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Analyzing the stability of gun violence patterns during the COVID-19 pandemic in Syracuse, New York

Peng Gao^{1*}, Sarah E. Van Horne², David A. Larsen³, Robert A. Rubinstein⁴ and Sandra D. Lane³

Abstract

Gun violence is a leading cause of death in the United States. Understanding the geospatial patterns of gun violence and how the COVID-19 pandemic may have affected them is essential for developing evidence-based prevention strategies. This study investigates whether COVID-19 altered the geospatial patterns of gun violence in Syracuse, New York. To assess spatial and temporal trends, we analyzed the annual total gunshots (ATG) from 2009–2023 aggregated in census block groups and applied geospatial techniques including mean center, standard distance, Moran's *I*, and Getis-Ord *G_i^**. The ATG number was higher before the pandemic than during the pandemic, something not observed in other studies. Its geographic centers before and during the pandemic clustered within or near one census block and the associated standard distance remained similar between the two periods. Both global patterns and local clusters of ATG in the two periods not only showed similar patterns and consistent local hotspots located in similar areas, but also logarithmically related to the ATG number with statistical significance, suggesting that gun violence rates intensified within established areas rather than spreading citywide and demonstrated a similar distance-decay effect in both periods. This effect suggests that the incidence of gunshots diminished with increasing distance from the core concentrated zone, challenging assumptions of spatial spillover or contagion models in crime studies. These findings suggest that entrenched structural conditions, such as neighborhood-level socioeconomic disparities, are the primary drivers of gun violence patterns, rather than temporary pandemic-related policies. Methodologically, the study highlights the importance of long-term, meso-scale geospatial analyses to uncover persistent violence dynamics and guide preventive interventions. We argue that future violence prevention strategies should focus on enduring geospatial patterns of gun violence and their underlying structural determinants, rather than reacting solely to short-term fluctuations in incident frequency.

Keywords Gun violence, Geospatial analysis, Hot spots, Spatial clustering, And COVID-19 pandemic

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Background

Gun violence is a social and public health crisis affecting communities across US cities [1, 2]. In particular, it has become the leading cause of death for children and teenagers in the US [3, 4]. Many studies have confirmed that gun violence tends to occur in small areas (i.e., hotspots) around individual locations or street segments and remains unchanged over time [5–9]. This spatial nature has been explained in terms of routine activity and crime pattern theories [10, 11], which emphasize the important role of both place and routine activities in crime. For gun violence, these theories suggest that gunshots may be linked to social phenomenon (e.g., residential instability), urban built environment factors, and individual behavior (e.g., mobility) [12]. Furthermore, gun violence activities could vary spatially even within local communities [13].

These findings reveal that gun violence follows spatial and temporal patterns shaped by complex socioeconomic conditions and policy decisions. However, the specific effects of COVID-19 pandemic policies on gun violence trends remain uncertain and warrant further study. Stay-at-home advisories, school closures, and other public-health related policies are well known to have disrupted modern public life in an unprecedented fashion. Gun violence is posited as a sensitive social determinant that can be examined to test the potential effect of the COVID-19 pandemic on social behaviors. Several studies focusing on the entire United States demonstrated that firearm violence (fatal and nonfatal) increased substantially during the pandemic (or at least in its first year) across the country with the noticeable expansion of gun violence to new areas, when compared with gunshot incidence before the pandemic [14–16]. This national trend was consistent with similar, but independent studies on large US cities, such as Philadelphia, New York, Los Angeles, and Richmond [17, 18]. The implication is that the policies implemented during the COVID-19 pandemic, although variable in different US states and cities, apparently worsened the conditions of gun violence both by number and extent across the entire country.

Nonetheless, these studies are limited by their use of non-geospatial statistical models that primarily count gun violence occurrences at broad spatial scales (e.g., over the entire city). For example, the apparent geographic expansion of gunshot incidents documented by Gebeloff et al. [14] frequently represents isolated occurrences of individual gunshots in previously unaffected areas, without confirmation through rigorous statistical analysis. Furthermore, the relatively brief time frames examined in existing research, that is— typically comparing 2016–2019 or 2019–2020 (pre-pandemic) with 2020–2021 (pandemic) data [15–17], do not capture representative patterns of pre-pandemic gun violence. These methodological constraints suggest that the question

of COVID-19's impact on gun violence across US cities remains incompletely answered and warrants further investigation. Without incorporating spatial data into studies of gun violence, it is difficult to understand the impact that COVID-19 may have had. With apparent increases in gun violence, at least in some cities, did the COVID-19 pandemic shift the geospatial pattern of gun violence?

The purpose of this study is to examine the geospatial patterns of gun violence and their temporal trends over an extended period before and during the pandemic to infer the possible impact of COVID-19 policies on gun violence. We analyze spatial patterns of gunshot incidents comparing pre-pandemic (2009–2019) and pandemic/post-pandemic (2020–2023) periods in a medium-sized city, revealing their local concentrations and determining the distance decay effect of gun violence. By comparing these analyses between pre-pandemic and pandemic periods, we provide a more comprehensive understanding of how COVID-19 policies may have influenced gun violence patterns.

Methods

Study area and data

The city of Syracuse located

in Central New York within Onondaga county (Fig. 1a and 1b) covers approximately 66 km². As of 2020, the city population reached 148,620 with African American and Latino residents comprising about 39% of the total [19]. Despite being only a medium-sized city, Syracuse exhibits the highest concentration of poverty among Black and Hispanics populations compared to the 100 largest US cities [20]. Racial segregation is deeply embedded in its sociocultural fabric and clearly visible at the neighborhood level. Historical practices of redlining, urban renewal programs, and displacement caused by interstate highway construction have created pronounced geographic disparities, with majority Black populations concentrated in the south and southwest areas of the city. Violence in Syracuse functions as a critical factor that generates and reinforces patterns of socioeconomic inequality across its urban landscape [21]. Gun-related violence, in particular, has persisted as a severe problem facing the city [22]. Thus, examining the geographic characteristics of gun violence and how these patterns changed before and during the pandemic could provide valuable insights into how pandemic-era policies affected public health outcomes in Syracuse and similar cities (e.g., those along the 'rust belt') facing comparable challenges.

Gunshot incidents reported annually in the 15-year period (2009–2023) were collected from two different sources. The first dataset of the gunshot incidents with known locations (x- and y-coordinates) in each year

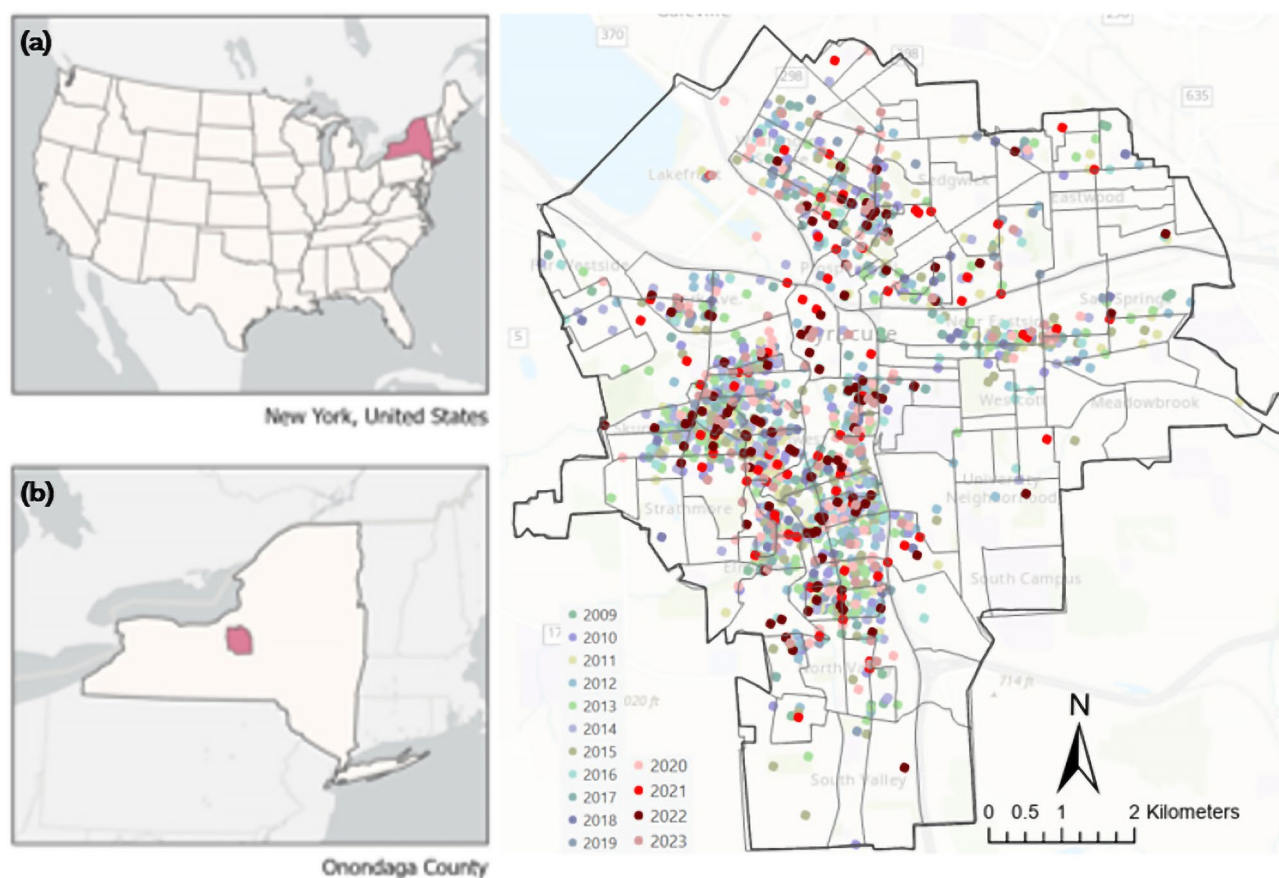


Fig. 1 The geographic location of the study area and the gunshot data. (a) The location of New York State; (b) The location of the Onondaga County; and (c) The City of Syracuse and the compiled gunshot incidents in the study period from 2009 to 2023

from 2009 to 2015 was compiled from the crime database provided by the Syracuse Police Department (SPD). While details of this database can be found in Larsen et al. [23], the dataset used in this study includes all (fatal and non-fatal) gunshot incidents and their locations and time. The second dataset was downloaded from National Gun Violence Archive (NGVA) (<https://www.gunviolencearchive.org/>). We carefully sorted the data and selected both the fatal and non-fatal gunshot incidents and their locations and time from 2016 to 2023. This dataset was selected primarily due to its availability during the initial analysis phase. Subsequently, we obtained a short-term dataset covering 2018–2023 directly from the SPD, which we used for validation purposes. Cross-validation of both datasets revealed less than 5% difference in total gunshot incidents, with highly consistent spatial patterns (Fig. S1). We then concluded that both datasets are consistent with each other. Combining the two datasets and converting them into the Geographic Information System (GIS) format led to a point shapefile including spatially distributed points representing gunshot incidents from 2009 to 2023 (Fig. 1c). The spatial distribution of each year can be found in Figure S2. These gunshot incidents were

distributed throughout most regions of the city, revealing widespread occurrence across the urban landscape.

Choice of the spatial unit

In principle, spatial patterns and relationships are sensitive to the spatial units at which the data are compiled. Studies on crime have commonly focused on two different spatial levels of analysis. Micro-scale analyses treat incident locations (points) [24], street segments (lines) [25], Thiessen polygon (irregular rectangular street blocks) [26], or grids (regular squares of street blocks) [27] as the basic spatial units and perform various geo-spatial analyses, most of them being hot spot analyses. Using these smaller spatial units allows for identifying the streets or small blocks that suffer the most from gun violence, such that they can be easily prioritized for police patrolling or for developing intervention strategies, for instance the Group Violence Intervention [5] and gun violence prevention among at-risk adolescents [28].

Macro-scale analyses typically aggregate gunshot incidents to larger spatial units that have social and administrative meanings such as states [29, 30], districts [31], zip codes, or census tracts [32]. A significant advantage

of analyzing gun violence at these macro scales is that the identified geospatial patterns or hot spots can be subsequently linked to relevant social determinant factors for uncovering the possible socioeconomic causes of gun violence [33].

However, the macro-scale results are incapable of explaining local variability of gun violence or informing place-specific interventions, while the micro-scale hotspot analyses fail to address issues such as collective efficacy [34] and spillover effects [35], which typically exist at the neighborhood, census tract, or block group levels, termed as the meso scale. The meso-scale analyses allow for examining the impact of urban morphology, land use, access to resources, and social cohesion on gun violence [36], the gap micro- and macro-level studies may overlook. Apparently, the meso-scale analyses are under-represented in crime and gun violence literature, but they may provide insights into the structural and environmental contributors to gun violence. For this reason, we analyzed the geospatial patterns of gunshot incidents over the entire study period (2009–2023) at the census block group level (meso scale).

Syracuse is divided into three spatial hierarchies according to the US Census Bureau: census blocks (CBs, $n=2,099$), census block groups (CBGs, $n=133$) (Fig. 2), and census tracts (CTs, $n=55$). Their mean areas are 0.031, 0.497, and 1.203 km², respectively. For our analysis, we selected the CBG scale (i.e., the meso scale) as the optimal spatial unit. The average CBG takes 0.7% of the

Syracuse area, providing an appropriate resolution for our purposes. This choice avoided the limitations of the CB scale, where many blocks would record zero incidents in a given year, potentially compromising analytical reliability. It also addressed the drawbacks of the CT scale, which would have produced only 55 observed units, significantly reducing statistical power, while obscuring important spatial variations within each tract due to excessive aggregation. We summed the annual total gunshots (ATG) within each CBG (Fig. 2) and used these counts for all subsequent geospatial analyses.

Geospatial analyses

Our analysis begins with presenting the temporal trend of the ATG over the 2009–2023 period and comparing their means before and during the pandemic. Since gun violence is well established to concentrate in specific areas or “hot spots” [37, 38, 8], identifying these concentrations using geostatistical tools has become a standard approach [39]. However, from a Geospatial Science perspective [40], geospatial patterns can be characterized through multiple approaches beyond hot spot identification.

In this study, we identify three types of geospatial patterns for each ATG dataset: the geographic distribution, global pattern, and local cluster. [41]. All geospatial analyses were performed in ArcGIS Pro 3.3.1. The geographic distribution of ATGs describes central tendency of gun violence annually across the city and its compactness regarding to locations of annual gunshot incidents. It is characterized by the mean center and its associated standard distance [41]. The mean center of each ATG dataset represented as a point (or a location) $(\bar{x}_w, \bar{y}_w)$ is calculated as

$$\bar{x}_w = \frac{\sum_{i=1}^n w_i x_i}{\sum_{i=1}^n w_i}, \bar{y}_w = \frac{\sum_{i=1}^n w_i y_i}{\sum_{i=1}^n w_i} \quad (1)$$

where x_i and y_i are coordinates of the centroid of each census block group (CBG), w_i is the proportion of the ATG falling in the same CBG, and n is the total number of CBGs. The associated standard distance (SD) is calculated as:

$$SD = \sqrt{\frac{\sum_{i=1}^n w_i ((x_i - \bar{x}_w)^2 + (y_i - \bar{y}_w)^2)}{\sum_{i=1}^n w_i}} \quad (2)$$

where x_i and y_i are the coordinates of a CBG centroid, $\bar{x}_w$ and $\bar{y}_w$ are the coordinates of the mean center, and n is the total number of CBGs. For ATGs aggregated in all CBGs, the mean center is a point within Syracuse and SD is the radius of a circle centered on the mean center (Fig. 2). We then performed the average nearest neighbor

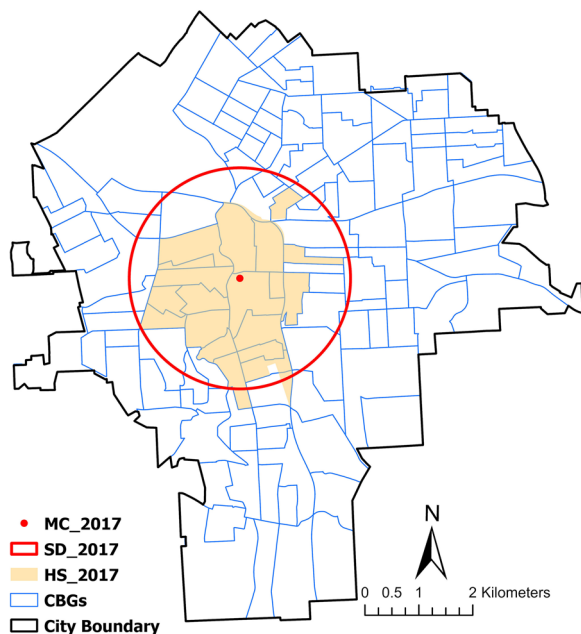


Fig. 2 Illustration of geostatistical analysis based on the 2017 annual total gunshots (ATG) dataset. MC_2017 is the mean center of the 2017 ATGs, SD_2017 is the associated standard distance, and HS_2017 is the hotspot of the 2017 ATGs, termed as the Standardized Hotspot Area (SHA)

analysis for the mean centers of the studied 15 years. The result is represented by the nearest neighbor ratio (NNR), which is the ratio of the observed average distance between each point and its nearest neighbor to the expected average distance for a random distribution of the same number of points within the same area. $NNR < 1$ means that the points are clustered with a smaller NNR value representing a higher degree of cluster. $NNR > 1$ indicates that the points are dispersed with a NNR number reflecting a more even distribution of the points.

The citywide spatial distribution of ATGs aggregated at the CBG level reveals patterns of spatial clustering through the measurement of spatial autocorrelation. This analysis examines how similar ATG counts are distributed across neighboring CBGs throughout the urban area [42]. The degree of spatial autocorrelation is quantified using Moran's I , a single summary statistic defined as

$$I = \frac{n \sum_{i=1}^n \sum_{j=1}^n w_{ij} (x_i - \bar{x})(x_j - \bar{x})}{W \sum_{i=1}^n (x_i - \bar{x})^2} \quad (3)$$

where n is the total number of CBGs, x_i and x_j are the numbers of the ATGs in CBG i and j , $\bar{x}$ is the mean of the ATG numbers in all CBGs, w_{ij} is the spatial weight between centroids of CBG i and j , and, W is the sum of all spatial weights ($\sum w_{ij}$). Moran's I ranges between -1 and 1 [43]. A value near 0 indicates a random spatial distribution of the ATGs at the CBG scale, a negative value ($I < 0$) reflects spatial dispersion, while a positive value ($I > 0$) indicates clustering of similar values (e.g., high-high or low-low values). Using the calculated Moran's I for all 15 years, we also examined their relationship with the ATGs for the two time periods to reveal the temporal

trend of the global spatial patterns of gun violence in Syracuse.

Local clustering patterns of ATGs across all CBGs in Syracuse are identified using the Getis-Ord G_i^* statistic [44]. This statistic identifies statistically significant spatial concentrations of either high values (hot spots) or low values (cold spots) within the study area. It is expressed as [41]:

$$G_i^* = \frac{\sum_{j=1}^n w_{ij} x_j - \bar{X} \sum_{j=1}^n w_{ij}}{S \sqrt{\frac{[n \sum_{j=1}^n w_{ij}^2 - (\sum_{j=1}^n w_{ij})^2]}{n-1}}} \quad (4)$$

where x_j is the number of the ATGs in CBG j , w_{ij} is the spatial weight between CBG i and j , n is the total number of CBGs, $\bar{X}$ is the mean of the aggregated ATGs in all CBGs, and S is the associated standard deviation. Using calculated values of G_i^* , we identified statistically significant clusters of CBGs with high or low ATG numbers (i.e., hot and cold spots) at 90% confidence or above, respectively. This study concentrated specifically on hotspot clusters, calculating their combined area for each study year (Fig. 2). These areas are then normalized by the total city area to create a Standardized Hotspot Area (SHA), expressed as a percentage. By relating the SHA to ATGs over the study period, we investigated the temporal trends of local clusters of gun violence before and during the pandemic.

Finally, we analyzed gunshot spatial distance effects in Syracuse through a four-zone approach and compared these effects between the two periods. Zone 1 represented the core area with hotspots appearing most frequently over 15 years, Zone 2 included its neighboring CBGs, Zone 3 is the next neighboring CBGs, and Zone 4 comprises the most outside CBGs of the city. Therefore, moving from Zone 1 to Zone 4 represents increased distance away from the center of high-frequency gun violence. We then calculated gunshot density (the total gunshot incidents in each period per unit area) for each zone and compared spatial decay patterns before and during the pandemic.

Results

Temporal trends of annual total gunshots in the two periods

During the pre-pandemic period (2009–2019), the annual total gunshots (ATGs) showed a consistent linear decrease at a rate of approximately 25 incidents (or 19.9%) per year ($R^2 = 0.708$, $p < 0.05$), suggesting a gradual improvement in public safety conditions. In contrast, during the pandemic period (2020–2023), the ATGs did not follow any statistically significant trend, varying between 89 and 137 (Table 1 and Fig. 3). It appears that

Table 1 Summary of the geospatial analysis

Year	Gunshot No.	Spatial patterns		
		Standard distance (m)	Moran's I (p -value)	SHA*
2009	169	2538	0.4301 (<0.001)	35.95
2010	255	1953	0.5596 (<0.001)	41.33
2011	262	2540	0.4823 (<0.001)	41.94
2012	232	2481	0.4536 (<0.001)	53.56
2013	256	2501	0.4478 (<0.001)	47.10
2014	189	2310	0.4486 (<0.001)	48.96
2015	136	2491	0.3937 (<0.001)	32.79
2016	107	2323	0.3308 (<0.001)	26.74
2017	88	2053	0.2703 (<0.001)	20.10
2018	75	2239	0.2608 (<0.001)	21.46
2019	54	2572	0.1025 (0.0295)	2.95
2020	106	2313	0.1392 (0.0036)	34.96
2021	100	2306	0.2797 (<0.001)	26.70
2022	137	2092	0.3602 (0.0000)	28.04
2023	89	2217	0.1283 (<0.001)	31.81

*SHA – Standardized Hotspot Area (in percentage)

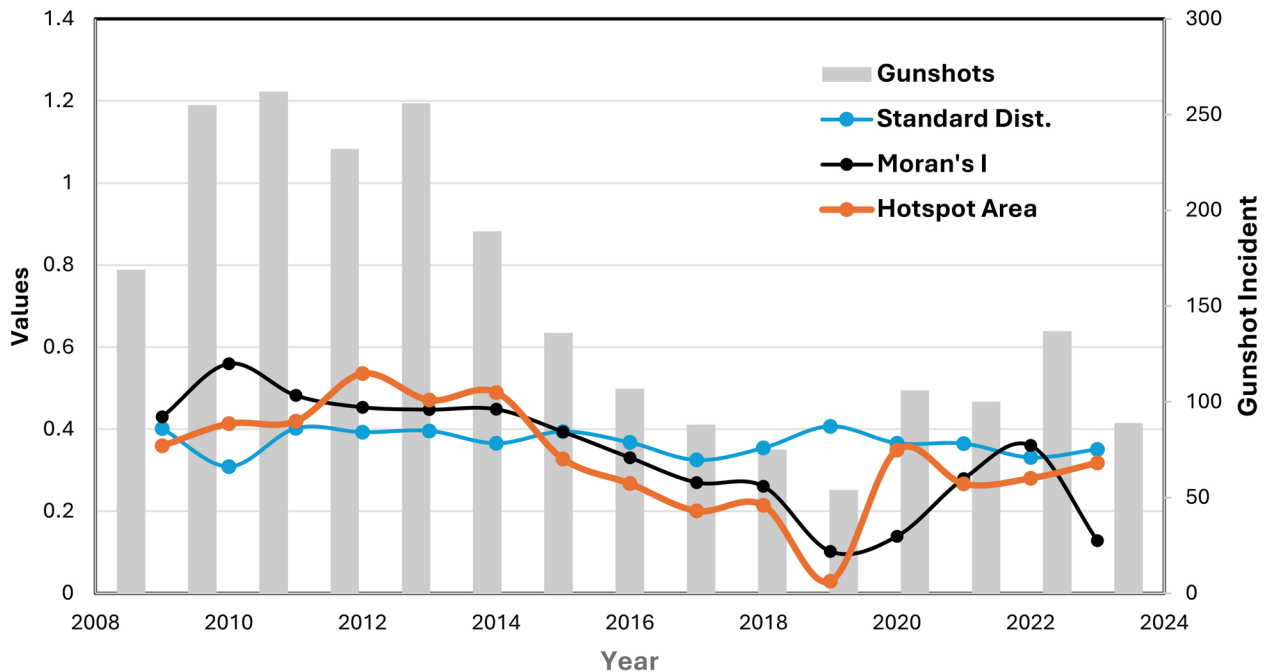


Fig. 3 Temporal trends of gunshot incidents (the gray bars) and geostatistical metrics including Standard Distance (blue), Moran's *I* (black), and Hotspot area (orange), expressed as Standardized Hotspot Area (SHA)

the decreasing trend of gun violence over a decade before the pandemic stopped during the pandemic. The two-sample difference test revealed that the mean ATG count during pandemic years (108) was significantly lower than pre-pandemic years (178), with a p -value of 0.0152. This statistical significance demonstrates a clear decline in gunshot incidents from the pre-pandemic to the pandemic period.

Geographic distributions of gun violence in the two periods

Graphically, the mean centers of almost all ATGs at the CBG scale fall within the same CBG located near the geographic center of the city (Fig. 4). Those in 2010 and 2023 are positioned just outside this CBG boundary on the north and southwest. The average nearest neighbor analysis showed that they are highly clustered with statistical significance ($NNR=0.12$, p -value < 0.00001). This distribution indicates that annual gun violence at the CBG scale has remained a similar central tendency over 15 years of the study period, though the ATGs varied from 54 to 262. Furthermore, the mean centers before and during the pandemic are well mixed without any distinct patterns (Fig. 4). These patterns suggest that gun violence activities at the CBG (or meso) scale maintained similar geographic central tendencies regardless of pandemic conditions. This temporal stability in central locations persisted despite significant changes in the volume of gunshot incidents.

Over these 15 years, the standard distance did not exhibit clear directional trends (Fig. 3). The areas of compactness determined by circles whose radius are the standard distances for the 15 years largely overlap (Fig. 4). These similar geographic patterns suggest relative stability of gunshot activities at the CBG scale over the entire city, despite temporal fluctuations in ATGs. In other words, gun violence in Syracuse tends to occur in a geographically concentrated fashion rather than spreading evenly throughout the city before and during the pandemic. Even as the overall volume of incidents changed dramatically in the two periods, the spatial footprints of these activities remained relatively stable.

Global- and local-scale spatial patterns of gun violence in the two periods

Moran's *I* decreased with time before the pandemic, while increased during the pandemic (Fig. 3), showing that the spatial pattern of ATGs over the entire city responded to the temporal changes of the ATG counts. However, Moran's *I* values range from 0.103 (2019) to 0.560 (2010), all with statistical significance (Table 1). These consistently positive values confirm that ATG spatial distributions throughout the city exhibited clustering patterns, though their temporal trends are different during pre-pandemic and pandemic periods across the entire city.

Locally, in all years studied except 2019 and 2023, CBGs with high gunshot incidences formed distinct concentrated zones, creating localized 'hot spots' for gun

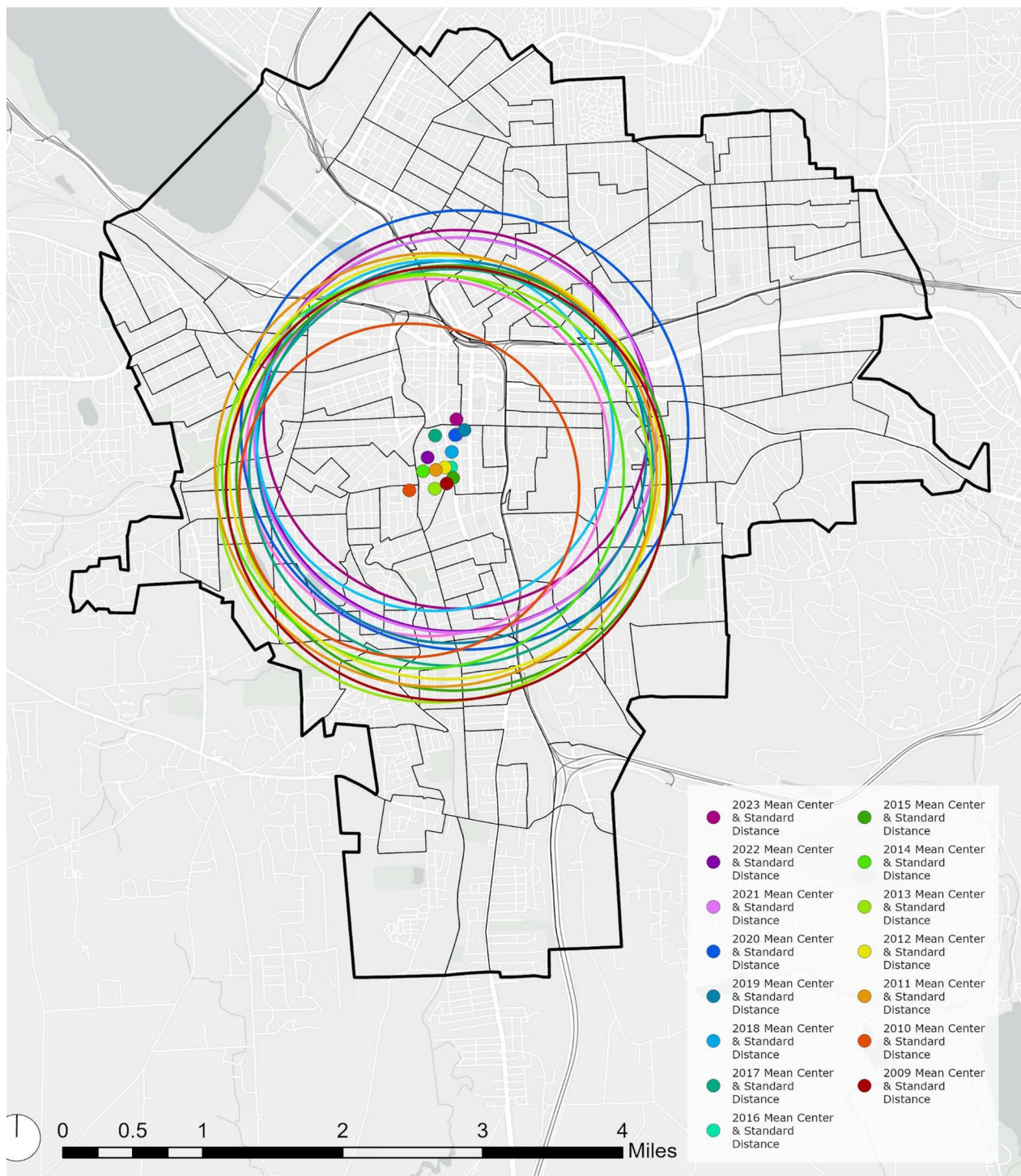


Fig. 4 Locations of the mean centers for the ATGs in the selected 15 years at the CBG scale and the associated standard distances (i.e., the radii of the circles)

violence as shown in Fig. 3 (see details in Fig. S3). A smaller concentration area appeared in the northeastern section of the city during 2019 and 2023 (see Fig. S3), corresponding to random gun violence incidents at Central New York's largest shopping mall located in that area.

This development does not compromise the consistency of the primary hotspot areas throughout the entire study period. This primary area, represented as SHA, ranged from 2.95 to 53.56 with statistical significance over the entire study period (Table 1). The SHA followed a similar

temporal pattern to Moran's I (Fig. 3), suggesting that local clusters of ATGs changed in response to the change of their associated global patterns. When the degree of the global cluster reduces, the SHA shrinks. In other words, the dispersion of ATGs across the entire city must be accompanied with more concentrated high-frequency gun violence. Although the temporal trends of SHA are different in the two periods, the SHA always includes a local cluster of high-frequency gun violence and this cluster tends to cover similar geographic locations.

The consistency of spatial patterns (both globally and locally) over the two periods suggests an intrinsic pattern of gun violence that persists through the pre-pandemic and pandemic periods regardless of temporal fluctuations in overall incident rates. The average SHA before (33.9%) and during the pandemic (30.4%) periods remained remarkably similar. This similarity further reinforces that the geographic footprint of severe gun violence maintained consistent regardless of pandemic conditions, suggesting that established socio-spatial patterns of violence persisted despite significant societal disruptions.

Although the temporal trends of both global (Moran's I) and local (SHA) patterns of AGTs are opposite during the two periods, they showed a similar strong logarithmic relationship with ATG counts (Fig. 5). These two relationships reveal that years with higher gun violence activities demonstrate stronger spatial clustering over the entire city, with incidents becoming increasingly concentrated within more neighboring CBGs (i.e., a high SHA). This correlation suggests a critical insight: when gun violence intensity increases, it primarily intensifies within already-affected areas rather than expanding geographically to new locations. This pattern of intensification rather than expansion leads to higher degrees of spatial clustering as gunshot counts rise. In years with higher overall gunshot incidents, the hot spot zone expanded in size, suggesting that increased gun violence activities tend to intensify within established neighborhoods before spreading to adjacent areas. This relationship maintained its mathematical form both before and during the pandemic, indicating that fundamental spatial dynamics of gun violence remained unchanged despite the public health crisis.

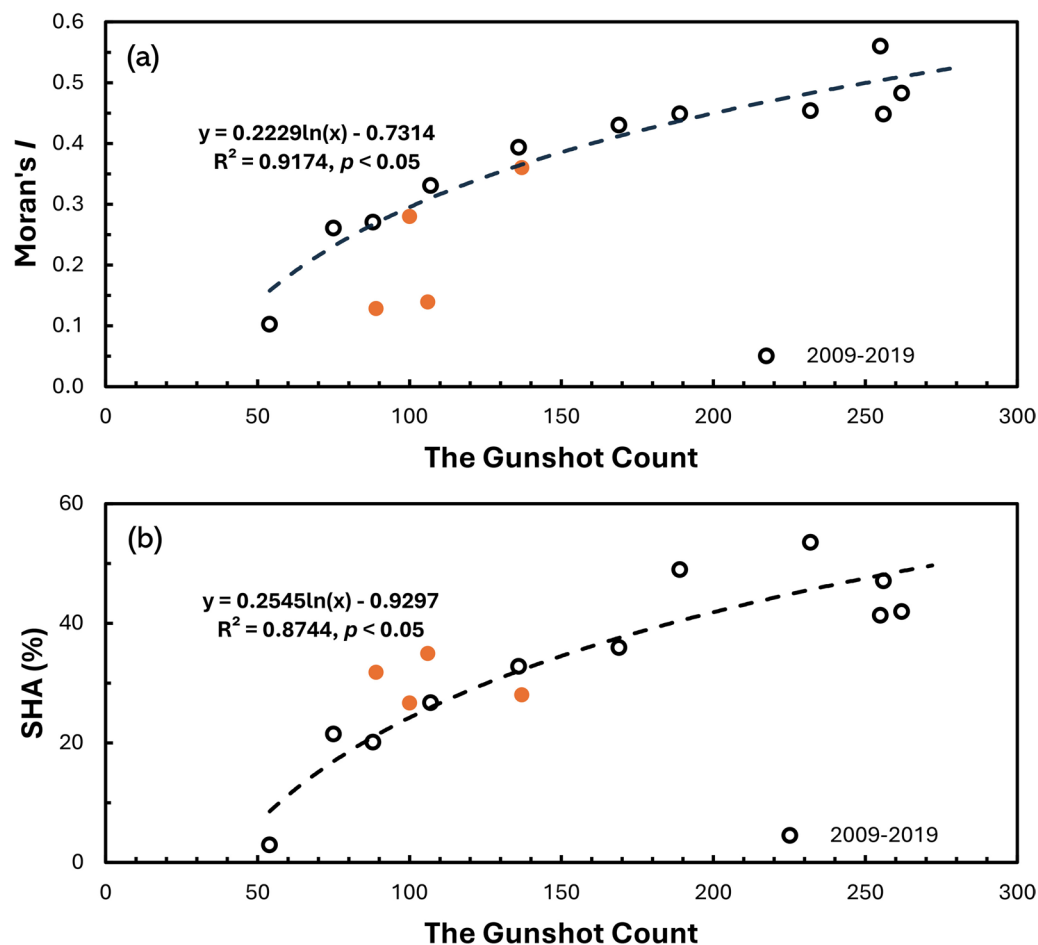


Fig. 5 The relationships between geostatistical metrics and the annual total gunshots before (2009–2019) and during pandemic (2020–2023). (a) the Moran's I ; and (b) the SHA

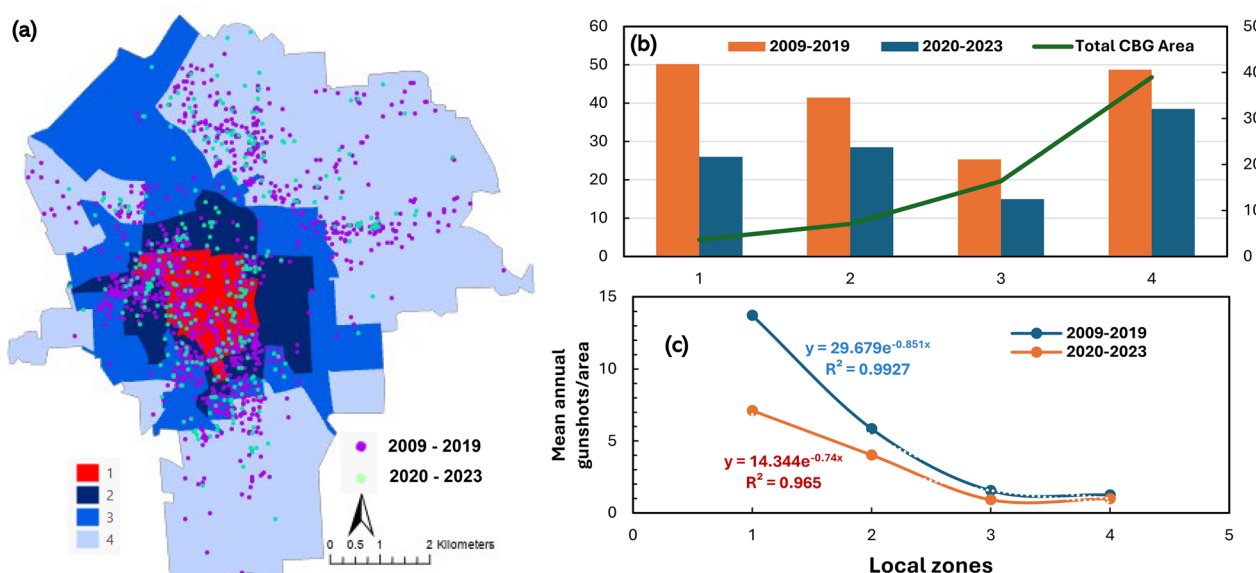


Fig. 6 Variations of geospatial patterns of gun violence in Syracuse. **(a)** Spatial distributions of individual gunshot incidents in the four zones; **(b)** The total number of gunshot incidents in each of the four zones before (2009–2019) and during (2020–2023) pandemic; and **(c)** changes of the total number of gunshots along the four zones in the two periods

Spatial distance effects of Gun violence in the two periods

It is important to note that gun violence activities were not exclusively confined to the identified hot spot areas (zone 1 in Fig. 6a). When examining surrounding areas at increasing distances, including the immediately adjacent areas (zone 2 with dark blue in Fig. 6a), the next adjacent zones (zone 3 with blue in Fig. 6a), and farther areas (zone 4 with light blue in Fig. 6a), we observed substantial gunshot incidents in both periods (Fig. 6a and 6b). However, the areas of these zones also increase with the distance away from zone 1 (the green line in Fig. 6b). The density of the ATGs in each zone expressed as the ratio of the ATG count to the zone area decreases progressively from the concentrated zone to the moderate zone in the pre-pandemic and pandemic periods (Fig. 6c), demonstrating a clear distance-decay effect. This effect suggests a strong spatial cluster of gunshot incidents in the identified hot spot areas and validates the distance-decay effect as a fundamental characteristic of gun violence distribution in Syracuse.

Perhaps most significantly, the spatial distributions and distance-decay patterns of gunshot incidents show remarkably similar trends in both the pre-pandemic and pandemic periods (Fig. 6b and c). This consistency in spatial patterns, despite dramatic societal changes during the pandemic, further reveals that COVID-19 and associated public health measures did not fundamentally alter the geographic distribution of gun violence in Syracuse.

Discussion

Structural determinants of gun violence persistence

Despite the diametrically opposed temporal trends of the annual total gunshot (ATG) counts before and during the pandemic (Fig. 3), a striking consistency exists in their geographic distributions (i.e., the central tendency and dispersion) (Fig. 4). Furthermore, the global (or city)-scale spatial patterns and local clustering characteristics maintained remarkable temporal similarity across both time periods (Fig. 3). This temporal stability of ATG's geospatial characteristics strongly suggests that while the COVID-19 pandemic altered many aspects of urban life, it did not fundamentally reshape the geospatial landscape of gun violence in Syracuse. Therefore, gun violence is a public health condition profoundly rooted in social and economic status of the city.

There are broadly two explanations and subsequent interventions. One emphasizes individual responsibility, focusing on the choices people make and their behavior based on those choices, for instance, the choices to smoke or chew tobacco, engage in unprotected sex, or eat unhealthy foods. Approaches linked to this explanation attribute gun violence to individual agency and poor decision-making, focusing on changing individual behavior [45] and [46]. Consequently, gun violence reduction interventions in Syracuse focus on behavioral change through strategies such as Cognitive Behavioral Therapy, reducing school absenteeism, providing weekly stipends to gang associates, offering case management for individuals in the criminal justice system and implementing gun buyback programs [47, 48]. These interventions aimed to create incentives for individual behavioral change, but

appear to have been insufficient in altering the spatial patterns of gun violence as demonstrated in this current study.

In contrast, the ecological or social ecological approach emphasizes the environmental, social, and policy contexts that promote or diminish public health. This approach typically employs the social determinants of health (SDH) framework at the population level to explain how social policies and structural barriers affect access to health resources [49]. While recognizing that individual choices influence health outcomes and public health broadly, the SDH approach considers the constraints on individual decision-making by examining how structures and policies limit available choices, particularly for poor and disadvantaged populations. In Syracuse, studies have examined the geospatial, historical, and policy contexts within which gun violence occurs. These contexts stem from historical processes that have destabilized communities of color and relate to SDH factors including elevated lead poisoning levels, unintended consequences of urban renewal, implementation of Rockefeller drug laws and RICO statutes, disproportionate incarceration of people of color, family disruption, and economic devastation. Community responses to the resulting stress include developing local social support networks and, unfortunately, gun violence [50], which call for the needs of understanding geospatial nature of gun violence at the aggregated spatial level (e.g., communities).

The temporal stability in spatial patterns provides compelling evidence that gun violence in Syracuse is fundamentally rooted in persistent structural factors rather than primarily responsive to temporary societal changes such as those experienced during the pandemic. While lockdowns, economic uncertainty, and other pandemic-related disruptions may have influenced the frequency of incidents, they did not significantly alter their locations, suggesting that observed gun violence stems from enduring structural and policy constraints rather than individual decision-making and behavior. The consistent spatial patterns observed throughout the study period indicate that gun violence in urban settings operates within established socio-spatial frameworks that resist short-term external disruptions. These frameworks likely reflect deeper structural issues including socioeconomic inequality, historical patterns of investment and disinvestment, and persistent neighborhood conditions that transcend temporary disruptions. This study provides geospatial evidence supporting the need to connect gun violence to social determinants of health at the meso scale.

Policy implications and methodological advantages

The findings of this study have significant implications for violence prevention strategies and policy interventions. The spatial persistence of gun violence patterns, regardless of pandemic conditions, suggests that effective interventions must address underlying structural determinants rather than focusing solely on individuals' behavior and habits as many crime theories have focused on. Place-based interventions targeting the consistently identified hot spots may prove more effective than city-wide approaches that fail to account for the concentrated nature of gun violence. Those interventions must go beyond intensive policing and address the factors that make the hotspots especially vulnerable to the social determinants of health and the social policies context. Notably, the distance decay pattern we observed contradicts the spatial spillover effect, which typically suggests that areas with frequent gunshots influence neighboring areas to also experience higher incident rates [51]. In Syracuse, however, we found gunshot incidents decay exponentially from cluster CBGs to adjacent CBGs without spreading further, indicating that gun violence remains stable both spatially and temporally rather than being diffusive.

Furthermore, the spatial dynamics observed in Syracuse also challenge conventional infectious disease or contagion frameworks often applied to violence. In typical infectious disease transmission, higher clustering is generally associated with lower transmission levels [52], as limited outbreaks remain concentrated while widespread transmission shows more dispersed patterns. Our findings suggest the opposite relationship in gun violence, with higher incident volumes showing stronger clustering. This indicates that neighborhoods may exhibit resistance to the spreading of gun violence beyond already-affected communities. Increased gunshot incidents primarily impact communities that have historically experienced violence rather than diffusing to previously unaffected areas. These findings have important implications for intervention strategies, suggesting that targeted approaches focusing on historically affected neighborhoods may be more effective than city-wide initiatives, even during periods of changing violence rates.

The question arises of whether Syracuse, NY is an outlier or is the general consensus that pandemic-related policies exacerbated gun violence in US cities based on faulty analyses? Although entrenched socioeconomic problems might be the driving force in Syracuse, which persisted both before and during the pandemic, other cities with a large degree of gun violence such as Chicago and Detroit face similar challenges. Our analyses improve upon other studies of gun violence and the pandemic in two ways. First, we utilized data spanning a much longer period than the typical 2–3 years before the pandemic.

This extended time series allowed us to capture the true gun violence dynamics before COVID-19 emerged. For instance, if we merely compare the ATG numbers between 2016–2019 (pre-pandemic) and 2020–2022 (during pandemic) as shown in Fig. 3 and Table 1, the pandemic-era ATG number (114) is indeed higher than the pre-pandemic figure, consistent with previous studies [14–16]. Second, we revealed the temporal stability of spatial patterns of gun violence using advanced geostatistical techniques, demonstrating that geospatial-based approaches can provide new insights into understanding gun violence dynamics. For example, an earlier study [23] used a non-spatial two-stage process (a zero-inflated Poisson regression model) to examine gunshots between 2009 and 2015 in Syracuse, identifying five spatial-temporal clusters (see Fig. 3 in [23]). Notably, only one of these clusters falls within the statistically significant hotspot zone identified in our current study (Fig. 6a). These methodological advancements underscore the importance of comprehensive temporal and spatial analysis in revealing the true patterns of urban gun violence, potentially transforming how researchers and policymakers understand the impact of COVID-19 policies on gun violence and subsequently approach violence prevention strategies in diverse urban contexts.

Limitations of the study

The ATG counts represent individual gunshot incidents that occur annually at specific locations throughout Syracuse. For the proposed global (spatial autocorrelation) and local (hotspot) geospatial analyses, we aggregated the gunshot data at the census block group (CBG) level. Alternatively, global patterns of ATGs could be examined through average nearest neighbor (ANN) analysis. Using aggregated data inevitably introduces the Modifiable Areal Unit Problem (MAUP) [53]. Consequently, the global geospatial patterns identified in this study (specifically, Moran's I shown in Fig. 3) may differ from those derived through ANN analysis or from gunshot data aggregated at alternative spatial scales, such as census tracts. This inherent uncertainty may compromise the robustness of the findings presented in Fig. 3. However, our ANN analysis result reveal that while the temporal trends of annual patterns over the 15-year period differ from those displayed in Fig. 3, gunshots consistently exhibit clustered patterns each year, with statistically significant clustering degrees remaining similar between pre-pandemic and pandemic periods. This finding suggests that the results presented in Fig. 3 are not substantially affected by MAUP.

Although our geostatistical analyses revealed similar geospatial patterns of gunshots at the CBG scale across both periods, we did not examine how social determinant factors reflecting Syracuse's entrenched social structures

drive these persistent spatial patterns of gun violence. Future research is needed to elucidate the causal mechanisms underlying gun violence in Syracuse.

Conclusions

This study examined the spatial distribution of gun violence in Syracuse, NY over 15 years (2009–2023), analyzing how geographic patterns related to annual gunshot totals before and during the pandemic. Despite considerable variation in yearly gunshot incidents, the geographic distribution remained stable between periods, with measures of central tendency and standard distance showing no significant changes.

Statistical analyses using Moran's I and standardized hotspot area calculations revealed that gun violence maintained consistent clustering patterns throughout the study period. Similar neighborhoods experienced concentrated violence in both pre-pandemic and pandemic years. Notably, the logarithmic relationships between total annual gunshots and both clustering measures remained remarkably stable across periods, indicating that violence increases consistently occurred in the same specific areas regardless of pandemic conditions.

The results demonstrate that pandemic-related policies did not substantially alter gun violence geography in Syracuse. Instead, the persistent spatial patterns appear driven by deeper structural factors, particularly racial segregation and associated socioeconomic conditions.

Abbreviations

ATGs	Annual Total Gunshots (plural form)
CBs	Census Blocks
CBGs	Census Block Groups
CTs	Census Tracts
GIS	Geographic Information System
GVI	Group Violence Intervention
NNR	Nearest Neighbor Ratio
SHA	Standardized Hotspot Area
SPD	Syracuse Police Department

Supplementary Information

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Additional file 1

Additional file 2

Additional file 3

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Author contributions

PG—the conception; design of the work; data acquisition, analysis, and interpretation; manuscript draft and revision SVH—data acquisition and analysis DL—the conception, data acquisition, manuscript revision RR—data

acquisition and manuscript revision SL— data acquisition and manuscript revision.

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Data availability

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

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Competing interests

The authors declare no competing interests.

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