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## RESEARCH ARTICLE



# Socioeconomic drivers of urban pest prevalence

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**Handling Editor:** Laura Graham**Abstract**

1. Bed bugs have re-established themselves as a common household pest in the United States and pose significant public health and economic concerns, particularly in urban areas.
2. Documenting the scale of the bed bug resurgence and identifying the underlying predictors of the spatial patterns of their incidence is challenging, largely because available data come from biased self-reporting through local government code enforcement.
3. Here, we make use of a novel source of systematically collected data from periodic inspections of multifamily housing units in Chicago to investigate neighbourhood drivers of bed bug infestation prevalence in Chicago.
4. Bed bug infestations are strongly associated with income, eviction rates and crowding at the neighbourhood level.
5. That bed bug prevalence is higher in lower-income neighbourhoods with higher levels of household crowding and eviction notices provides unique empirical evidence of the disproportionate allocation of public health burdens upon neighbourhoods facing multiple dimensions of disadvantage.

**KEYWORDS**

bed bugs, metapopulation, public health, socioeconomic, spatial ecology

## 1 | INTRODUCTION

There has been a dramatic resurgence of bed bug infestations in cities across the globe (Biehler & Green, 2014; Boase, 2008; Potter, 2011) and, in the United States, they have re-established as a prevalent urban pest (Potter, Haynes, & Fredericks, 2015). Globally common prior to the 1930s, bed bug populations declined over the following 50 years. However, for reasons that are not well understood, but likely related to a general lack of responsiveness to infestation and the concurrence of increased global connectivity, pesticide resistance and decreased surveillance beginning in the 1990s, populations have begun to increase again with well-documented adverse public

health (Doggett, Miller, & Lee, 2018) and socioeconomic (Eddy & Jones, 2011) implications.

The public health concerns attributed to bed bugs are significant, ranging from minor dermatological concerns to allergic responses, sleeplessness, stress and shame, to more severe mental health conditions (Hwang, Doggett, & Fernandez-Penas, 2018; Perron, Hamelin, & Kaiser, 2018). These direct health impacts translate into potentially large social and economic costs (Doggett, Miller, Vail, & Wilson, 2018; Xie, Hill, Rehmann, & Levy, 2019); it can cost in excess of \$1,000 to efficiently treat and eradicate bed bugs from homes, and many affected by infestations resort to the needless disposal of their belongings or relocation in an effort

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**TABLE 1** Comparative descriptive summaries statistics of the variables used in the analysis at the census tract level between all census tracts (*Census Tract*) and census tracts in which inspections were conducted (*Periodic Inspections*). The census tracts in which inspections were conducted are generally representative of Chicago's socioeconomic population structure. Data are taken from the 2016 5-year American Community Survey (ACS) and Eviction Lab data for 2011–2016

Variable	Census tracts				Periodic inspection			
	Mean	SD	Min	Max	Mean	SD	Min	Max
Mobility rate (%)	4.29	2.18	0.00	13.06	4.30	2.24	0.00	13.06
Evictions	1.50	1.79	0.00	40.00	1.48	1.19	0.00	7.09
Median household income	55,070	28,141	9,485	159,583	60,458	32,304	9,485	159,583
Under 18 (%)	20.44	8.64	1.39	49.96	18.59	8.84	1.39	49.96
Over 65 (%)	11.69	6.27	0.00	50.15	9.75	6.05	0.00	50.15
Graduate degree (%)	15.92	13.44	0.00	82.43	20.04	13.93	0.00	82.43
Renters (%)	56.29	19.82	0.78	100.00	63.62	14.88	0.78	100.00
Overcrowded units (%)	1.34	1.67	0.00	11.71	1.41	1.67	0.00	11.71
Median home value (%)	254,695	133,508	53,300	1,023,600	301,910	149,874	53,300	1,023,600

to avoid their detrimental effects. There is a perception, that is not well-documented empirically, that these health and economic burdens tend to be levied on those who are least able to afford such remedial action or access to health care (Levi, 2009; Xie et al., 2019).

Current thinking about bed bug dispersal and control suggests that infestation rates should depend on a multitude of interacting factors associated with both socioeconomic status and human social interaction (Aultman, 2013; Eddy & Jones, 2011; Hwang, Svoboda, De Jong, Kabasele, & Gogosis, 2005; Xie et al., 2019). Specifically, Eddy and Jones (Eddy & Jones, 2011) posit that socioeconomic relationships influence bed bug colonization and eradication rates, and make a compelling case for viewing bed bug infestations as a social justice issue. As with many other urban pests (Biehler & Green, 2014), Eddy and Jones (2011) argue that the burden of infestation is not borne equally among communities and that bed bug prevalence is dependent upon housing tenure, housing density and quality, education, poverty, immigration status, employment status, occupant age, and city agency regulation and response capacity. These putative relationships, themselves emergent properties of interacting individual behaviours determined by social factors, are well-reasoned and indeed evidence to this effect would provide a basis for improved pest management and regulation, as well as public health and education initiatives (Schneider, 2019). Yet, compelling empirical support linking socioeconomic factors to bed bug prevalence is lacking.

The reactive nature of bed bug reporting and response, and hence the lack of systematic pest monitoring, results in data that preclude reliable general inferences about the scale of the bed bug resurgence and the socioeconomic drivers of spatiotemporal prevalence. In particular, recent attempts to do so have been limited in spatial extent (Hwang et al., 2005), have focused on narrow strata of socioeconomic condition (Cooper, Wang, & Singh, 2016; Gounder, Ralph, Maroko, & Thorpe, 2014; Wang, Saltzman, & Chin, 2010), and are based on self-reported data (Ralph, Jones, & Thorpe, 2013) that are

subject to known associated biases (Brown, Kelly, & Whitall, 2014). Specifically, self-reported bed bug complaints made directly to city services ('311 reporting') have known biases related to income, race, property type and property value (McLafferty, Schneider, & Abelt, 2020). In this paper, we go some way towards addressing these challenges by taking advantage of a large, multi-year dataset of systematic housing code inspections, rather than complaint-based reporting, to track the spatiotemporal bed bug resurgence in Chicago. These data represent a systematic longitudinal bed bug sampling regime, and are analysed using neighbourhood (census tract) level socioeconomic, demographic and geographic predictors (Table 1) to examine the sociodemographic correlates of infestation risk. Here, we describe a unique study that seeks to understand the socioeconomic drivers of bed bug prevalence in one of the largest cities in North America.

## 2 | MATERIALS AND METHODS

### 2.1 | Study area

In Chicago, contemporary reports of bed bugs began in the early 2000s. Health agencies reported an increase in bed bug-related calls in 2004, the same time as local tenant rights organizations began receiving increasing complaints about bed bugs. By 2011, pressure to act on bed bugs increased substantially—the Safer Pest Control Project, a Chicago non-profit and designated agency for the city planning department, released a report arguing for stronger municipal bed bug regulations. The state of Illinois' Structural Pest Control Advisory Council also released a legislatively mandated report that made similar recommendations. The increase in bed bug infestations coupled with attention from civic organizations and the media resulted in Chicago's city council passing the most comprehensive bed bug ordinance revision in the country in 2013 (Schneider, 2019).

Among the provisions, the ordinance declared bed bugs to be a public nuisance and subject to abatement. In residential buildings, the ordinance assigns responsibility for bed bug eradication to landlords and requires landlords to inspect and treat units adjacent to infested units. Condominiums and co-ops are required to have a pest management plan, and the governing association is required to treat for bed bugs. Tenants are required to cooperate with the landlord in treating bed bugs, by allowing access and preparing their apartment for treatment. The spread of bed bugs is addressed through regulations on the disposal of infested materials or the sale of second-hand bedding.

## 2.2 | Inspection data

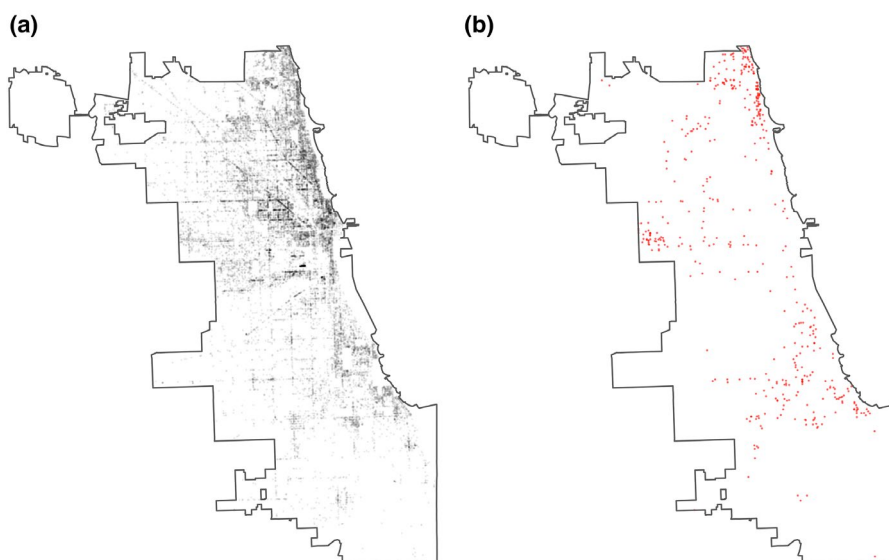
The Chicago Department of Buildings undertakes two general categories of inspections: (a) responses to individual citizen complaints generated through the 311 non-emergency city service system, and (b) a systematic periodic inspection program mandated by section 13-20-020 of the municipal code for compliance with housing codes. Until 2017, Chicago municipal code mandated annual inspections for all multi-story, multiple dwelling residential buildings four stories or higher, and mixed residential or commercial buildings three stories or higher. After 2017, the city reduced the required frequency of inspections and slightly changed which buildings were mandated. Approximately 22,000 buildings in Chicago are subject to periodic inspections (Figure 1). Here, to avoid the biases associated with 311 complaint data, we focus exclusively on the systematic inspection data.

Inspections are conducted by the Conservation Department of the Department of Buildings during which inspectors identify, among other code issues, infestations of pests, including bed bugs, cockroaches, mice and rats and issue notices of violation at the building level (i.e. not the apartment or unit). We searched the online violations database ([data.chicago.ci.il](http://data.chicago.ci.il)) for the term 'bed bugs' (and

all variants) to locate the addresses of all inspections that resulted in a bed bug-related code violation. The database lists only the addresses where violations were reported, not where inspections were all conducted. Through a request by the Freedom of Information Act (FOIA) to the Conservation Department of the Chicago Department of Buildings, we obtained the address and date of all periodic inspections conducted by the Conservation Department. The violation and inspection data were merged and used in this analysis (Figure 1).

## 2.3 | Socioeconomic data

The number of inspections and violations in each year was aggregated at the census tract level (Table 1). We derived socioeconomic measures of each census tract from the U.S. Census Bureau's 2016 5-year American Community Survey (ACS, census tract data from here), a widely used data source in social science research that provide relatively fine-grained geographic units of analysis, particularly in urban areas (Coulton, Korbin, Chan, & Su, 2001). Based on our review of the existing literature around the sociodemographic drivers of bed bug infestation (Eddy & Jones, 2011; Ralph et al., 2013), we identified four broad socioeconomic categories: (a) residential stability, (b) housing affordability, (c) resident demographics and (d) neighbourhood housing characteristics. Specifically, we identified nine variables associated with these categories (Table 1; Table S1): mobility rate (residential stability), eviction rate (residential stability), median household income (affordability), percent under 18 (demographic), percent over 65 (demographic), percent with a graduate degree (demographic), percentage of rental properties (neighbourhood characteristics), percentage of overcrowded units (neighbourhood characteristics), and median home value (neighbourhood characteristics). All variables are from the ACS except for eviction rate, the 2011–2016 average of the proportion of rental housing units within each census tract with an eviction judgement filed in which an actual eviction (involving the displacement of residents)



**FIGURE 1** Spatial summary of the distribution of inspections conducted between 2006 and 2018. Point locations of all inspections are shown in (a) with each blue point representing a building that was inspected ( $n = 56,384$ ). Point locations of all positive bed bug detections, that is, a bed bug code violation, are shown in (b) with each red point representing a building that resulted in a bed bug code violation ( $n = 491$ )

occurs (Desmond, Gromis, Edmonds, & Hendrickson, 2018). See also Table 1 for summary statistics and Appendix S1 for variable descriptors.

## 2.4 | Statistical analysis

We conducted two preliminary analyses prior to multivariable modelling: (a) a test for collinearity in our variables—a well-documented concern in census tract data, and (b) selection of an appropriate model structure to account for temporal variation in bed bug prevalence. We calculated variance inflation factors (VIF) to identify any issues of collinearity and to remove redundant covariates based on a conservative VIF cut-off of 4 (Zuur, Ieno, & Elphick, 2010). This process identified median home value, which is highly correlated with median household income ( $\rho = 0.80$ ), as a collinear term. We were more interested in neighbourhood economic status, which is best measured through income, and therefore removed median home value from the analysis. The removal of median home value meant the eight remaining predictors had VIF values below the cut-off and were therefore included in the modelling described below (Table 1; Table S2).

To account for inter-year variation in bed bug prevalence, we compared a series of models that measured how prevalence varied over time. Three formulations were considered: (a) a linear trend over time treating year as a continuous variable (Trend), (b) a polynomial function treating year and year<sup>2</sup> as continuous variables (Quadratic) and (c) estimating year-specific prevalence rates treating year as a factor (Year). Using Akaike's information criteria (AIC; Burnham & Anderson, 2002) we compared these three versions of the global model, that is, including each of the eight socioeconomic variables (Table 1). We found that a model with year specific estimates of prevalence was overwhelmingly supported relative to the trend or quadratic models (Table S3).

Our final analysis started with the definition of the 'global model' that included the additive combinations of year (as a factor), mobility rate, eviction rate, median household income, % renter households, % overcrowded units and the % population with graduate degree, that are under 18 and that are over 65 (Table 1). To allow direct comparisons of effect sizes, we standardized all continuous covariates (i.e. z-scores with mean = 0, standard deviation = 1). We analysed the periodic inspection data using a binomial response generalized linear model (McCullagh & Nelder, 2019), the response being the number of bed bug violations per census tract per year (successes) out of the number of periodic inspections in that census tract and year (trial size, Figure 1). We adopted an AIC-based multi-model inference approach (Burnham & Anderson, 2002), using AIC to compare all additive combinations of all the effects included in the global model. All nested subsets of the global model resulted in a total of 256 models which were fit in R.

Analyses were conducted using R (R Core Team, 2020). The R package CAR (Fox & Weisberg, 2019) was used to calculate variance inflation factors, and the 'all possible combinations' model fitting and model ranking and selection was conducted using the R package

MuMIn (Barton & Barton, 2019). Model validation was conducted using R package DHARMA which implements a simulation-based approach to residual diagnostic tests for violations of distributional and independence assumptions (Hartig, 2020, see Appendix S2 for results). All data and code to reproduce the analysis are freely available on our Open Science Framework repository (Sutherland, Greenlee, & Schneider, 2020).

## 3 | RESULTS

In the 13-year period from 2006 to 2018, multi-story, multiple dwelling residential buildings four stories or higher, and mixed residential/commercial building three stories or higher, in Chicago were subject to periodic inspections. In this time, 21,340 addresses were subject to a total of 56,384 periodic inspections in Chicago (Figure 1). Of these, 491 resulted in definitive evidence that bed bugs were present at the property and hence a housing code violation (Table 2). The 491 bed bug-positive inspections occurred at 446 unique properties indicating that some properties had bed bugs present across multiple periodic inspections. The distribution of the socioeconomic measures from the housing units that were subject to periodic inspections is generally representative of the city as a whole (Table 1) and is widely distributed throughout the city (Figure 1a).

Of the eight spatially explicit socioeconomic covariates considered here (Table 1), we found significant support for four predictors of bed bug prevalence (Table 3): time (or year), neighbourhood median household income (MHHI), eviction rate (proportion of rental units where an eviction occurred) and overcrowding (the proportion of units in the neighbourhood with >1.5 person per room).

**TABLE 2** Temporal summary of the outcomes of the periodic inspections of multi-story, multiple dwelling residential buildings four stories or higher, and mixed residential or commercial building three stories or higher from 2006 to 2018. We note that that data for 2018 is from January to July only

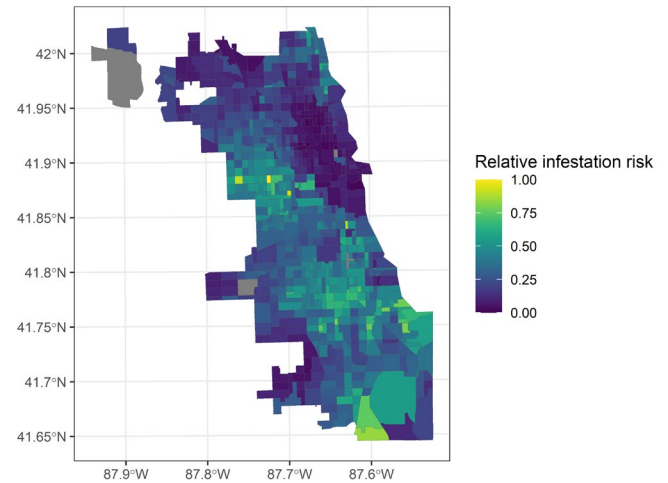
Year	Inspected units	Violations	Positive
2006	10,714	12	0.11
2007	6,563	6	0.09
2008	6,730	8	0.12
2009	5,218	32	0.61
2010	4,357	59	1.35
2011	2,259	70	3.10
2012	3,941	68	1.73
2013	2,389	43	1.80
2014	3,027	49	1.62
2015	2,566	70	2.73
2016	4,898	31	0.63
2017	2,712	35	1.29
2018	1,010	8	0.79
Total	56,384	491	0.87

Preliminary analysis did not support a linear trend in bed bug prevalence and thus the effect of year suggests significant variation among the 13 years (Figure 2). Bed bug prevalence was not randomly distributed but was highest in neighbourhoods with lower median household incomes, a greater share of overcrowded units, and higher eviction rates (Figures 2 and 3). Our results suggest that, in addition to significant variation among years, neighbourhood level median household income was the strongest predictor of bed bug prevalence. Eviction rate and crowding had significant, but relatively

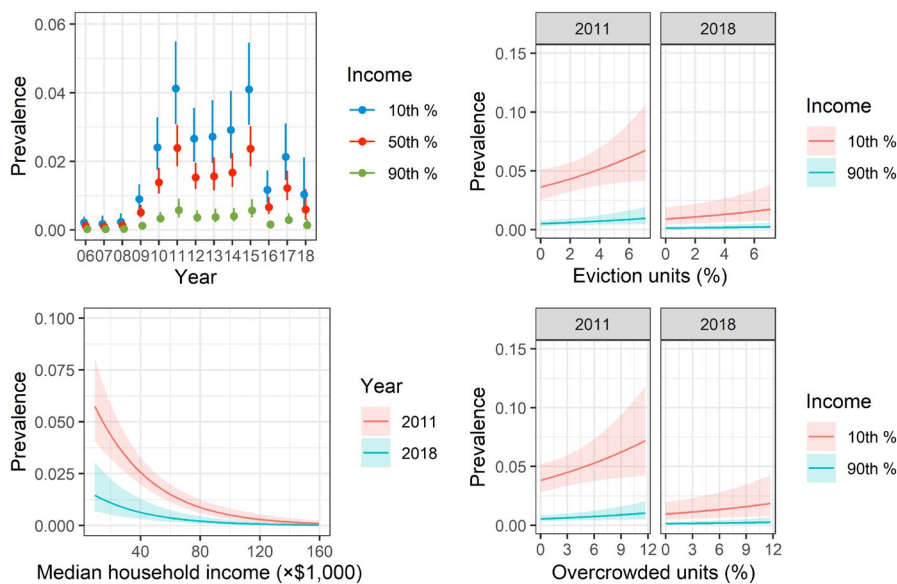
smaller effect (Figure 2). We did not find evidence that bed bug prevalence was influenced by mobility rate, % renter households, or the % population with graduate degree, that was under 18 and that were over 65 (Figure 2).

**TABLE 3** Estimated covariate effects ( $\theta$ ) with associated standard errors ( $SE(\theta)$ ) and 5%  $p$ -values from the global model (year-specific effects not shown). Variables are ordered by their relative variable weights (RVI: sum of AIC weights for models in which variables appear). Grey text denotes variables that were found not to be significant at the 5% level

Variable	$\theta$	$SE(\theta)$	$p$	RVI
Median household income	-0.77	0.13	0.00	1.00
Crowding	0.10	0.04	0.01	0.92
Evictions	0.12	0.05	0.01	0.90
Renters	0.06	0.08	0.41	0.54
Mobility rate	-0.05	0.06	0.37	0.48
Population under 18	-0.07	0.08	0.41	0.41
Population with graduate degree	0.02	0.09	0.79	0.33
Population over 65	-0.01	0.06	0.80	0.29



**FIGURE 3** Spatial predictions of the relative infestation risk at the census tract level (the relative likelihood of an infestation occurring in a unit in the census tract). The relative risk is computed by dividing the predicted probability of a positive inspection in a census tract by the maximum probability across all census tracts in Chicago under the model including year as a factor, median household income, crowding and eviction rate (i.e. the four significant predictors of bed bug prevalence). Grey areas are areas with no residential properties



**FIGURE 2** Model averaged predictions across all 128 models of the variables found to be significant drivers of bed bug prevalence. Top left: annual bed bug prevalence for the 10th, 50th and 90th median household income percentiles. Bottom left: the negative relationship between bed bug prevalence and median household income in 2011 (peak infestation year) and 2018 (most recent year). Top right: the positive relationship between bed bug prevalence and eviction rate in 2011 and 2018 for the 10th and 90th median household income percentiles. Bottom right: the positive relationship between bed bug prevalence and crowding in 2011 and 2018 for the 10th and 90th median household income percentiles



Holding all covariates at an average for comparisons, bed bug prevalence (prediction, 95% confidence intervals) was lowest in 2007 (0.001, CI: 0.0005–0.0023), highest in 2011 (0.0239, CI: 0.0186–0.0306) and in the most recent year, 2018, had declined again (0.0059, CI: 0.0029–0.0119, Figure 2). Allowing for unstructured annual variation shows clearly that bed bug prevalence increased to a peak in the middle years of the study period (2011–2015) before declining again.

Bed bug prevalence was strongly negatively associated with neighbourhood household income (effect:  $-0.77$ , CI:  $-1.03$  to  $-0.52$ , Figure 2). To illustrate this effect, we compare bed bug prevalence for two income scenarios: a low-income scenario of \$15,800, the Federal Extremely Low Income (ELI) threshold for a household of four in Chicago (HUD 2017), and a high-income scenario of \$94,800, 120% area median income in Chicago (HUD 2017). In the peak year (2011), this relates to a prevalence of 0.049 (CI: 0.035–0.066) in the low-income case and 0.006 (CI: 0.004–0.009) in the high-income case. In contrast, prevalence rates in 2018 are 0.012 (CI: 0.006–0.025) and 0.001 (CI: 0.001–0.003) for low and high-income cases, respectively. Prevalence in the high-income scenario is consistently an order of magnitude lower than in the low-income case (Figure 2).

The effect of eviction rates was positive and significant (effect: 0.12, CI: 0.03–0.21, Figure 2). Again, comparing the peak year (2011) and the most recent year (2018), predicted prevalence for a neighbourhood with the lowest eviction rates (i.e. 0.00%) is 0.017 (CI: 0.012–0.022) and 0.004 (CI: 0.002–0.008), respectively, which is markedly lower than for the highest observed eviction rate (i.e. 7%), which is 0.032 (CI: 0.019–0.053) and 0.008 (CI: 0.003–0.018), respectively (Figure 2). The effect of crowding was positive and significant (effect: 0.10, CI: 0.02–0.17, Figure 2). Again, comparing the peak year (2011) and the most recent year (2018), predicted prevalence for a neighbourhood with the lowest observed crowding (i.e. 0.00%) is 0.018 (CI: 0.014–0.024) and 0.004 (CI: 0.002–0.009), respectively, which is markedly lower than for the highest observed crowding (i.e. 12%), which is 0.034 (CI: 0.020–0.058) and 0.009 (CI: 0.004–0.020), respectively (Figure 2). The effects of eviction and crowding are similar in terms of direction and effects size, but were weaker than MHHI, the dominant driver of infestation risk.

## 4 | DISCUSSION

The systematic inspections span the period over which Chicago enacted one of the most comprehensive ordinances in the nation to combat bed bugs (Schneider, 2019), and our findings are consistent with Chicago's public policy discussion and response. The rapid increase in bed bug prevalence began in 2009, reaching a peak in 2011, a trend that matches the pace of the bed bug infestation in the United States more generally (Potter, 2011; Potter et al., 2015; Schneider, 2019). Prevalence peaked again in 2015, the year after the passage of Chicago's revised bed bug ordinance, reflecting perhaps an increased vigilance engendered by the ordinance (Figure 2). Since then, though, prevalence of bed bugs has declined and remained

relatively low, which is consistent with the desired impacts of ordinance (Kolomatsky, 2018), although the effects of concurrent nationwide improvements in control techniques, education and knowledge of bed bug biology (Doggett, Miller, & Lee, 2018) are likely to be important contributors as well. Unlike previous research (Ralph et al., 2013), our data come from systematic inspections with known sampling effort and are, therefore, uniquely able to attribute observed reductions to declines in bed bug prevalence rather than trends in reporting. As policies continue to be implemented in cities across the United States (Schneider, 2019; Xie et al., 2019), monitoring initiatives such as Chicago's periodic inspection program will be critical in evaluating the efficacy of policy interventions in response to the bed bug epidemic.

In Chicago, neighbourhood income is the principle driver of many forms of structural advantage and disadvantage and associated public health concerns (Chetty, Hendren, & Katz, 2016; Sampson & Sharkey, 2008; Wilkinson & Pickett, 2006). It is perhaps unsurprising then that we find that median household income is the best predictor of bed bug infestation risk: prevalence is highest in low-income neighbourhoods. Two patterns emerge under this income driven prevalence system. First, poorer neighbourhoods always have higher prevalence rates, but in outbreak years, they disproportionately bear the burden of increased infestation risk (Figure 2). Second, this results in non-random city-scale spatial clustering of infestation rates (Figure 3) that contribute to growing and compounding hot spots of public health concern as has been documented with, for example, asthma (Gupta, Zhang, Sharp, Shannon, & Weiss, 2008) and high blood lead concentration (Hanna-Attisha, LaChance, Sadler, & Champney, 2016; Sampson & Winter, 2016). This is rare empirical support for Eddy and Jones' (Eddy & Jones, 2011) contention that, as with many public health concerns, bed bug infestations are an issue of social justice.

Bed bug populations are inherently structured as metapopulations (Fountain, Duvaux, & Horsburgh, 2014; Wang et al., 2010) and incidences such as those documented in the inspection data are emergent properties of infestation (colonization) and eradication (extinction) processes. Like other studies investigating urban pest prevalence, household income explains much of the spatial variation in prevalence. For bed bugs populations specifically, and in the context of metapopulation theory, financial capacity plays a large regulatory role, either through its effect on bed bug colonization (e.g. poorer households have a greater reliance on second-hand furniture which can introduce bed bugs to dwellings), or more likely, the ability to afford the high (>\$1,000) eradication costs once an infestation is found (Aultman, 2013; Cooper et al., 2016).

Eviction practices are also likely to play an important role in colonization–extinction dynamics and the clustering of bed bugs in disadvantaged neighbourhoods (Xie et al., 2019). Landlords typically place the blame on tenants for bed bug infestations, seeking to evict tenants of infested units (Schneider, 2019). Further, they may also seek reimbursement for eradication costs and pursue eviction for non-payment if tenants are unable to pay these costs. In a study of displacement in Milwaukee (Desmond & Shollenberger, 2015), almost one in eight Milwaukee renters were forced to move through formal or informal eviction. Those forced to move relocated to more disadvantaged

neighbourhoods than those who moved voluntarily, establishing a link between eviction and concentration of poverty. As residents with bed bug infestations are forced to relocate by landlords, or 'voluntarily' relocate to escape infestations, they may carry bed bugs with them, leading to new infestations. Indeed, we find empirical support for the role of evictions in determining the spatial distribution of bed bug infestations. Prevalence is highest in neighbourhoods where eviction is more likely to occur resulting in spatial clustering of high infestation risk in lower income neighbourhoods (Figure 3). This interesting finding demonstrates the importance of considering proximate (eviction practices) versus ultimate (income patterns) predictors of bed bug outbreaks, especially in the context of policy recommendations. Forced relocation, therefore, can act as a colonization mechanism and facilitate increased concentration of bed bugs in low-income neighbourhoods.

We also found evidence that bed bug prevalence was positively related to overcrowding, which, while intuitive, has not been explicitly and empirically documented as a bed bug risk factor. Overcrowding is symptomatic of housing stress, and has historically been identified as a major public health concern (Office of the Deputy Prime Minister, 2004), but specifically with regard to the spread of disease (Shaw & Clarke, 2015), with disproportionate effects on low-income renter households residing in central cities. Instances of infestations have previously been positively associated with household size (Ralph et al., 2013). Considering the ecology of bed bugs, and the disease spread in general, clearly overcrowding creates more opportunities for spread, recolonization, reduced control efficacy and ultimately persistence. Again, it is worth noting that the issue of overcrowding is disproportionately amplified in lower income neighbourhoods (Figure 2).

It is important to acknowledge the spatial resolution of our investigation. The census tract is used here to approximate neighbourhoods, which have limitations (Coulton et al., 2001; Kwan, 2012). In particular, such aggregation ignores finer scale within-neighbourhood heterogeneity (Soobader, LeClere, Hadden, & Maury, 2001). Achieving unit-level resolution of bed bug infestation is possible at small spatial scales (e.g. an apartment building, Wang et al., 2010), but prohibitively difficult when the scope of inference is describing prevalence patterns at the scale of an entire city and that span the full socioeconomic gradient. Despite these limitations, our analysis identifies median household income, overcrowded housing units and forced displacement as significant predictors of bed bug prevalence underscoring the structural disadvantage low-income households face. Interestingly, though, patterns of bed bug infestation identified at a much finer, within-building, spatial scale identified proximity to bed bug infested units as a principle predictor of a future infestation (Wang et al., 2010). This is much more aligned with bed bug ecology than city level socioeconomic structure and highlights the multi-scale complexity that is a critical, but challenging, consideration for bed bug control and pest management in general (Figure 3).

In summary, we are able to link spatiotemporal variation in bed bug infestation to Chicago's socioeconomic structure, in particular to income, crowding and evictions. We have provided evidence that bed bug infestations are a problem of poverty in which the public

health burden falls disproportionately on poorer neighbourhoods, and provide empirical support for the argument that the contemporary bed bug crisis is an issue of social justice (Eddy & Jones, 2011). This refined understanding of where infestations are more or less likely to occur has important implications for developing mechanisms able to interrupt the recolonization and persistence patterns of bed bug infestations.

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## CONFLICT OF INTEREST

We declare no conflicts of interest.

## AUTHORS' CONTRIBUTIONS

C.S., A.J.G. and D.S. designed the research, performed the research and wrote the paper.

## DATA AVAILABILITY STATEMENT

Data available at the following Open Science Framework Repository <https://doi.org/10.17605/OSF.IO/VE9WT> (Sutherland et al., 2020).

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## SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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