Overdose mortality incidence and supervised consumption services in Toronto, Canada: an ecological study and spatial analysis

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Summary

Background Supervised consumption services (SCS) prevent overdose deaths onsite; however, less is known about their effect on population-level overdose mortality. We aimed to characterise overdose mortality in Toronto, ON, Canada, and to establish the spatial association between SCS locations and overdose mortality events.

Methods For this ecological study and spatial analysis, we compared crude overdose mortality rates before and after the implementation of nine SCS in Toronto in 2017. Data were obtained from the Office of the Chief Coroner of Ontario on cases of accidental death within the City of Toronto for which the cause of death involved the use of an opiate, synthetic or semi-synthetic opioid, or other psychoactive substance. We assessed overdose incident data for global spatial autocorrelation and local clustering, then used geographically weighted regression to model the association between SCS proximity and overdose mortality incidence in 2018 and 2019.

Findings We included 787 overdose mortality events in Toronto between May 1, 2017, and Dec 31, 2019. The overdose mortality rate decreased significantly in neighbourhoods that implemented SCS (8·10 deaths per 100 000 people for May 1–July 31, 2017, *vs* 2·70 deaths per 100 000 people for May 1–July 31, 2019; p=0·037), but not in other neighbourhoods. In a geographically weighted regression analysis that adjusted for the availability of substance-use-related services and overdose-related sociodemographic factors by neighbourhood, the strongest local regression coefficients of the association between SCS and overdose mortality location ranged from –0·60 to –0·64 per mile in 2018 and from –1·68 to –1·96 per mile in 2019, suggesting an inverse association.

Interpretation We found that the period during which SCS were implemented in Toronto was associated with a reduced overdose mortality in surrounding neighbourhoods. The magnitude of this inverse association increased from 2018 to 2019, equalling approximately two overdose fatalities per 100 000 people averted in the square mile surrounding SCS in 2019. Policy makers should consider implementing and sustaining SCS across neighbourhoods where overdose mortality is high.

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Introduction

Toronto—the capital of Ontario, Canada's largest city, and the fourth most populous city in North America—has been highly affected by overdose mortality. Between 2015 and 2021, annual deaths from opioid overdose in Toronto increased by more than 300%, from 137 to 574.[1] This increase has largely been attributed to the saturation of the unregulated drug supply with synthetic fentanyl and adulterants.[2–4] In response to this and other health risks (eg, HIV and hepatitis C transmission, access to health care, and public order concerns[5]) among people who use drugs in Toronto, nine supervised consumption services (SCS) were implemented in the city beginning in 2017, providing people who use drugs with a private, supervised space in which to access sterile drug use equipment and use pre-obtained drugs under the supervision of trained staff.[5] SCS have been shown to reduce harms associated with drug injecting, including overdose mortality, syringe sharing, and public injecting; some evidence also suggests that SCS increase initiation of opioid agonist treatment and engagement with primary care.[6,7]

Less is known about potential community spillover effects of SCS.[8] Some data suggest that SCS do not contribute to risk compensation nor to drug-related public disorder.[6,9–12] However, because SCS modify built environments, they have been shown to positively influence substance-related outcomes among people who use drugs beyond their immediate clients.[13] A cohort study in Vancouver, BC, Canada, found that SCS use was associated with reduced all-cause mortality among study participants.[14] This reduction in mortality could result from the fact that, beyond their immediate function of overseeing and responding to overdoses onsite, SCS provide services that can reduce the risk of overdose among clientele and other people who use drugs: they

Research in context

Evidence before this study

The influence of supervised consumption services (SCS) on client outcomes is well known. However, the evidence base regarding how SCS influence population-level public health outcomes is small, particularly with respect to overdose mortality in neighbourhoods in which they are implemented. We searched PubMed and Google Scholar to identify any studies, published in English from database inception to June 6, 2022, that explored the potential effects of SCS on population-level overdose mortality, using the search terms ("supervised consumption services" OR "supervised injection services" OR "supervised injection services" OR "supervised injection sites") AND ("overdose mortality" OR "overdose" OR "death" AND "overdose" OR "fatality" AND "overdose" OR "drug toxicity" OR "mortality rate") AND ("population" OR "neighbourhood" OR "spatial" OR "spillover") AND ("spatial analysis" OR "spatial" OR "population effects"). We placed no restrictions on the country where studies were conducted. To be included, studies had to consider associations between spatial or population-level overdose mortality and the implementation of SCS. Studies with other outcomes, such as drug-related disorder or litter potentially associated with SCS implementation, were excluded. We also searched the references cited in relevant studies. We found two studies that estimated the potential population-level effects of SCS implementation on overdose and related outcomes (eg, ambulance call-outs) in surrounding areas. However, we could not find any studies from any country that had estimated the effects of multiple SCS, nor any studies that assessed this potential association in a context in which high-potency opioid use (which is associated with a high risk of overdose mortality) was prevalent.

Added value of this study

This study, which used coroner's data from Toronto, ON, Canada, involved a spatial analysis of the association between SCS and overdose mortality during the current synthetic opioid crisis in North America across 2017–19. Overall, we found a 67% reduction in the overdose mortality rate in neighbourhoods after their implementation of SCS. In a geographically weighted regression analysis that adjusted for a range of neighbourhood-level variables, we found an inverse association between the location of SCS and that of overdose fatalities. This association was stronger in 2019 than in 2018. These findings add evidence from a new setting for the positive spillover effects of SCS during the current epidemic of overdose mortality.

Implications of all the available evidence

The evidence to date suggests that SCS are likely to be inversely associated with population-level overdose mortality in distinct settings with differing drug use patterns (eg, heroin *vs* higher-potency opioids such as fentanyl). Policy makers should consider establishing and sustaining SCS to prevent overdose mortality associated with the use of synthetic opioids and other adulterants.

distribute naloxone (an opioid antagonist that blocks the action of opioids on the brain and thereby reverses overdose events), provide referral or low-barrier access to substance use treatment, and disseminate safer injection education. However, only two evaluations of SCS using population-level data on overdose outcomes have been conducted, and both assessed the effect of a single, stand-alone SCS at one timepoint, finding that SCS were associated with reduced overdose mortality and ambulance call-outs in surrounding areas.[15,16] Furthermore, these studies were conducted before the so-called fentanyl era, which began around 2016,[8] and it is plausible that the higher risk of overdose associated with fentanyl use could attenuate the effect of SCS on community-level overdose prevention.

This study sought to characterise overdose mortality in Toronto, a large urban centre with high overdose mortality, and to establish the spatial association between SCS locations and overdose mortality events at two timepoints. Our specific objectives were to characterise overdose mortality at the neighbourhood level; compare the spatial incidence of overdose mortality before and after the implementation of multiple SCS in adjacent downtown neighbourhoods; identify global and local spatial patterns in the incidence of overdose deaths; and model the spatial relationship between overdose mortality incidence and SCS proximity over two discrete timepoints.

Methods

Study design

This ecological and spatial analysis was conducted between May 1, 2017 and Dec 31, 2019 (appendix p 1), during which nine SCS became operational in Toronto. The start date is when overdose incident data became available in a digital repository maintained by the Office of the Chief Coroner of Ontario, and the end date was selected to ensure that the effects of service changes and restrictions as a result of COVID-19 did not influence study outcomes. The first SCS was implemented in August, 2017,[17] with subsequent sites implemented throughout the study period (appendix p 1). SCS in Toronto operate either as an integrated service with medical supervision within existing health services (eg, sterile syringe and naloxone distribution, onsite or through referral to clinical and social services) or as low-threshold services that are not necessarily overseen by clinical staff, termed overdose prevention sites—we will collectively refer to all sites in Toronto as SCS.[4,17]

Our approach was guided by a recognition of the effect of the built environment on drug-related risks and

See Online for appendix

harms. Understanding that neighbourhoods can reflect discrete built environments that could differentially influence outcomes such as overdose mortality, and consistent with previous studies,[13] we selected neighbourhood, as defined by the City of Toronto,[18] as our unit of analysis. Toronto has 140 neighbourhoods, with a median land area of 3·3 km² (minimum 0·42 km²; maximum 36·9 km²) and a median population of 16 775 (IQR 4904–28 646; appendix pp 2–4).[19] We used the RECORD guidelines in designing this study.[20] Ethical approval was obtained from the St Michael's Hospital Research Ethics Board (REB 18-156).

Data sources and measures

The primary outcome was defined as the fatal overdose incident location. This information was derived via decedent files from the Office of the Chief Coroner of Ontario for death investigations in Toronto in which a psychoactive substance was implicated in the cause of death; decedent files include, at minimum, the coroner's final report, post-mortem examination, and toxicological analysis, and in many cases also include paramedic reports, police reports, and hospital admission records.[21] Inclusion criteria were that the overdose incident location (distinct from site of death, and including hospital and carceral institutions), recorded as a postal code, was within the City of Toronto; that the death was deemed accidental; and that the cause of death involved use of an opiate, synthetic or semi-synthetic opioid, or other psychoactive substance (via injection or non-injection). These criteria were based on the rationale that the incidence of overdose deaths resulting from substances not likely to be consumed in an SCS would not reasonably be expected to be affected by SCS proximity. We expressed the primary outcome as a crude incidence rate per 100 000 people, except for the local clusters of the incidence of overdose deaths, which used an aggregate count of overdose events. We also extracted the following data from the decedent files: demographics (median age and sex); whether the death was opioid-related (opioid-related *vs* non-opioid-related, and fentanyl [or analogue]-related), involved benzodiazepines, or was related to multiple drug classes; incident death location type (at decedent's home *vs* outside of home); and the decedent's history of drug use (known history of substance use; known history of opioid use disorder; known history of other substance use disorder; known history of past overdose; previous or current treatment for opioid use disorder; and previous or current treatment with suboxone, methadone, or both; all data recorded as yes or no unless otherwise specified).

The primary explanatory variable was SCS proximity, defined as the distance from a given neighbourhood's centroid to the nearest SCS (physical addresses were obtained from the City of Toronto's service directory). We also defined two neighbourhood-level explanatory variables. First, the count of registered substance-use-related health services, which comprised the following: emergency departments, rapid access addiction medicine clinics, community health centres, methadone clinics, other outpatient treatment services for substance use disorder, residential treatment services, supportive housing for people who use drugs, withdrawal management services, and 24-hour respite sites. Service locations were geocoded to derive neighbourhood-level counts of health service availability. Second, the following neighbourhood-level sociodemographic predictors of overdose were included in the geographically weighted regression models: population density, median household income, median age, labour force participation in the construction industry (count), unemployment (count), visible minority population (count; defined by Statistics Canada as people who are non-White and non-Indigenous), and education level (categorical; defined as none, high school, trades apprenticeship, college diploma, bachelor's degree, or other post-secondary above bachelor's degree). These predictors were obtained via data from the City of Toronto Open Data Portal, Statistics Canada and the 2016 Canadian Census, and Environics (using ArcGIS Pro version 2.9.0; Environmental Systems Research Institute, Redlands, CA, USA) and were aggregated at the neighbourhood level to derive explanatory variables (appendix pp 4–5).

Data analysis

To descriptively analyse overdose deaths, we aggregated overdose incident data for each of the 140 neighbourhoods in Toronto. We also described the nature of overdose deaths occurring between May 1, 2017, and Dec 31, 2019, stratified by year.

We defined the pre-SCS implementation period as May 1–July 31, 2017, as the first SCS in Toronto began operating midway through August, 2017. The post-SCS period, from May 1 to July 31, 2019, was selected to match the pre-SCS period and thereby account for seasonal factors affecting overdose incidence[22] in addition to post-implementation changes over time. To compare the effect of SCS implementation on the spatial incidence of overdose mortality, we mapped fatal overdose incidents for the pre-SCS and post-SCS periods, along with corresponding radius buffers for all nine SCS. To avoid potentially overestimating people's willingness to travel, we selected a buffer radius of 500 m as a conservative estimate of the SCS catchment area on the basis of previous research, which found that approximately half of all people who inject drugs in Toronto were willing to travel 1 km or less to access an SCS.[5] Neighbourhoods with geographical boundaries that intersected with the buffer area were defined as SCS-surrounding neighbourhoods.

The distribution of neighbourhood-level overdose mortality rates in the pre-SCS and post-SCS periods was non-normal, as confirmed by the Shapiro–Wilk test. As such, we used the Wilcoxon signed-rank test for matched pairs to establish whether pre-SCS and post-SCS mortality rate differences were significant among

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	All (n=787)	2017* (n=274)	2018 (n=302)	2019 (n=211)
Age, years	44 (33–55)	41 (32–52)	44 (32–54)	44 (34–55)
Sex				
Male	590 (75%)	214 (78%)	220 (73%)	156 (74%)
Female	197 (25%)	60 (22%)	82 (27%)	55 (26%)
Type of overdose				
Opioid-related	654 (83%)	241 (88%)	235 (78%)	178 (84%)
Non-opioid-related	133 (17%)	33 (13%)	67 (22%)	33 (16%)
Fentanyl present†	518 (66%)	186 (68%)	184 (61%)	148 (70%)
Benzodiazepines present‡	107 (14%)	62 (23%)	28 (9%)	17 (8%)
Multiple drug classes contributing to death§	528 (67%)	231 (84%)	180 (60%)	117 (55%)
Overdose occurred outside of decedent's home	515 (65%)	230 (84%)	157 (52%)	128 (61%)
Known history of substance use	503 (64%)	73 (27%)	222 (74%)	166 (79%)
Known history of opioid use disorder	406 (52%)	133 (49%)	154 (51%)	119 (56%)
Known history of other substance use disorder	295 (37%)	8 (3%)	158 (52%)	129 (61%)
Known history of past overdose	69 (9%)	26 (9%)	27 (9%)	16 (8%)
Previous or current opioid use disorder treatment	140 (18%)	7 (3%)	75 (25%)	58 (27%)
Previous or current suboxone, methadone, or both	111 (14%)	10 (4%)	56 (19%)	45 (21%)

Data are median (IQR) or n (%). *May 1–Dec 31, 2017. †Presence of fentanyl or a fentanyl analogue (eg, carfentanil, furanyl fentanyl, despropionyl fentanyl, *para*-fluorobutyryl fentanyl, or cyclopropyl fentanyl) in post-mortem toxicological analysis. ‡Presence of a benzodiazepine in post-mortem toxicological analysis, regardless of whether it was a direct contributor to death and regardless of whether it was prescribed to the decedent. §Two or more drug classes contributed to the cause of death. Drug classes were opioids; cocaine and crack cocaine; crystal methamphetamine; benzodiazepines; alcohol; and other.

Table 1: **Overdose deaths in Toronto, May 1, 2017–Dec 31, 2019**

	Pre-SCS	Post-SCS	Rate reduction (95% CI)	Equivalent percentage reduction	p value
City-wide					
Total overdose deaths	64	37	..	..	..
Opioid-related	58	31	..	..	..
Non-opioid-related	6	6	..	..	..
Overdose mortality rate*	2·34	1·35	0·99 (−0·01 to 5·46)	42%	0·051
Neighbourhoods within 500 m of SCS (n=15)					
Total overdose deaths	27	9	..	..	..
Opioid-related	24	6	..	..	..
Non-opioid-related	3	3	..	..	..
Overdose mortality rate*	8·10	2·70	5·40 (1·52 to 15·86)	67%	0·037
Neighbourhoods beyond 500 m of SCS (n=125)					
Total overdose deaths	37	28	..	..	..
Opioid-related	34	25	..	..	..
Non-opioid-related	3	3	..	..	..
Overdose mortality rate*	1·54	1·17	0·37 (−1·88 to 4·13)	24%	0·38

Data are n unless otherwise stated. SCS=supervised consumption services. *Crude rate per 100 000 people. CIs and p values were generated using the Wilcoxon signed-rank test on pre-SCS and post-SCS overdose mortality rates among neighbourhoods both within and beyond the 500 m buffer.

Table 2: **Comparison of overdose mortality rates before and after the implementation of nine SCS in Toronto**

SCS-surrounding neighbourhoods and the rest of the city. The null hypothesis was that the median of the difference in overdose mortality rates before and after SCS implementation was 0; therefore, the confidence intervals and p values for each rate reduction estimate were generated on the basis of the median of the difference between mortality rates in the pre-SCS and post-SCS conditions. We also conducted a sensitivity analysis with buffer radii of 250 m, 1000 m, 2500 m, and 5000 m to establish whether buffer size selection influenced the detection of significant changes in overdose mortality incidence.

To assess changes in the spatial density of overdose mortality over time, local clusters (ie, hot spots) of fatal overdose incidents in 2018 and 2019 were identified using the optimised hot spot analysis approach.[23] We tested global spatial autocorrelation of overdose mortality at the neighbourhood level by calculating Moran's *I* for each of 2018 (April 25–Dec 31, 2018) and 2019 (Jan 1–Dec 31, 2019); to avoid misclassification of SCS effects, the analysis of data from 2018 was restricted to the time period during which the majority of SCS had already been implemented.[24] Descriptive analyses of overdose fatalities were stratified by whether the incident neighbourhood contained an SCS, and we used the Wilcoxon signed-rank test to calculate whether differences between the two samples were significant. Because Toronto neighbourhoods vary in size considerably, we used the inverse distance method to ensure that all neighbourhoods were portrayed as neighbours, with nearby neighbourhoods assigned higher spatial weighting than those farther away.

To be considered a significant hot spot (a spatial cluster of high *z*-scores relative to the others in the dataset; $p<0·05$), several adjacent neighbourhoods must also have a higher number of fatal overdoses than all other neighbourhoods.[23] We calculated the Getis–Ord G_i^* statistic (ie, the *z*-score) for each neighbourhood using aggregated overdose mortality incidence (ie, count) data (appendix pp 8–10). Optimal fixed distance bands were selected by algorithmically assessing the intensity of clustering at increasing distances using ArcGIS Pro. We adjusted the significance level for multiple testing and spatial dependence using the false discovery rate correction method.[23]

To identify the confounder-adjusted spatial relationship between overdose mortality incidence and SCS proximity, we used geographically weighted regression[25] (appendix p 11). To assess potential changes in the spatial association between SCS and neighbourhood overdose mortality over time, separate geographically weighted regression models were estimated for 2018 (April 25–Dec 31, 2018) and 2019 (Jan 1–Dec 31, 2019) using identical explanatory variables and parameter settings. The outcome was the neighbourhood-level overdose crude mortality rate per 100 000 people, and the primary explanatory variable was SCS proximity. All

	Pre-SCS overdose mortality rate* (N)	Post-SCS overdose mortality rate* (N)	Rate reduction (95% CI)	Equivalent percentage reduction	p value
250 m					
Neighbourhoods within (n=13)	8·77 (27)	2·92 (9)	5·85 (1·52 to 15·86)	67%	0·037
Neighbourhoods beyond (n=127)	1·53 (37)	1·16 (28)	0·37 (−1·88 to 4·13)	24%	0·38
500 m					
Neighbourhoods within (n=15)	8·10 (27)	2·70 (9)	5·40 (1·52 to 15·86)	67%	0·037
Neighbourhoods beyond (n=125)	1·54 (37)	1·17 (28)	0·37 (−1·88 to 4·13)	24%	0·38
1000 m					
Neighbourhoods within (n=20)	7·11 (29)	2·21 (9)	4·91 (3·44 to 13·15)	69%	0·018
Neighbourhoods beyond (n=120)	1·64 (38)	1·20 (28)	0·43 (−2·51 to 3·88)	26%	0·53
2500 m					
Neighbourhoods within (n=35)	5·25 (35)	2·10 (14)	3·15 (3·06 to 11·32)	60%	0·0077
Neighbourhoods beyond (n=105)	1·40 (29)	1·11 (23)	0·29 (−2·90 to 3·86)	21%	0·71
5000 m					
Neighbourhoods within (n=54)	4·35 (44)	1·78 (18)	2·57 (1·81 to 10·12)	59%	0·0064
Neighbourhoods beyond (n=86)	1·16 (20)	1·10 (19)	0·06 (−3·68 to 3·22)	5%	0·80

SCS=supervised consumption services. *Crude rate per 100 000 people; number of mortality events is given in brackets. CIs and p values were generated using the Wilcoxon signed-rank test on pre-SCS and post-SCS overdose mortality rates among neighbourhoods both within and beyond the stated buffer sizes.

Table 3: **Changes in overdose mortality rates in different buffer zones surrounding SCS in Toronto, before and after SCS implementation**

possible combinations of other explanatory variables were considered on the basis of several indicators of model fit using ordinary least-squares regression and spatial autocorrelation analysis.[26] We assessed multicollinearity among candidate explanatory variables on the basis of a maximum variance inflation factor of 7·5.[26] Variables affected by multicollinearity were excluded from the model, leaving the following explanatory variables included in the final multivariable geographically weighted regression model: population density, median age, median household income, unemployment, visible minority population, and substance-use-related health services.

The adaptive kernel approach with bisquare weighting function was used to calculate the optimal kernel bandwidth (ie, the number of neighbourhoods to include in the weighting matrix for each local regression equation) based on minimising the Akaike information criterion value[27] and to generate the geographical weights for each neighbourhood as a function of distance.[25] Standardised residuals were assessed for normality and spatial autocorrelation to ensure that the model was appropriately specified. All analyses were conducted using R statistical software and ESRI ArcGIS Pro (version 2.9.0).

Role of the funding source

The funder of the study had no role in study design, data collection, data analysis, data interpretation, or writing of the report.

Results

From May 1, 2017, to Dec 31, 2019, among a total of 795 overdose mortality events in Toronto, 787 (99%; 654 opioid-related and 133 non-opioid-related) met the case definition for this study and had available geographical incident data (eight events did not include location data). All deaths met our inclusion criteria (ie, were deemed accidental and resulted from the use of an opiate, synthetic or semi-synthetic opioid, or other psychoactive substances). The majority of overdose deaths occurred among males (n=590, 75%), involved fentanyl or a fentanyl analogue (n=518, 66%), involved more than one class of drugs contributing to death (n=528, 67%), and occurred outside of the decedent's home (n=515, 65%; table 1).

Overall, a city-wide reduction in overdose mortality rate of 42% (p=0·051) was observed between the pre-SCS period (2·34 deaths per 100 000 people; May 1–July 31, 2017) and the post-SCS period (1·35 deaths per 100 000 people; May 1–July 31, 2019; table 2). When we compared overdose mortality rates between neighbourhoods that were within 500 m of an SCS (n=15) and those that were not (n=125), we found that the rate decreased by 67%—from 8·10 to 2·70 deaths per 100 000 people (p=0·037)—in SCS-surrounding neighbourhoods after SCS were implemented, while we detected no significant change in non-SCS-surrounding neighbourhoods (from 1·54 to 1·17 deaths per 100 000 people; p=0·38). In a sensitivity analysis (table 3), significant reductions in overdose mortality were detected with buffer radii of up to 5000 m surrounding SCS after their implementation.

Among 140 neighbourhoods in Toronto, 92 (66%) had at least one fatal overdose in 2018, compared with 88 (63%) in 2019. 15 neighbourhoods had geographical boundaries within 500 m of at least one SCS, and together these neighbourhoods accounted for 33% (n=71) of fatal overdoses in 2018 and 30% (n=64) in 2019

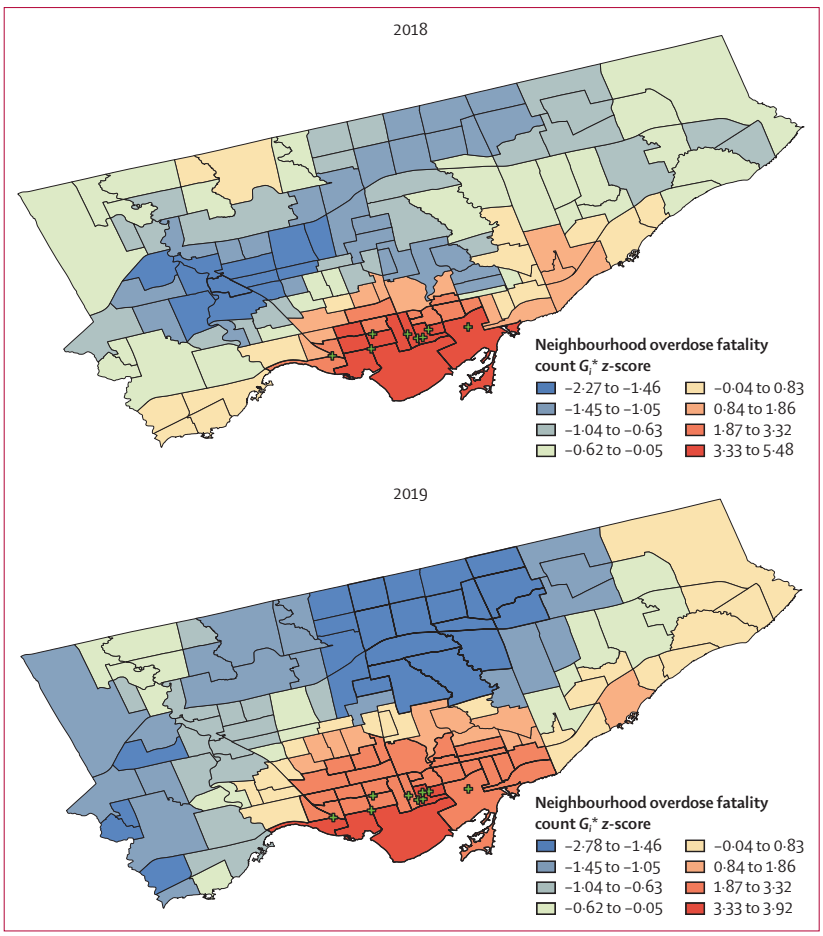

Figure 1: **Hot spot and cold spot neighbourhoods in 2018 and 2019**
Increasingly negative G_i* z-scores indicate neighbourhoods with fewer overdose deaths than all other neighbourhoods (ie, cold spots), whereas increasingly positive G_i* z-scores indicate neighbourhoods with more overdose deaths than other neighbourhoods. Neighbourhoods outlined in bold are significant hot and cold spots (surrounded by neighbourhoods with similar G_i* z-scores). The green crosses indicate supervised consumption services and overdose prevention sites.

(figure 1). Fatal overdose incidence showed significant positive spatial autocorrelation in both 2018 (Moran's I=0·22, z-score=4·91, p<0·0001) and 2019 (0·16, 3·73, p=0·0002), supporting the use of a geographically weighted regression model to assess the relationship between SCS proximity and overdose mortality incidence.

Significant hot spots of overdose mortality were observed at the neighbourhood level within Toronto's central neighbourhoods. Neighbourhood-level overdose mortality rates did not differ significantly between 2018 and 2019 within SCS-surrounding neighbourhoods (p=0·38) nor across the city overall (p=0·81). Although the number of significant hot spots increased from 19 in 2018 to 34 in 2019, the magnitude of clustering of overdose mortality decreased during this time. Specifically, whereas eight neighbourhoods had a G_i* z-score of at least 3·92 in 2018, only one met this threshold in 2019 (p<0·0001; appendix p 9). In addition, the number and magnitude of cold spots (ie, neighbourhoods with significantly lower overdose mortality rates than all other neighbourhoods) increased after the implementation of SCS in Toronto: in 2018, only one neighbourhood was identified as a significant cold spot (G_i* z-score=–2·27, p<0·023), whereas in 2019, 16 neighbourhoods were identified as cold spots, with G_i* z-scores between –2·34 and –1·94 (p<0·05; appendix pp 9–10).

Diagnostics for both the 2018 and 2019 geographically weighted regression models indicated appropriate model fit (r^2=0·43, Akaike information criterion value=1010·14 for the 2018 model; 0·37, 1035·82 for the 2019 model). The r^2 values generated for each neighbourhood regression suggest that the model accounted for between 41% and 48% of the variation in overdose mortality incidence in 2018, and between 30% and 38% in 2019. Furthermore, Moran's I for each model's residuals showed no spatial autocorrelation (2018: Moran's I=0·02, z-score=0·68, p=0·50; 2019: –0·05, –0·91, p=0·36), indicating that the spatial weighting matrix sufficiently corrected for the spatial clustering in overdose mortality observed across the city.

The association between neighbourhood-level overdose mortality and SCS proximity varied significantly across the city and between years, although we observed a consistent inverse spatial association between the location of SCS and overdose mortality incidents, with the greatest reductions in overdose deaths occurring in downtown neighbourhoods proximal to SCS. This inverse spatial association also increased in magnitude over time, with the strongest local regression coefficients ranging from –0·60 to –0·64 per mile in 2018 and –1·68 to –1·96 per mile in 2019 (figure 2).

Discussion

We found that overdose deaths were spatially correlated in Toronto, that neighbourhoods surrounding SCS had the greatest reduction in overdose mortality after implementation, and that the magnitude of the inverse spatial association between SCS and overdose mortality increased from 2018 to 2019. Neighbourhoods containing or near to SCS had the greatest reduction in overdose death rates. In 2019, this reduction was approximately equivalent to the prevention of two overdose deaths per 100 000 residents in each square mile immediately surrounding SCS sites, with fewer deaths prevented in less proximal areas. These findings suggest that, compared with a period in which SCS had been implemented within the past year, SCS proximity had a stronger inverse association with overdose mortality after SCS had been implemented for at least 1 year.

To our knowledge, this study is the first spatial analysis of the effects of SCS on overdose mortality during a fentanyl-driven overdose epidemic in North America. SCS modify built environments that contribute to overdose mortality risk by providing settings within which overdoses can be responded to by trained staff and by

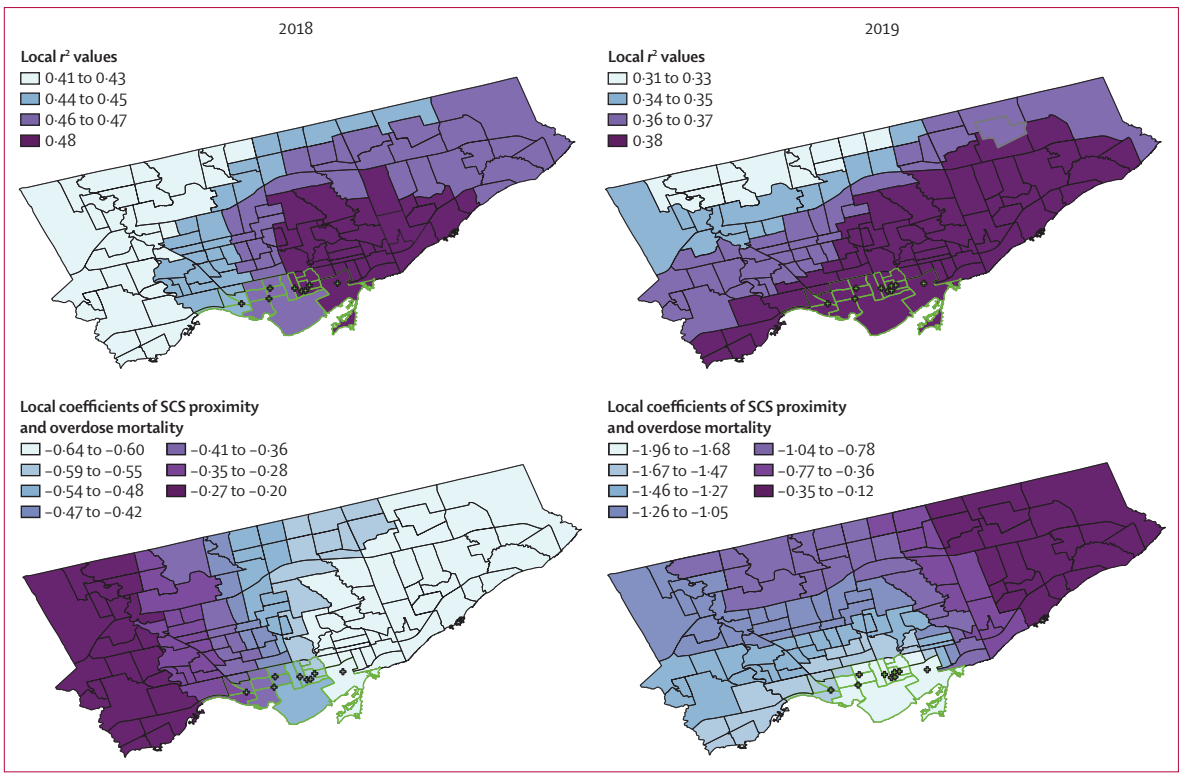

Figure 2: **Geographically weighted regression analysis of neighbourhood-level overdose mortality incidence on distance to nearest SCS in 2018 and 2019**
Local r^2 values represent the proportion of variation in overdose mortality accounted for by the geographically weighted regression model. Local coefficients of SCS proximity (in miles) and overdose mortality (per 100 000 people) represent the reduction (negative coefficient) in deaths for every 1 mile increase from the neighbourhood centroid, within that neighborhood. Green crosses indicate SCS or overdose prevention sites, and green outlined neighbourhoods are those within 500 m of either SCS or an overdose prevention site. SCS=supervised consumption services.

providing overdose prevention tools (eg, naloxone, treatment referrals, and education on safer injecting) to surrounding communities.[28,29] Additionally, as a structural harm reduction intervention, SCS could increase the range of choices that people who use drugs have to avoid overdose mortality (eg, by enabling the use of drugs in a private, safe environment free of policing and providing access to resources) and attenuate the stigma that is enacted in public and contested spaces regarding drug use. These reasons could explain why, after the implementation of SCS in Toronto, a significant reduction in the overdose mortality rate was observed within 250 m of sites. Nevertheless, that this rate reduction remained significant (although slightly weaker) even at a distance of 5000 m is surprising. We posit that rate reduction at larger distances is potentially a result of naloxone dissemination across neighbourhoods, or an indirect effect of SCS acting as sites of low-barrier referrals to opioid agonist treatment, which is protective against overdose mortality.[13,30] However, such reduction could also be explained by overlapping buffers, given the clustering of SCS in Toronto's downtown core. Furthermore, given that SCS were implemented in neighbourhoods with a high prevalence of unregulated drug use and overdose and a demonstrated need for harm reduction services,[5] our findings suggest that the neighbourhoods with the greatest burden of overdose mortality had the greatest decrease in overdose death rate during the SCS implementation period.

In Toronto, SCS are part of a larger, comprehensive approach to overdose prevention, and are expected to facilitate access to substance use treatment and other harm reduction strategies.[31] As such, the neighbourhood-level effects observed in our study are probably attributable not only to acute onsite overdose reversals but also to increased community access to naloxone, drug checking (eg, fentanyl test strips), sterile drug use equipment, and substance use treatment referrals, and to the dissemination of safer drug use practices by harm-reduction service providers. Future efforts to assess the effect of SCS could therefore benefit from considering their potential neighbourhood-level effects.

We found that the proportion of variation in overdose mortality accounted for by the geographically weighted regression models, represented by the r^2 value, decreased from 2018 to 2019. Simultaneously, we observed an increase in the number of overdose hot spots—and a reduction of their overall magnitude—across the city. We hypothesise that this finding is likely to be related to the increasing saturation of drug markets across the city with fentanyl, which largely replaced heroin during this

time.[32] Notably, though, despite this period of transition to higher-potency opioid use, the inverse spatial association between SCS and overdose mortality increased. In any event, to address drug market dynamics and other potential sources of unmeasured variation, multi-level analyses should be undertaken to combine neighbourhood-level and individual-level factors to better delineate the spatial risk environment for overdose fatalities in Toronto. In addition, incorporating SCS-specific operational data (eg, wait times, operating hours, client capacity, presence of integrated services or referrals, and inhalation booths) could help to identify SCS models that are most effective in contributing to community-level reductions in overdose mortality.

This study has several important limitations. First, as an ecological study, our modelling did not include factors at the individual level that influence overdose risk, although geographically weighted regression models accounted for substantial proportions of the neighbourhood-level variation observed in overdose mortality during our study period. Second, the study period was restricted in multiple ways: for example, the earliest data we could obtain were from 3 months before the implementation of the first SCS in Toronto, and therefore we could not account for pre-intervention trends. Additionally, we restricted our study period for the hot spot analysis and geographically weighted regression analysis to a time during which the majority of SCS had already been implemented; this was done to avoid misclassification of SCS effects, as we posited that they might not be immediate. As a result, the analyses in this study, with the exception of the pre-SCS and post-SCS comparison, used a study period of April 25, 2018–Dec 31, 2019, which excludes 309 overdose mortality events from May 1, 2017 to April 24, 2018—a time period during which two additional SCS were implemented. The window during which analysed data were obtained was therefore relatively short. Additionally, as result of the attenuated time period representing 2018 (April 25, 2018–Dec 31, 2019), our hot spot analysis and geographically weighted regression analysis provide considerably conservative value estimates given the number of cases that were excluded from Jan 1 to April 24, 2018. Third, owing to privacy concerns, we obtained postal codes for the locations of overdose events (which were in some cases distinct from the locations of deaths) rather than complete addresses, which reduces the geospatial specificity to some extent. However, in densely populated areas, postal codes are still highly specific and provide sufficient geographical distinction, approximately equivalent to one side of a city block.[15] Fourth, to derive the count variable for substance-use-related health services, we assumed that all services listed in the public directories remained constant throughout the study period, although this was probably not the case. Fifth, because of privacy concerns, we were unable to disaggregate data by ethnicity; this limits our capacity to understand whether changes in the spatial patterns of overdose mortality were distributed differentially across ethnoracial populations. Finally, our analyses did not distinguish between supervised consumption sites and overdose prevention sites, which limits the granularity of our findings. Further, we did not distinguish between overdoses by route of drug administration (eg, injection *vs* non-injection), and no SCS offered supervised smoking during the study period despite a trend towards greater preference for inhalation drug use in Ontario over the past 4 years.[33] Nevertheless, given that SCS serve as community-integrated harm-reduction hubs, individuals engaging in non-injection drug use would have been able to access services other than supervised injecting that could have reduced their risk of overdose mortality (eg, drug checking, naloxone, and education on safer drug use).

In conclusion, we found that areas where SCS were implemented in Toronto subsequently had significant reductions in overdose mortality incidence, although other areas in the city did not. Furthermore, we found an inverse spatial association between SCS and overdose mortality incident locations, and this association increased in magnitude over time. This finding suggests that the implementation of SCS could contribute to reductions in overdose mortality in proximal areas. Criticisms of SCS have focused on the lack of evidence of their capacity to meaningfully affect population-level overdose mortality.[8] Our finding of potential positive community spillover effects of SCS suggests that, beyond their immediate capacity to reverse onsite overdoses among onsite clients, they might also contribute to population-level overdose prevention efforts. As such, the inclusion of population-level metrics to evaluate the effectiveness of SCS is not only warranted but can also inform policy planning regarding SCS service design, implementation, and operation.

Contributors

IR and DW conceptualised the study. IR, DW, and TG accessed and verified the underlying data. IR conducted all analyses with guidance and supervision from TG and DW. IR drafted the manuscript with guidance and input from DW. AS and AB provided substantial revisions and guidance on the analytical approaches, interpretation, and drafting of the manuscript. All authors had full access to all the data in the study, have seen and approved of the final text, and had final responsibility for the decision to submit for publication.

Declaration of interests

DW is named on a provisional patent for a mobile drug checking instrument. All other authors declare no competing interests.

Data sharing

Individual data from this study are restricted by a data sharing agreement with the Office of the Chief Coroner of Ontario. The study protocol and statistical analysis plan will be shared on request following publication to investigators whose proposed use of the data has been approved by an independent review committee identified for this purpose, to achieve aims in the approved proposal. Individuals can request to become an approved investigator, or to learn more about conditions of data access, by contacting the Centre on Drug Policy Evaluation at info@cdpe.org.

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