46	20280	1340879	(ref)
	low	25	26915	1363184	1.13 (1.02, 1.23)	36	41928	2153133	0.89 (0.84, 0.94)
	medium	25	22475	922266	1.23 (1.10, 1.37)	36	40799	1968293	0.94 (0.87, 1.00)

		Hog				Poultry			
Group	**Density (count/km^2)**	**ZIP codes[a]**	**UTI episodes**	**Person-years**	**RR (95% CI)**	**ZIP codes[a]**	**UTI episodes**	**Person-years**	**RR (95% CI)**
	high	24	18734	753472	1.30 (1.14, 1.49)	38	25215	1134078	0.96 (0.88, 1.04)
	continuous	155	128222	6596383	1.13 (1.05, 1.22)	155	128222	6596383	0.98 (0.93, 1.02)
Sex									
Female	unexposed	324	206825	7149281	(ref)	184	68574	2736889	(ref)
	low	99	89605	2760892	1.07 (0.98, 1.17)	145	140745	4397540	0.87 (0.83, 0.92)
	medium	99	73001	1866981	1.13 (1.02, 1.25)	146	139124	3920252	0.95 (0.89, 1.02)
	high	98	61645	1519919	1.19 (1.05, 1.34)	145	82633	2242392	0.94 (0.86, 1.01)
	continuous	620	431076	13297073	1.08 (1.01, 1.16)	620	431076	13297073	0.97 (0.93, 1.02)
Male	unexposed	324	46265	6867487	(ref)	184	16399	2639020	(ref)
	low	99	19956	2614441	1.08 (0.99, 1.18)	145	31398	4134385	0.83 (0.79, 0.88)
	medium	99	15899	1781804	1.11 (1.00, 1.23)	146	29690	3796482	0.85 (0.79, 0.90)
	high	98	13799	1496054	1.17 (1.03, 1.32)	145	18432	2189899	0.85 (0.79, 0.93)
	continuous	620	95919	12759786	1.07 (1.00, 1.15)	620	95919	12759786	0.92 (0.88, 0.96)
Age (years)									
0 - 4	unexposed	324	5308	768645	(ref)	184	1505	287175	(ref)
	low	99	2497	318964	1.13 (1.02, 1.24)	145	3904	505352	0.90 (0.83, 0.97)
	medium	99	2026	234775	1.06 (0.94, 1.18)	146	3682	461126	0.94 (0.86, 1.03)
	high	98	1576	189530	1.07 (0.94, 1.22)	145	2316	258261	0.98 (0.89, 1.09)
	continuous	620	11407	1511914	1.03 (0.96, 1.11)	620	11407	1511914	0.97 (0.92, 1.03)
5 - 17	unexposed	324	13973	2349661	(ref)	184	4379	809221	(ref)
	low	99	6745	908291	1.21 (1.11, 1.33)	145	10253	1497772	0.80 (0.75, 0.86)
	medium	99	5467	649816	1.19 (1.07, 1.32)	146	9789	1349055	0.85 (0.79, 0.92)
	high	98	4258	516359	1.19 (1.05, 1.35)	145	6022	768079	0.86 (0.78, 0.94)
	continuous	620	30443	4424127	1.07 (1.00, 1.16)	620	30443	4424127	0.94 (0.89, 0.99)
18 - 34	unexposed	324	61942	2733291	(ref)	184	18586	1081350	(ref)
	low	99	27872	1082246	1.10 (1.01, 1.20)	145	45678	1696866	0.93 (0.87, 0.98)
	medium	99	25370	781916	1.19 (1.08, 1.32)	146	46056	1580922	1.01 (0.94, 1.08)
	high	98	20434	677180	1.20 (1.06, 1.35)	145	25298	915495	0.90 (0.83, 0.98)
	continuous	620	135618	5274633	1.09 (1.02, 1.17)	620	135618	5274633	0.96 (0.92, 1.01)

		Hog				Poultry			
Group	**Density (count/km^2)**	**ZIP codes[a]**	**UTI episodes**	**Person-years**	**RR (95% CI)**	**ZIP codes[a]**	**UTI episodes**	**Person-years**	**RR (95% CI)**
35 - 64	unexposed	324	74093	5704441	(ref)	184	23556	2120386	(ref)
	low	99	32379	2135191	1.12 (1.03, 1.22)	145	51677	3451280	0.86 (0.81, 0.91)
	medium	99	28015	1435027	1.27 (1.14, 1.40)	146	51762	3096246	0.94 (0.88, 1.00)
	high	98	23382	1148902	1.34 (1.18, 1.51)	145	30874	1755649	0.93 (0.86, 1.01)
	continuous	620	157869	10423561	1.15 (1.07, 1.23)	620	157869	10423561	0.98 (0.93, 1.03)
65+	unexposed	324	97886	2460725	(ref)	184	37044	1077774	(ref)
	low	99	40317	930641	1.03 (0.94, 1.13)	145	61115	1380658	0.81 (0.76, 0.86)
	medium	99	28471	547250	1.07 (0.96, 1.18)	146	57832	1229401	0.82 (0.77, 0.88)
	high	98	26050	483996	1.14 (1.01, 1.29)	145	36733	734779	0.86 (0.79, 0.93)
	continuous	620	192724	4422612	1.05 (0.98, 1.13)	620	192724	4422612	0.92 (0.88, 0.97)
Combined race/ethnicity[b]									
American Indian	unexposed	247	2272	114897	(ref)	132	466	54713	(ref)
	low	84	1323	69490	1.04 (0.92, 1.18)	126	938	49003	1.35 (1.18, 1.53)
	medium	80	3504	99871	1.68 (1.47, 1.91)	123	3483	116708	1.73 (1.53, 1.95)
	high	84	3299	112103	1.45 (1.24, 1.69)	115	5511	175937	1.53 (1.34, 1.75)
	continuous	496	10398	396361	1.17 (1.08, 1.27)	496	10398	396361	1.06 (0.99, 1.13)
Asian	unexposed	252	853	225466	(ref)	131	266	77392	(ref)
	low	86	412	67874	1.45 (1.24, 1.69)	122	384	106634	0.81 (0.69, 0.96)
	medium	80	384	30091	2.93 (2.47, 3.45)	123	822	121197	1.65 (1.41, 1.92)
	high	69	260	20150	2.78 (2.27, 3.36)	112	437	38358	2.26 (1.89, 2.69)
	continuous	487	1909	343581	1.83 (1.65, 2.03)	487	1909	343581	1.56 (1.43, 1.69)
Black	unexposed	301	35004	1562175	(ref)	166	9686	516142	(ref)
	low	99	30151	1093138	1.21 (1.09, 1.33)	144	49955	1842746	1.00 (0.94, 1.06)
	medium	99	31854	1095552	1.13 (1.00, 1.27)	144	40985	1434587	1.14 (1.06, 1.22)
	high	98	26353	812592	1.35 (1.17, 1.55)	143	22736	769982	1.11 (1.02, 1.22)
	continuous	597	123362	4563457	1.14 (1.05, 1.23)	597	123362	4563457	1.00 (0.95, 1.05)
Hispanic	unexposed	310	8992	1044896	(ref)	172	4250	359609	(ref)
	low	96	4975	458977	1.26 (1.14, 1.40)	143	8112	686884	0.68 (0.63, 0.72)
	medium	97	6020	339370	1.92 (1.69, 2.15)	142	6128	638846	0.61 (0.56, 0.66)

		Hog				Poultry			
Group	**Density (count/km^2)**	**ZIP codes[a]**	**UTI episodes**	**Person-years**	**RR (95% CI)**	**ZIP codes[a]**	**UTI episodes**	**Person-years**	**RR (95% CI)**
	high	98	2660	329014	0.85 (0.74, 0.98)	144	4157	486918	0.49 (0.45, 0.54)
	continuous	602	22647	2172257	0.97 (0.89, 1.05)	602	22647	2172257	0.74 (0.70, 0.78)
White	unexposed	324	186609	10792819	(ref)	184	66719	4253990	(ref)
	low	99	68346	3561738	1.06 (0.96, 1.16)	145	102757	5654218	0.82 (0.77, 0.87)
	medium	99	42661	1994490	1.15 (1.02, 1.29)	146	105597	5230198	0.94 (0.88, 1.01)
	high	98	38789	1667482	1.21 (1.05, 1.38)	145	61332	2878123	0.96 (0.88, 1.05)
	continuous	620	336405	18016529	1.10 (1.02, 1.19)	620	336405	18016529	0.99 (0.94, 1.04)
Other	unexposed	300	3364	276612	(ref)	166	1137	114138	(ref)
	low	98	1927	124144	1.25 (1.12, 1.40)	142	2622	192497	0.94 (0.86, 1.03)
	medium	98	2348	89492	1.91 (1.67, 2.16)	142	4344	175264	1.81 (1.65, 1.99)
	high	96	2172	74701	2.14 (1.84, 2.48)	142	1708	83050	1.32 (1.18, 1.48)
	continuous	592	9811	564949	1.48 (1.36, 1.61)	592	9811	564949	1.16 (1.10, 1.23)
Health insurance[c]									
Private	unexposed	324	45901	9228813	(ref)	184	14490	3556669	(ref)
	low	99	22461	3414107	1.23 (1.12, 1.34)	145	34237	5513378	1.17 (1.11, 1.24)
	medium	99	17014	2156852	1.36 (1.22, 1.51)	146	30051	4788860	1.17 (1.09, 1.25)
	high	98	12945	1627423	1.39 (1.22, 1.58)	145	19543	2568288	1.27 (1.17, 1.38)
	continuous	620	98321	16427195	1.23 (1.15, 1.31)	620	98321	16427195	1.10 (1.05, 1.15)
Public	unexposed	324	142254	2995284	(ref)	184	52087	1075955	(ref)
	low	99	62790	1238546	0.99 (0.91, 1.08)	145	95876	1938936	0.76 (0.72, 0.80)
	medium	99	52980	943208	0.99 (0.89, 1.10)	146	98939	1839810	0.79 (0.74, 0.84)
	high	98	46688	850936	1.04 (0.92, 1.18)	145	57810	1173273	0.69 (0.63, 0.75)
	continuous	620	304712	6027974	1.00 (0.94, 1.07)	620	304712	6027974	0.88 (0.84, 0.93)
Uninsured	unexposed	324	37241	1551081	(ref)	184	11428	600228	(ref)
	low	99	15509	612755	0.98 (0.90, 1.07)	145	26579	941158	1.11 (1.05, 1.18)
	medium	99	14887	465807	1.13 (1.01, 1.25)	146	27118	898213	1.16 (1.08, 1.24)
	high	98	12457	417213	1.13 (0.99, 1.28)	145	14969	607257	0.90 (0.82, 0.98)
	continuous	620	80094	3046856	1.06 (0.99, 1.13)	620	80094	3046856	0.96 (0.92, 1.01)

		Hog				Poultry			
Group	**Density (count/km^2)**	**ZIP codes[a]**	**UTI episodes**	**Person-years**	**RR (95% CI)**	**ZIP codes[a]**	**UTI episodes**	**Person-years**	**RR (95% CI)**
Rurality[d]									
Suburban	unexposed	157	200062	11027225	(ref)	74	59513	3826742	(ref)
	low	46	82894	4177019	1.12 (0.99, 1.25)	81	145349	7149221	0.85 (0.81, 0.91)
	medium	32	58782	2278579	1.20 (1.03, 1.38)	76	132524	6169754	0.92 (0.86, 0.99)
	high	20	27828	1185489	1.24 (1.04, 1.46)	24	32180	1522595	0.90 (0.80, 1.02)
	continuous	255	369566	18668312	1.10 (0.99, 1.21)	255	369566	18668312	0.90 (0.85, 0.96)
Small town	unexposed	82	39877	2209728	(ref)	45	18094	1094883	(ref)
	low	32	22001	975255	1.10 (0.96, 1.26)	26	15831	809704	0.89 (0.77, 1.03)
	medium	32	20714	957370	1.12 (0.97, 1.29)	35	28193	1190447	0.93 (0.81, 1.07)
	high	36	31863	1213374	1.24 (1.05, 1.44)	75	52337	2260693	0.93 (0.80, 1.07)
	continuous	182	114455	5355727	1.08 (0.99, 1.17)	182	114455	5355727	1.01 (0.94, 1.08)
Rural	unexposed	85	13263	779805	(ref)	65	7463	454275	(ref)
	low	21	4919	223049	0.98 (0.82, 1.18)	38	11448	573005	0.90 (0.77, 1.05)
	medium	35	9854	412834	1.08 (0.92, 1.27)	34	8408	356539	0.96 (0.82, 1.13)
	high	42	16010	617116	1.14 (0.95, 1.35)	46	16727	648985	0.92 (0.78, 1.08)
	continuous	183	44046	2032804	1.07 (0.98, 1.17)	183	44046	2032804	1.00 (0.93, 1.08)

[a] Average number of ZIP codes in each exposure category by group in 2016-2019

[b] Individuals of any race reporting Hispanic ethnicity were included in a combined Hispanic race/ethnicity group; all other race/ethnicity groups contained only individuals of non-Hispanic ethnicity, with the Other race group comprising individuals of two or more races and Pacific Islanders

[c] Health insurance EMM models were not adjusted for percent of ZIP code population lacking health insurance

[d] Rurality EMM models were not adjusted for ZIP code isolation score

Table S6. Population and incidence of UTI episodes and total ED visits by hog exposure category and combined race/ethnicity in 2019.

	Hog exposure category				
	unexposed	**low**	**medium**	**high**	**all**
Hog density (count/km^2), range	0	>0 - 7	7 - 56	56 - 1436	0 - 1436
Total population					
UTI episodes, N (rate per 1000)	120196 (17)	53435 (20)	45746 (24)	37067 (26)	256444 (19)
Total ED visits, N (rate per 1000)	3308856 (465)	1447224 (528)	1151499 (610)	902923 (622)	6810502 (516)
Population, N	3557461	1363184	922266	753472	6596383
American Indian					
UTI episodes, N (rate per 1000)	519 (18)	332 (18)	866 (35)	879 (31)	2596 (26)
Total ED visits, N (rate per 1000)	11237 (385)	7768 (425)	18869 (761)	18290 (647)	56164 (559)
Population, N (%)	29155 (1)	18287 (1)	24785 (3)	28267 (4)	100494 (2)
Asian					
UTI episodes, N (rate per 1000)	213 (4)	82 (5)	39 (5)	35 (7)	369 (4)
Total ED visits, N (rate per 1000)	6512 (107)	2483 (140)	1035 (138)	756 (146)	10786 (118)
Population, N (%)	60670 (2)	17765 (1)	7498 (1)	5185 (1)	91118 (1)
Black					
UTI episodes, N (rate per 1000)	9250 (23)	7758 (28)	8955 (33)	6856 (34)	32819 (28)
Total ED visits, N (rate per 1000)	290616 (723)	230869 (840)	237902 (863)	180571 (899)	939958 (815)
Population, N (%)	401753 (11)	274689 (20)	275521 (30)	200948 (27)	1152911 (17)
White					
UTI episodes, N (rate per 1000)	45170 (17)	16806 (19)	10501 (21)	9542 (23)	82019 (18)
Total ED visits, N (rate per 1000)	1187293 (437)	418328 (464)	246964 (491)	219967 (531)	2072552 (457)
Population, N (%)	2717300 (76)	902123 (66)	503311 (55)	413861 (55)	4536595 (69)
Hispanic					
UTI episodes, N (rate per 1000)	2393 (9)	1296 (11)	1394 (16)	662 (8)	5745 (10)
Total ED visits, N (rate per 1000)	79804 (290)	43586 (373)	39898 (454)	25448 (298)	188736 (334)
Population, N (%)	274755 (8)	116954 (9)	87815 (10)	85528 (11)	565052 (9)
Other race					
UTI episodes, N (rate per 1000)	1018 (14)	505 (15)	542 (23)	443 (22)	2508 (17)
Total ED visits, N (rate per 1000)	36787 (498)	17913 (537)	14841 (635)	12858 (653)	82399 (548)
Population, N (%)	73839 (2)	33372 (2)	23354 (3)	19699 (3)	150264 (2)

S5. Stan Model Code

```
// bym2: adapted from Morris et al. 2019
// adapted BRMS code to accommodate multiple observations per zip code

functions {
  real icar_normal_lpdf(vector phi, int N_locs, int[] node1, int[] node2) {
    return -0.5 * dot_self(phi[node1] - phi[node2])
      + normal_lpdf(sum(phi) | 0, 0.001 * N_locs); // soft sum-to-zero constraint
  }
}

data {
  int<lower = 0> N_obs;         // number of observations
  int<lower = 0> loc[N_obs] ;   // location ID
  int<lower = 0> y[N_obs];      // count outcomes
  vector<lower = 0>[N_obs] E;   // exposure (offset)
  int<lower = 1> K;             // num covariates
  matrix[N_obs, K] x;           // design matrix
  int<lower = 0, upper = 1> binary[K]; // indicator if predictor is binary (do not std)

  int<lower = 0> N_locs;  // number of locations
  int<lower = 0> N_edges;  // number of connections between locations
  int<lower = 1, upper = N_locs> node1[N_edges];  // node1[i], node2[i] neighbors
  int<lower = 1, upper = N_locs> node2[N_edges];  // node1[i] < node2[i]

  real<lower = 0> scaling_factor;  // scales the variance of the spatial effects
}

transformed data {
  vector[N_obs] log_E = log(E);  // log offset

  // standardize
  vector[K] x_mean;
  vector[K] x_sd;
  matrix[N_obs, K] x_std;

  for (k in 1:K) {
    if (binary[k] == 0) {
      x_mean[k] = mean(x[,k]);
      x_sd[k] = sd(x[,k]);
      x_std[,k] = (x[,k] - x_mean[k]) / x_sd[k];
    } else {
      x_mean[k] = 0;
      x_sd[k] = 1;
      x_std[,k] = x[,k];
    }
  }
}

parameters {
  vector[K] betas_std;          // standardized covariates
  real logit_rho;               // log-odds of proportion spatial random effect

  vector[N_locs] phi;           // spatial effects
  vector[N_locs] theta;         // heterogeneous effects
  real<lower = 0> sigma;        // overall standard deviation
}

transformed parameters {
  real<lower = 0, upper = 1> rho = inv_logit(logit_rho);  // proportion spatial RE

```

```
  // combine spatial and non-spatial random effects for each location
  vector[N_locs] convolved_re = sqrt(rho / scaling_factor) * phi
                              + sqrt(1 - rho) * theta;
}

model {
  y ~ poisson_log(log_E + x_std * betas_std + convolved_re[loc] * sigma);

  betas_std[1] ~ normal(0, 2.5);
  betas_std[2:K] ~ normal(0, 1);
  logit_rho ~ normal(0, 1);
  sigma ~ normal(0, 1);
  theta ~ normal(0, 1);
  phi ~ icar_normal(N_locs, node1, node2);
}

generated quantities{
  vector[K] betas;
  vector[K] RRs;

  // posterior
  vector[N_obs] eta = log_E + x_std * betas_std + convolved_re[loc] * sigma;
  vector[N_obs] mu = exp(eta);

int y_rep[N_obs];  // posterior predictions
  if (max(eta) > 20) {
    // avoid overflow in poisson_log_rng
    print("max eta too big: ", max(eta));
    for (n in 1:N_obs)
      y_rep[n] = -1;
  } else {
      for (n in 1:N_obs)
        y_rep[n] = poisson_log_rng(eta[n]);
  }

  // unstandardized coeficients
  for(k in 1:K){
    betas[k] = betas_std[k] / x_sd[k];
  }

   RRs = exp(betas);
  }

```

S6. Supplementary References

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