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Overdose as a complex contagion: modeling the community spread of overdose events following law enforcement efforts to disrupt the drug market

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Abstract

Background: The opioid overdose mortality crisis in the US is an ongoing public health epidemic. Ongoing law enforcement strategies to disrupt local unregulated drug markets can have an iatrogenic effect of increasing overdose by driving consumers towards new suppliers with unpredictable drug products of unknown potency.

Methods: Cross-sectional study using point-level information on law enforcement opioid-related drug seizures from property room data, opioid-related nonfatal overdose events from emergency medical services, and block group-level social determinants of health data from multiple sources. Using an endemic-epidemic spatio-temporal regression model, we estimated the degree to which exposure to drug supply disruptions trigger future overdose events within small space-time distances in Indianapolis, IN.

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Contributorship Statement

BRR and JLH developed the study idea. JLH performed the analysis with assistance from CS. All authors discussed and interpreted the study findings. BRR and JLH wrote the first draft of the manuscript. All authors provided substantive comments and suggestions. All authors have reviewed the final version of the manuscript and have approved it for submission. JLH is the guarantor for this study.

Competing Interests

None to declare.

Ethics Statements

Patient consent for publication

Not applicable.

Ethics approval

This study, including waiver of the Health Insurance Portability and Accountability Act authorization and analysis of limited data sets, was approved by the Wayne State University institutional review board (#21–09-3996).

Results: Neighborhoods with more structural racism, economic deprivation, or urban blight were associated with higher rates of nonfatal overdose. Exposure to an opioid-related drug seizure event had a significant and positive effect on the epidemic probability of nonfatal overdose. An opioid seizure that occurred within 250 meters and 3 days, 250 meters and 7 days, and 250 meters and 14 days of an overdose event increased the risk of a new nonfatal overdose by 2.62 (RR=2.62, 95% CI: 1.87–3.67), 2.17 (RR=2.17, 95% CI: 1.87–2.59), and 1.83 (RR=1.83, 95% CI: 1.66–2.02), respectively. Similar spatiotemporal patterns were observed in a smaller spatial bandwidth.

Conclusions: Results demonstrated that overdoses exhibit a community spread process, which is exacerbated following law enforcement strategies to disrupt the unregulated drug market. We discuss decriminalization and increasing resources that promote safer drug use to combat this public health crisis.

INTRODUCTION

Overdose mortality is a persistent public health crisis in the United States (US).[1] Mortality rates are currently driven by fentanyl, which has largely replaced heroin in the unregulated drug markets in the US. The unregulated opioid market is continually evolving as supply-side drug enforcement (interdiction and drug seizures) results in progression towards more potent yet accessible substances. With opioids, people rapidly develop a tolerance though overdose occurs when dosage exceeds tolerance to the point of respiratory failure. Those dependent on opioids can experience painful withdrawal symptoms and diminished biological tolerance even after short periods of abstinence.[2] As such, fear of withdrawal and unknown tolerance to fentanyl has contributed to increases in overdose rates nationally. Naloxone, the opioid-overdose agonist,[3] has been standard among emergency medical services (EMS) for decades and as overdoses increased nationally there has also been a corresponding increase in naloxone administration by EMS.[4]

Social contagion may play a significant role in the spread of opioid overdose in US communities. Drug use behaviors and access to opioids can spread through social networks, especially in illicit markets where word-of-mouth is crucial.[5] Social connections among family, friends, and peers have been shown to significantly shape drug use behavior,[6] while spatial connections have demonstrated spatial spillovers of opioid use.[5] As such, opioid-related overdoses may behave like a complex contagion.[7] The spread of overdoses may be enhanced or constrained by the social determinants of health (SDOH),[8,9] the conditions where people are born, live, learn, work, play, and age. SDOH factors such as socioeconomic deprivation, the neighborhood and built environment, and structural racism[10,11] affect a range of health outcomes,[12] including overdose risk.[13] However, research on SDOH and overdose often fails to examine the role of criminal-legal systems in driving and exacerbating social adversities.[14,15]

Recent research suggests overdose events increase in the days after an opioid-related drug seizure.[16–18] When persons have developed a chemical dependency to opioids that they can no longer obtain, they might shift to alternative source to avoid withdrawal symptoms. Depending on time since last use, biological tolerance may have altered in unpredictable ways and those using unregulated drugs with unknown content, especially with a new

supplier, are unable to estimate their tolerance accurately increasing the likelihood of overdose. The current study aims to determine whether spatiotemporal patterns of opioid-related nonfatal overdose are consistent with a contagion process and to assess the degree to which exposure to drug supply disruptions trigger future overdose events across varying space-time distances. Using an endemic-epidemic framework that integrates mathematical tools from epidemiology to understand contagions of social behaviors across geographic space[7] we developed a two-component spatiotemporal intensity model (twinstim).[19] Our underlying uses SDOH community measures (*endemic*) and event-level information on opioid-related drug seizures and EMS naloxone administrations (*epidemic*) to assess the spatiotemporal process and whether overdose events spread when police disrupt the illicit supply there.

METHODS

Study Setting

This study takes place in Marion County, Indiana, home to Indianapolis, the 15th largest city in the US by population,[20] and was conducted as part of research study funded by the Centers for Disease Control and Prevention (CDC) and the National Science Foundation. This geographic area was selected because of high overdose rates but also because two-years of data (January 1, 2020 through December 31, 2021) have been curated from administrative systems that contain point-level information required for the twinstim model.

Data Sources and Measures

Outcome Measure.—The study outcome, nonfatal opioid-related overdoses, are measured using EMS call-for-service events where naloxone was administered in the field (Figure 1). These data were obtained from the Indianapolis EMS and include the time and location of these events and are described in detail in prior research.[21] EMS data provides spatial and temporal variation based on overdose with first responders observing “localized spikes in overdoses immediately following drug seizures”[22] During the two-year study period there were N = 212,886 EMS events of which 3.03% (n = 6,442) had naloxone administered. Hereafter, we refer to the outcome measure as nonfatal overdose events.

Endemic Measures.—Spatial *endemic* measures at the block group-level were obtained from multiple sources. *Socioeconomic deprivation* was calculated from a neighborhood deprivation index (NDI) using the 2016–2020 American Community Survey (ACS). Measures of *urban blight,* including the total population and number of housing units per block group, were also obtained from the ACS and used alongside information from the Indianapolis open data portal to determine the percentages of abandoned and vacant residential homes within each block group. Both the NDI and percent vacant homes were standardized with mean equal to 0 and a standard deviation equal to 1, where a higher value represents greater deprivation or blight. We constructed a measure of *structural racism* from the 1937 Home Owner’s Loan Corporation (HOLC) redlining shapefiles [23]. Following prior research,[24] we assigned historical redlining grades to 2020 block group boundaries (A=“Best,” B=“Still Desirable,” C=“Definitely Declining,” D= “Hazardous”); block groups with multiple redlining grades were categorized as “Mixed” and block groups that were

not assessed in 1937 were classified as "Missing." Due to limited sample size, A and B grades were collapsed into a single category. We also included temporal endemic measures. Given seasonal trends in policing and overdose events and increases following the onset of the COVID-19 pandemic,[25] we included a categorical variable of *seasons* and an indicator variable of whether the nonfatal overdose event occurred during the *COVID-19 stay-at-home orders* (March 25, 2020 to May 18, 2020) in Indianpolis.

Epidemic Measure.—Opioid-related drug seizures were obtained from the Indianapolis Metropolitan Police Department property room. During the two-year study period, n = 12,505 drug-related pieces of property were booked into the local police department, including drugs seized with support from state and federal agencies. These data contained information on the location, date, and physical description of the substance. We dropped events that were not appropriate for testing the hypothesized drug market disruption mechanism, including controlled buys, paraphernalia, seizures outside of the community settings (airport and hospital) and other events. We include events n = 1,926 where substances were seized in the community and suspected to be opioid-related based on the description of the substance (fentanyl, heroin, prescription pain analgesics).[21]

Statistical Analysis

Descriptive statistics for endemic measures were calculated. We visualized the spatial distribution of nonfatal overdose events and opioid-related drug seizure events using heat maps. We visualized the temporal distribution using line graphs. We used a twinstim model to determine whether spatiotemporal patterns of nonfatal overdose are consistent with a contagion process and to assess the degree to which exposure to drug supply disruptions trigger future overdose events in the surrounding community. The twinstim treats nonfatal overdose events as resulting from a self-exciting process [19] that decays with increasing spatial and temporal distance from the focal event. The rate of community spread $\lambda(t, s)$ at a specific location s and time point t, given all nonfatal overdose events, was additively decomposed into endemic and epidemic components:

$$\lambda(t, s) = v[s][t] + \sum_{j \in I(s,t)} \eta_j f(s - s_j) g(t - t_j) \quad (1)$$

where:

- s was the geocoded location of each nonfatal overdose event, t is the time of overdose. The index $[s][t]$ referenced a spatiotemporal grid covering Indianapolis;
- $v[s][t]$ was a log-linear predictor of the endemic component and included communitylevel SDOH and temporal measures;
- η_j was a log-linear predictor of the epidemic component and included the number of opioid-related drug seizure events that occurred within s spatial distance (100 and 250 meters) and in t days *prior* to the nonfatal overdose event (3, 7, and

14 days). $I(s,t)$ was the set of prior nonfatal events that, for each overdose j, triggered secondary events during its temporal window and within its spatial interaction radius.

- f and g were positive spatial and temporal interaction step functions, respectively, that described the decay of infectivity with an increasing spatial or temporal distance from the infection source.

Population density at the block group-level was log-transformed and used as an offset endemic term. A centered time trend was included to determine whether the strength of the endemic component shifted over the 2-year study period. Historical redlining grade (reference = mixed), the NDI, and percent vacant households were included as block group-level time-invariant covariates. An indicator of whether the nonfatal overdose event occurred during the COVID-19 lock down period and a categorical variable indicating the season (reference = fall) in which the event occurred were also included in the endemic component.

The epidemic component specified a self-exciting point process effect among overdoses and described the degree to which exposure to drug supply disruptions trigger future overdose events. The epidemic component was implemented across multiple space-time kernels to assess thresholds and patterns in the spatiotemporal relationship between community spread of overdose and exposure to opioid-related drug seizure events. Given the local nature of our hypothesized mechanism and observed localized spikes around opioid-related drug seizures,[22] we created two spatial bandwidths (100 and 250 meters) and three temporal bandwidths (3, 7, and 14 days). Each overdose event exerted its effect on future nonfatal overdose events within these space-time kernels assuming a decay of the infection force as the spatial and temporal distance from it increased.

We first conducted a series of models that only incorporated the endemic components and then expanded these to include epidemic components with comparisons conducted using Akaike's Information Criterion (AIC) to assess the superiority of one model over another at accurately representing the underlying data. We parameterized the upper-limits for whether nonfatal overdose events were triggered by past events with step functions (f and g).[19] Alternative decay functions were assessed but deemed insufficient by AIC. We formally tested the space-time interaction with permutation tests, likelihood ratio tests (LRT), and standard Knox tests (see Supplementary Materials) (Supplementary 1, 2 and 3). Rate ratios (RR) and 95% confidence intervals (CI) for endemic and epidemic factors were calculated and the spatiotemporal analyses were carried out using R package "surveillance".[19]

RESULTS

In the two years of pooled data, the densest area for opioid-related drug seizures is in the downtown area with overdose events most dense immediately to the east of downtown (Figure 2). There are also concentrations for drug seizures near the airport in the southwest and in the northeast at highway interchanges. Temporal trends in opioid-related seizures suggest a seasonal pattern, with reductions in colder months, and notable increases following the COVID-19 pandemic as illustrated by the vertical gray line in Figure 2c. Nonfatal overdose events were relatively consistent following a decrease during the onset of the

pandemic stay-at-home orders and increases in the summer thereafter. See Supplementary Material for summary statistics and spatial patterning.

Endemic Model

The annual time trend was not significant, indicating that the endemic rate of nonfatal overdose did not change between 2020 and 2021 (Table 1). During the COVID-19 lockdown period, the endemic rate of nonfatal overdose decreased by 15% (RR=0.85, 95% CI: 0.77–0.93) and relative to the fall season, nonfatal overdose events increased in the spring (RR=1.28, 95% CI: 1.18–1.38) and summer (RR=1.33, 95% CI: 1.24–1.43) and decreased in the winter (RR=0.80, 95% CI: 0.73–0.86).

Historical redlining grades were positively and negatively associated with the endemic rate of nonfatal overdose, depending on the redlining grade. Compared to neighborhoods with a Mixed-grade, nonfatal overdose was 66% lower in areas graded as Missing/Suburban (RR=0.34, 95% CI: 0.31–0.37) while the risk in neighborhoods with a grade of Hazardous was 12% higher (RR=1.12, 95% CI: 1.03–1.22). Neighborhoods with higher economic deprivation or urban blight were associated with higher rates of nonfatal overdose. For every standard deviation increase in the NDI, the rate of nonfatal overdose events increased by 36% (RR=1.36, 95% CI: 1.27–1.34). Similarly, a one standard deviation increase in the portion of vacant homes was associated with a 31% increase in the rate of nonfatal overdose (RR=1.31, 95% CI: 1.27–1.34).

Epidemic Models

Exposure to an opioid-related drug seizure event had a significant and positive effect on the epidemic probability of nonfatal overdose, with strong and consistent spatiotemporal patterning (Table 2). Within each spatial bandwidth (100 and 250 meters), the rate of nonfatal overdose decreased as the number of days following the exposure increased. An opioid seizure that occurred within 250 meters and 3 days, 250 meters and 7 days, and 250 meters and 14 days of an overdose event increased the rate of a new nonfatal overdose by 2.62 (RR=2.62, 95% CI: 1.87–3.67), 2.17 (RR=2.17, 95% CI: 1.87–2.59), and 1.83 (RR=1.83, 95% CI: 1.66–2.02), respectively. Similar spatiotemporal patterns were observed in the 100-meter spatial bandwidth.

Estimates of the decaying spatial and temporal interaction functions, as well as model diagnostics, can be seen in the Supplementary Materials. The observed R0 values are significantly higher than the null distributions of the converged permutations ($p < 0.001$), indicating that the spatio-temporal interaction in the epidemic model is significant. Both the LRT ($p < 0.0001$) and the Knox tests ($p < 0.0001$) support this result, indicating that the twinstim models provide useful descriptions of the contagion process of nonfatal overdose events and the exacerbation of the epidemic probability following exposure to opioid-related drug seizures.

DISCUSSION

Using an endemic-epidemic framework that statistically accounts for community-level and temporal factors, we found that nonfatal overdose, as measured by EMS naloxone

administration, demonstrates a contagion process. The rate of a future nonfatal overdose was more than twice as high in close spatiotemporal proximity following an opioid-related drug seizure. The strength by which police seizures increased the epidemic probability of future overdose events varied by space-time kernel, with stronger associations occurring in the smaller space-time bandwidths.

While the notion that police drug seizures are associated with increased overdose is jarring, it is important to note that the mechanism resulting in these harms is well documented. When persons who have developed a chemical dependency to opioids have their supply disrupted, they shift to alternative sources or different drugs to avoid withdrawal symptoms. There is no shortage of suppliers, in fact it may be even easier to enter the drug trade with synthetic opioids like fentanyl,[26] but consumers are unable to estimate their biological tolerance, leading to overdose.[27] This drug supply disruption mechanism is well understood with incarceration and overdose as people are rarely provided evidence-based medications while incarcerated or following release, and with biological changes in tolerance, they are more suspectable to overdose if they resume use, particularly at pre-incarceration levels.[28] This disruption mechanism has also been tied to changes in the prescription drug supply,[29] so much so that the CDC developed programming aimed at facilitating mitigation strategies before patients experience a disruption to their opioid supply when law enforcement arrest a medication provider.[30]

Consistent with other research, we found community-level measures of SDOH were associated with increased nonfatal overdose events,[8,9,31,32] which included a strong influence of historical redlining that is tied to several negative health outcomes.[24] Research with Black residents in Indianapolis found stigma, fear, and mistrust as barriers to accessing and using overdose prevention strategies.[33] Therefore, with limited access to naloxone, residents in these communities may be in greater need of EMS for an overdose. Our study also found socioeconomic deprivation is associated with increased nonfatal overdose.[34] Similar to work in Ohio,[35] our study found that rate of overdose events were higher in communities characterized by a higher proportion of vacant housing, which may be related to community disinvestment and lack of social services and health care.

The twinstim endemic-epidemic modeling approach is ideal for understanding whether the spread of nonfatal overdose proceeds through a contagion process, and the degree to which law-enforcement related drug supply disruption enhances the spread of overdose. Given the gravity of the overdose epidemic, this study should be replicated in other jurisdictions immediately. Prior research that explored the relationship between law enforcement-involved drug seizures and overdose events[17] was unable to disentangle the temporal sequence of overdose and drug seizure events. This approach explicitly tests for the self-exciting processes in the overdose data and ensures that the exposure (drug seizures) precedes the outcome when assessing how drug seizures enhance the community spread of overdose. Moreover, within this spatiotemporal regression framework we can adjust for temporal and community-level SDOH factors relevant to the study area, providing cross-jurisdictional comparison.

The single setting is a limitation, and Indianapolis could have biased our results as it is located in a state with some of the lowest health ratings in the US and racial-ethnic disparities in criminal-legal systems involvement, behavioral health treatment, and overdose. In terms of drug policy, it is a state where cannabis is not medically or recreationally legal, Good Samaritan Laws offer limited protections to the caller and none to the overdose victim, and the possession of a syringe without a prescription is a felony.[36] Thus, cities where police conduct fewer drug interdictions may have lower overdose events. Without additional information we cannot determine whether our spatiotemporal patterns are most suited to this setting and hypothesized mechanism. Despite these limitations, our study provides a blueprint for replication which could inform these limitations.

Conclusion

Nonfatal overdose data is driving public health decisions in many communities[37] and this study suggests that information from law enforcement drug seizures has predictive utility in the spread of overdose events. Importantly though, communities also need to recognize that incredibly well funded policing efforts to seize drugs have had little public utility and have not resulted in any sustained reduction in the price or availability of drugs. Communities need to determine if there are any benefits of these policing efforts and if not move to reduce harms and reallocate resources away from drug enforcement and toward public safety. Drug decriminalization and regulation are needed, but any meaningful reduction in overdose deaths is not going to occur without large scale investments and policies that address SDOH. In the more immediate period, there needs to be a massive scaling up of evidence-based treatment and harm reduction interventions to help people who use drugs and reduce the risk of overdose.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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KEY MESSAGES

What is already known on this topic:

- The opioid overdose mortality crisis remains one of the most pressing and persistent public health issues in the United States.
- Beyond individual level behaviors, nonfatal overdose events are driven by social determinants of health and criminal-legal systems, including law enforcement efforts to disrupt the unregulated drug market.
- Whether drug supply disruptions impact the community spread of nonfatal overdose events remains unclear

What this study adds:

- Neighborhoods with more structural racism, economic deprivation, or urban blight were associated with higher rates of nonfatal overdose.
- Nonfatal overdose demonstrates a community spread process, which is enhanced following opioid-related drug seizures.
- The risk of a future nonfatal overdose was more than twice as high in close spatiotemporal proximity following an opioid-related drug seizure.

How might this affect research, practice or policy:

- Information from law enforcement drug seizures has predictive utility in the spread of overdose events.
- From a policy standpoint, communities need to determine if there are any benefits of these policing efforts and if not move to reduce harms and reallocate resources away from drug enforcement and toward public safety.

Contagion Component	Variable	Measurement	Unit	Data Source
Contagious Outcome	Nonfatal overdose events	Time & location of naloxone administrations by EMS	Point-level	Indianapolis Emergency Medical Services
Endemic Predictors	Socioeconomic deprivation	Neighborhood Deprivation Index	Block group	2016-2020 American Community Survey
	Urban blight	Abandoned and vacant residential homes	Block group	Indianapolis Open Data Portal
	Structural racism (categorical)	Grades: A *Best*, B *Still Desirable*, C *Declining*, D *Hazardous*, *Missing*, *Mixed*	Block group	1937 Home Owner's Loan Corporation
	Annual time trend	Calendar year	Temporal	Calendar
	Season (categorical)	Winter, Spring, Summer, Fall	Temporal	Calendar
	COVID-19 stay-at-home period	March 25, 2020 to May 18, 2020	Temporal	COVID-19 US State Policies
Epidemic Predictor	Opioid drug seizures	Time and location of opioid drug seizures	Point-level	Indianapolis Metropolitan Police Department

Figure 1.

Data source and measurement by modeling component.

NOTES: Socioeconomic deprivation and urban blight are standardized with a mean of 0. The reference category for Structural racism is Mixed; due to limited sample size, A and B redlining grades were collapsed into a single category. The reference category for Season is Fall. Indianapolis Open Data Portal can be found at https://data.indy.gov/. Point-level indicates latitude, longitude, and date.

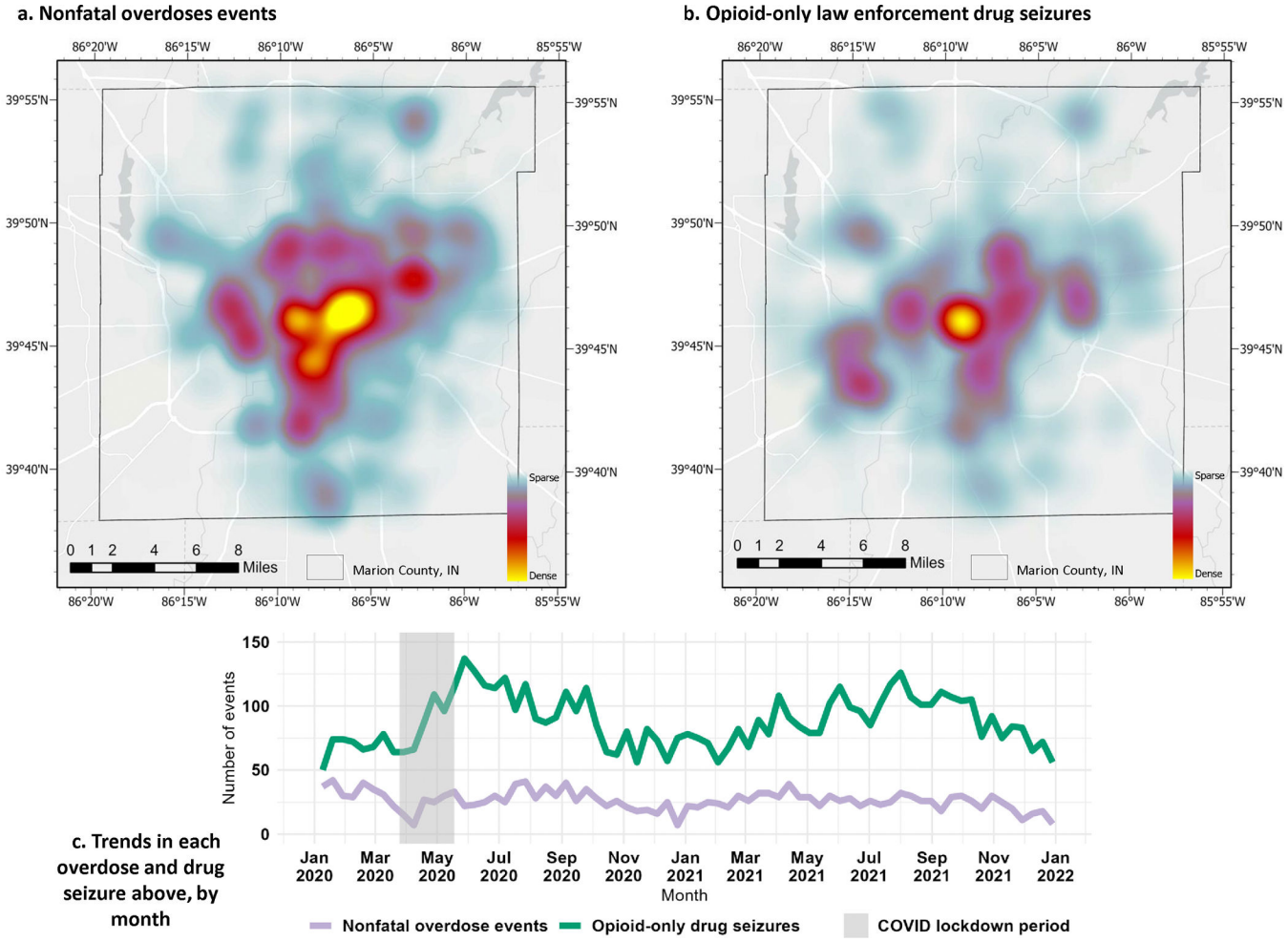

Figure 2.

Spatial and temporal trends of the outcome (nonfatal overdose events) and epidemic predictor (opioid drug seizures).

Table 1.

Endemic model predicting nonfatal overdose events.

	RR	95% CI	P value
Annual Time Trend	0.98	(0.93, 1.03)	0.34
COVID Lockdown Period	0.84	(0.76, 0.93)	0.002
Season (Ref = Fall)			
Spring	1.28	(1.18, 1.38)	<0.001
Summer	1.33	(1.24, 1.42)	<0.001
Winter	0.8	(0.73, 0.87)	<0.001
Historical Redlining (Ref = Mixed)			
AB - Best, Still Desirable	1.03	(0.93, 1.15)	0.55
C - Definitely Declining	0.79	(0.73, 0.85)	<0.001
D - Hazardous	1.12	(1.03, 1.22)	0.008
Missing (suburban areas)	0.34	(0.31, 0.37)	<0.001
Neighborhood Deprivation Index	1.36	(1.32, 1.4)	<0.001
% Vacant Households	1.31	(1.27, 1.34)	<0.001

RR = rate ratio; CI = confidence interval.

Table 2.

Epidemic model predicting nonfatal overdose events following opioid-related drug seizures.

	RR	95% CI	P value
100 Meters			
3 Days	2.55	(1.37, 4.72)	0.003
7 Days	1.93	(1.42, 2.63)	<0.001
14 Days	1.93	(1.62, 2.29)	<0.001
250 Meters			
3 Days	2.62	(1.87, 3.67)	<0.001
7 Days	2.17	(1.82, 2.59)	<0.001
14 Days	1.83	(1.66, 2.02)	<0.001

RR = rate ratio; CI = confidence interval.