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Review

The Impact of Green Space on Violent Crime in Urban Environments: An Evidence Synthesis

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Abstract: Can the presence of green space in urban environments reduce the frequency of violent crime? To ascertain the evidence on this topic, we conducted an in-depth literature review using the PRISMA checklist. The search parameters included US articles written in English and published since 2000. More than 30,000 potential paper titles were identified and ultimately, 45 papers were selected for inclusion. Green spaces typically comprised tree cover, parks and ground cover. Criminal behaviors typically included murder, assault, and theft. The majority of the research reviewed involved quantitative methods (e.g., comparison of green space area to crime data). We extracted multiple mechanisms from the literature that may account for the impact of green space on crime including social interaction and recreation, community perception, biophilic stress reduction, climate modulation, and spaces expressing territorial definition. Recommendations are made for future research, such as meta-analysis of existing data and the development of grounded theory through qualitative data-gathering methods. By providing evidence that access to nature has a mitigating impact on violence in urban settings, city governments and communities are empowered to support these interventions.

Keywords: violent crime; urban parks; greenspace; green space; scoping review; systematic review; literature review

1. Introduction

In this literature review, we investigate whether the presence of nature in urban environments reduce the frequency of violent crime. Research suggests that, in many circumstances, green space in the form of trees, parks, and other natural areas, may have a mitigating impact. By providing evidence that the presence of nature contributes to the reduction of violence in urban settings, city governments and communities will be empowered to support these interventions.

The positive impact of nature and green space on human health and well-being has been documented by over 100 studies [1–3], including several literature reviews and meta-analyses which have examined the benefits of the nature connection [2,4–10]. Several researchers have begun to explore the relationship between nature and urban crime, focusing on outcomes such as reduced aggression and improved community cohesion [11–14]. Multiple new papers and dissertations have been published in the last three years [15,16], and an expansive update is essential to setting future research agenda.

The following paper synthesizes the evidence of the impact of green space on violence by utilizing methods from systematic and scoping reviews. We are both addressing a specific question and describing the broader literature. A systematic review incorporates "appropriate" study designs that are pre-identified and include a paper quality assessment, which the research in this paper also undertakes [17]. A scoping review shares similar methods and aims, although the scoping review is concerned with presenting the characteristics of existing literature on a topic, whereas a systematic review aims to summarize the "best available research" on a topic [18].

Although violent crime in the United States has fallen since 1997 [19], Grinshteyn and Hemenway found that in 2010, the US gun homicide rate was 25 times higher than the rate in other high-income countries despite a similar rate of nonlethal crimes [20]. The study also reported that Americans are ten times more likely to die by firearms compared with residents of other countries. While many of these crimes are homicides, approximately 60% are suicides [21]. Additionally, there has been an increase in mass shootings. In 1994–2004, the average annual rate of mass shootings was 1.12 shooting per 100 million, while in 2005–2013, the average annual rate was 1.41 shooting per 100 million [22].

1.1. Definitions

According to Pati and Lorusso [23], one of the major challenges in conducting a systematic literature review is identifying the search terms. In this paper, the two primary categories were "green space" and "violent crime."

Greenspace. Green space is defined as "synonymous with nature" and "explicitly urban vegetation" [24]. In reviewing a range of journals, the authors identified many related terms including garden, ecological garden, urban forest, urban parks, urban habitat, greenery, greenbelt, green area, green environments, green network, green infrastructure, natural environment, parkland, walkable area, blue space, green patches, riparian greenspace, sky garden trees, urban farm, urban ecosystem, water bodies, woodland, and vegetated areas. This study uncovered six definitions of green space in the literature:

- Vegetation, ranging from sparsely landscaped streets to tree-lined walkways to playfields and forest parks [25].
- Combined areas of open land, cropland, urban open land, pasture, forest, and woody perennial [26].
- Land use that has notable contributions to urban environments in terms of ecology, aesthetics, or public health, but which basically serves human needs and uses [27].
- Areas with substantial green elements [28].
- Recreational or undeveloped land [29].
- Predominantly covered with vegetation [30].

Informed by this analysis, we defined green space using the broad description provided by the US Environmental Protection Agency (EPA). According to the EPA, green space is "land that is partly or completely covered with grass, trees, shrubs, or other vegetation … Green space includes parks, community gardens, and cemeteries" [31].

Violent crime. The U.S. Department of Justice Federal Bureau of Investigation, in their Uniform Crime Reporting (UCR) program, defines violent crime as "composed of four offenses: murder and nonnegligent manslaughter, forcible rape, robbery, and aggravated assault. Violent crimes are defined in the UCR Program as "those offenses which involve force or threat of force" [32].

1.2. Goals

We have three goals associated with this research. First, to assess through a literature review where we stand with regard to studies that address the question: Can the presence of nature in urban environments reduce violent crime? Second, to generate an agenda for future research based on the gaps that are identified as part of this assessment. Lastly, to explore the mechanisms that might account for the interaction between urban nature and violent crime.

2. Materials and Methods

Using the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) checklist [33], the authors drafted a plan for the literature review. Those articles written in English, published since 2000, and covering research in urban areas (not rural or suburban) within the United States were eligible for inclusion. The independent variable had to include at least one type of green space. At least one of the dependent variables had to be violent crime. No age, sex, socio-economic, health, or gender limitations were placed on study participants. The focus of the search was on original, primary peer-reviewed literature, although doctoral dissertations and master's theses, white papers, conference proceedings, and articles from organization websites were also eligible. Literature reviews were excluded because they were not primary research. No meta-analysis was undertaken because a range of research types (experimental, quasi-experimental, interventional, non-interventional, qualitative, quantitative, case study, cross-sectional, and longitudinal studies) was eligible for inclusion. Conflicting opinions about the relevance of a particular paper were resolved by a third, independent reviewer. The independent reviewer was blind to who had made the evaluation and the motivations for making the decisions, thus enhancing the validity of the evaluations.

2.1. Search Strategy and Database Selection

Databases were selected based on relevance and journal coverage. Subject area specific databases were identified, and a broad interdisciplinary database (Scopus) was also searched. Initial searches took place in December 2017 with updates to the searches run in July 2019. Using the EBSCOhost research platform, a joint search was performed on PsycINFO, Academic Search Premier, and Greenfile. Sociological Abstracts and ProQuest Dissertations and Theses–Global were searched jointly using ProQuest. The results of the searches were de-duplicated using Zotero reference software and then uploaded to Covidence (a systematic review platform), where another round of de-duplication took place. One deviation from the protocol was that title screening for inclusion or exclusion took place ahead of traditional abstract screening because of the large volume of results. Following initial blinded title screening in Covidence, the authors switched to Rayyan, another systematic review platform, for all subsequent screening. Full-text articles emerging from the screening process were evaluated by the authors and eliminated at that stage if they did not meet inclusion criteria.

Search terms were drafted using keywords and terms from papers known to be relevant to the review. Following testing in the chosen databases, the following terms were used in all searches, though the syntax of the search was adapted per database requirements as necessary:

(urban OR cities OR city OR neighborhood OR communit * OR "public housing *")

AND

("green space *" OR green * OR greenspace OR park * OR natur * OR "landscape architecture *" OR "city plan *" OR tree * OR "environment * design" OR ecosystem * OR environment * OR "urban design" OR horticulture OR playground OR garden OR trail OR "urban forestry")

AND

(crime * OR criminology OR violence OR rape * OR assault OR murder OR aggression OR firearm * OR gun * OR "public safe *")

2.2. Evaluation Process

Two researchers independently screened the titles and abstracts. A third researcher resolved conflicting decisions. Once the final list of papers was established, they were reviewed by the same two researchers to confirm that they were appropriate for inclusion. As previously, when the two paper reviewers disagreed on their evaluation, a third reviewer broke the tie. Once the final list of papers was determined, the three researchers entered summary information into a common spreadsheet, which was later distilled into a literature matrix (see Appendix A).

3. Results

3.1. PRISMA Summary

In January 2018 and July 2019, 31,414 records were identified via the database search (n = 21,704 in 2018 and n = 9710 in 2019). Excluding duplicates, 14,520 titles were ultimately screened. After the subsequent title screening, 3798 abstracts remained as potentially relevant publications. After the abstract review, 327 articles were selected for evaluation. Ultimately, 45 papers were selected for inclusion in this study, representing a little over 1% of the original abstracts (see Figure 1).

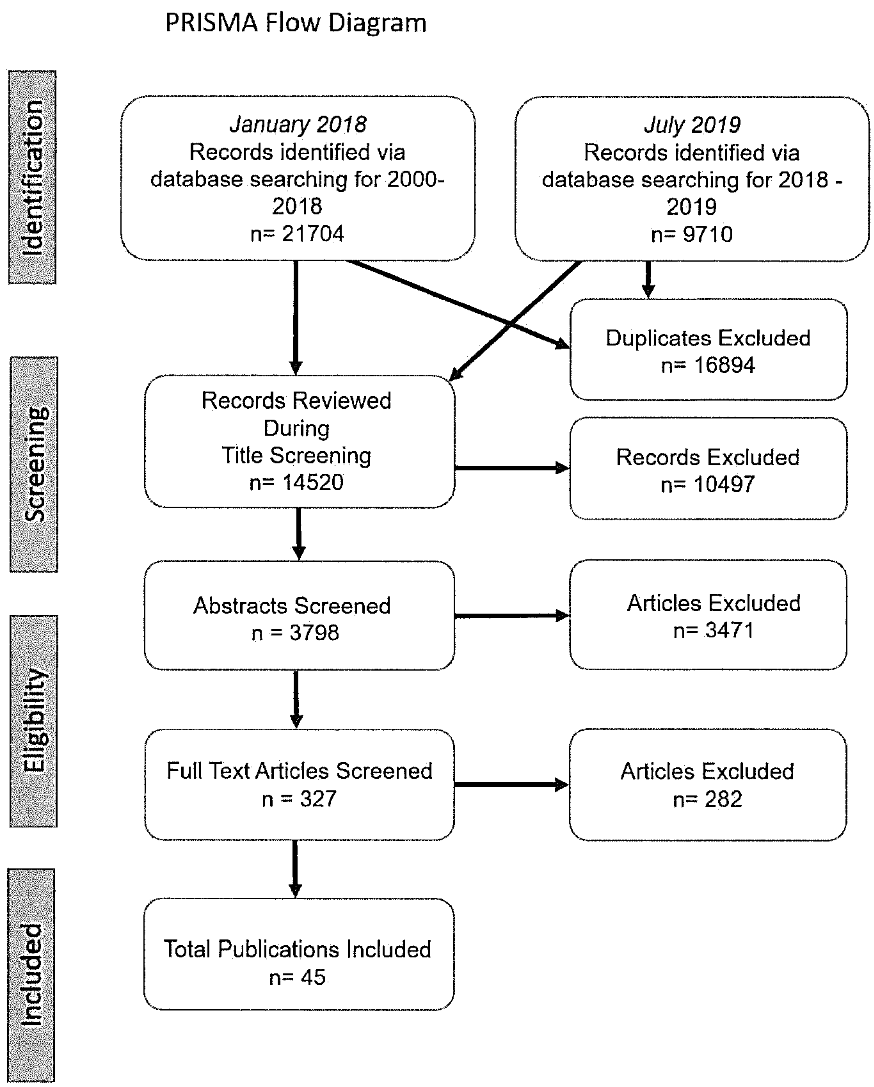

Figure 1. Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow chart.

3.2. Patterns in Study Topics and Methods

Green space independent variables fell into five main categories: (1) parks, (2) community gardens and vacant lot remediation, (3) vegetated/tree-lined streets and walkways (including elevated trails), (4) tree canopies and groundcover, and (5) undeveloped or partially developed areas such as ground sewer enhancements, croplands, wetlands, undeveloped nature environments and landscape diversity endeavors (see Table 1).

Criminal behaviors typically addressed by researchers included homicide, assault (including rape), and theft (burglary). Most studies involved both violent personal crime and non-violent property crime (e.g., theft and vandalism). Several studies included disorderly crime, like narcotics use or distribution.

The majority of the 45 selected articles used quantitative methods. Quantitative studies tended to use ArcGIS or other spatial-image analysis tools to assess the presence of parks, vacant lots, or tree canopy. Most studies sought to correlate GIS/image data with jurisdictional crime data. Studies involving tree cover were correlational because almost all employed GIS or image-related data instead of interventions. A few studies predicted causality by employing before and after greening interventions (e.g., greening blighted lots, installing an elevated trail).

Much of the literature we reviewed and decided to omit was anecdotal, although we were interested in high-quality qualitative studies. Only a handful of studies used qualitative methods. Branas et al., Blair, and Garvin et al. employed a mixed-methods approach by combining quantitative crime analyses with interviews or surveys to assess perceptions of crime and neighborhood disorder [34–36]. While most studies included in the scope of this review used jurisdictional crime data, a few research teams used survey measures to assess the risk of aggressive behavior or perceptions of crime and safety.

When considering the methodological challenges shared between these studies, homicide and forcible rape were excluded from the analysis of violent crime in some studies (e.g., Wolfe and Mennis [37]), as these incidents are relatively few. In the case of rape, the data is questionable for other reasons; researchers noted that measuring the frequency of rape is misleading due to the low levels of formal reporting [38].

3.3. *Study Findings*

For studies involving a large range of violent crimes, the most consistent results aligning nature interventions and crime reduction were among studies involving vegetated streets and walkways. As might be expected, the majority of all studies were correlational, and the quasi-experimental studies involving greening interventions were typically limited to community gardens and site greening interventions, likely due to the scale of these projects. Several notable exceptions include the street/walkway improvements research described by Locke et al. [39] and the lot improvements performed by Branas et al. in Philadelphia [11,34,40].

As indicated in Table 1, of the 26 studies addressing all violent crimes, 12 identified a negative relationship between nature and crime (such that crime decreased as nature increased), while four ran contrary to our expectation. Ten studies were deemed inconclusive by their respective authors, as the results did not reach statistical significance or involved a number of confounds. With regard to violent crime (not involving homicide or rape), four of the six relevant studies demonstrated nature's contribution to crime reduction. The single study specifically focused on homicide [41] found reductions in homicide in parks, although the results regarding the impact of remediated sites were inconclusive.

Studies that focused specifically on gun violence support the hypothesis that green space reduces this violence [11,34,36,40,42–46]. Of the nine studies (two reported in a single publication by Branas et al. [11]), six had the expected outcomes. Three of the 45 studies were from the same team of researchers (Branas, Kondo, South) who investigated the potential link between green space and crime through the cleaning and greening of vacant lots, primarily in Philadelphia, PA.

3.3.1. Parks

Ten studies addressed the relationship between parks and crime, though all of these studies were correlational and did not study a specific intervention. Three studies found that the presence of parks was associated with reductions in crime, two were inconclusive, and three demonstrated trends in the opposite direction (Abu-Lughod [47], Kim and Hipp [48], and McCord and Houser [49]). Abu-Lughod found that violent crime increased as the number of city-owned parks increased while Kim and Hipp and McCord and Houser suggest that areas near parks experienced higher levels of crime and disorder. These findings may be explained by Jane Jacobs' "eyes on the street" theory [50] and C. Ray Jeffrey's Crime Prevention through Environmental Design (CPTED) principles [51], such that an open public place where strangers may be less easily identified by members of the community may create opportunities for crime. McCord and Houser support this explanation, specifically addressing the guardianship theory in their study.

Overall, regarding parks, there are insufficient studies to reflect on the impact on violent crime (not homicide or rape), homicide only, and gun violence. None of the studies in these categories involved interventions, possibly due to the construction cost of a large park intervention and the delays in the development of landscape growth once a park was in place.

3.3.2. Community Gardens/Greening

A larger number of studies (n = 12) addressed community gardens and greening of lots. All of these studies suggested that greening interventions or the presence of community gardens were related to a reduction in crime. Included in this group is a series of pre-post studies by Branas et al. in which researchers "cleaned and greened" a series of lots over several years in Philadelphia, PA, resulting in decreased incidence of gun violence [11,34,40]. Heinze et al. [52], Kondo et al. [53], and Sadler et al. [54] also reported similar results from vacant lot greening interventions. The overall positive effects of blighted lot remediation (compared to the mixed results from parks) may also be attributed to CPTED and defensible space theories, such that the removal of abandoned buildings and overgrown brush reduces the amount of shelter and improves visual guardianship of an area.

Interventions (n = 7) were most common in this category, likely due to the lower fiscal and physical challenges associated with creating community gardens and greening—they are easier to add to the urban fabric. Branas et al. suggest that their interventions in Philadelphia were inexpensive, scalable, and readily executed in low-income residential areas [11].

3.3.3. Vegetated Streets and Walkways

Although we found a limited number of studies on the impact of vegetated streets and walkways (n = 6), all of them support the hypothesis that this type of green space influences crime. Four of the six studies involving vegetated streets found decreases in crime, while crime remained unchanged in the Auchincloss [55] and Locke [39] et al. studies. Auchincloss et al. suggest greenways require associated comprehensive social interventions in order to be effective. Locke et al. raised concerns surrounding the spillover effects, such as a reduction in crime around greened streets may simply spread to perimeter areas. Indeed, Branas et al. echoed this concern in their blighted lot greening studies [11]. Null findings may also be the result of poor operationalization of green space or selection bias in the greening process such that community partners may have not been random in their choice of streets on which to plant trees [39].

Included in the group are four quasi-experimental studies (Auchincloss et al. [55], Harris et al. [56], Harris [57], and Crewe [58]). Quasi-experimental studies were particularly common in this category, as most were pre–post studies examining the influence of a newly established greenway on crime in surrounding areas, including Philadelphia's 58th St Greenway (Auchincloss et al.), Chicago's Bloomingdale Trail (Harris et al.), and Boston's Southwest Corridor (Crewe).

3.3.4. Trees and Ground Cover

The largest number of studies fell into the category of trees and ground cover (n = 14), perhaps due to ease of analysis from readily available GIS data. Aerial GIS information can provide detailed information on large-scale urban vegetation and may allow for examination over time due to the natural growth of vegetation. As such, most studies were correlational—none of the studies involved large-scale greening interventions, but they often involved substantially larger datasets than studies in the previous categories. Many papers reported results from geographic and crime data involving entire cities, including Austin, Baltimore, Chicago, Milwaukee, New Haven, Philadelphia, and Portland. Donahue used GIS tools to investigate tree cover in over 200 cities (and 59 individual communities within one city) [59].

The majority of the papers described in this category reflect decreases in crime ($n = 9$), with four others reporting inconclusive results. Of the inconclusive, two revealed nuances in the relationship between urban green space and crime. In their investigation of population density and crime, Lim found a significant moderating effect of vegetation on crime rates, such as high vegetation buffering the influence of high density on violent crime, providing support for cognitive restoration theories [60]. Li also observed a moderated relationship, such as view-blocking vegetation being associated with more violent crime but less property crime [61]. Just as Auchincloss et al. suggested, greenway interventions must be accompanied by appropriate policy changes [55]. Donahue also provides evidence for the importance of implementation plans accompanying urban tree cover interventions [59].

3.3.5. Undeveloped Green Areas (and Other)

Studies by Kondo et al. [45] and Sparks [62] did not demonstrate significant or conclusive relationships. They were placed under this heading due to the uniqueness of the independent variables that they measured. The Kondo study focused on green stormwater infrastructure and the Sparks study focused on land use diversity such as wetlands, forested land, agricultural land, and barren land. The inclusion of these studies highlight the methodological challenges and nuances associated with green space studies, as the operationalization of greenspace can take many different forms.

Table 1. Literature Review Matrix by Predictors and Outcomes.

	All Violent Crime		Violent Crime (Not Homicide or Rape)	Homicide Only	Gun Violence
Parks	Abu-Lughod ('06) ° ↑ Blair et al. ('17) ° ~ Brown ('18) ° ↓	Lee ('13) ° ~ McCord et al. ('17) † ↑ Nitkowski ('17) ° ↓	Boessen et al. ('18) ° ~ Kim et al. ('18) ° ↑	Culyba et al. ('16) ° ↓	DeMotto et al. ('06) ° ~
Community gardens/greening	Blair ('14) † ♦ ~ Blair et al. ('17) ° ~ Gorham et al. ('09) ° ♦ ~ Heinze et al. ('18) Δ ↓	Kondo et al. ('16) Δ ↓ Sadler et al. ('17) Δ ↓ Wilcox et al. ('13)		Culyba et al. ('16) ° ~	Branas et al. ('11) Δ ↓ Branas et al. ('16) Δ ↓ Branas et al. ('18) Δ ♦ ↓ Garvin et al. ('13) Δ ♦ ~
Vegetated streets and walkways	Auchincloss ('19) † ~ Burley ('18) ° ↓ ~ Harris et al. ('18) † ↓	Harris ('18) † ♦ ↓ Locke et al. ('17) Δ ~	Crewe ('01) † ♦ ↓		
Trees and ground cover	Donahue et al. ('11) ° ~ Gilstad-Hayden ('15) ° ↓ Kondo et al. ('17-A) † ↓ Kuo et al. ('01) † ↓	Li ('08) ° ~ Lim ('05) ° ~ Schusler et al. ('18) ° ~ Snelgrove et al. ('04) ° ↓	Deng ('15) ° ~ Donovan et al. ('12) ° ↓ Wolfe et al. ('12) ° ↓		Troy et al. ('12) ° ↓ Troy et al. ('16) ° ↓ Kondo et al. ('17-B) † ↓
Undeveloped green areas	Sparks ('11) ° ~				Kondo et al. ('15) Δ ~

Study Design: ° Correlational, † Quasi-experimental (pre-post or control group); Δ Greening intervention; ♦ Included a qualitative component; Findings: ↓ Negative relationship between green space and crime; ↑ Positive relationship between green space and crime; ~ Inconclusive or no significant relationship found; Strictly qualitative studies excluded from this matrix but included in Appendix A.

4. Discussion

4.1. State of the Research

Research on the impact of green space crime is limited. Among the prominent findings of this hybrid review was that potentially confounding variables are rarely addressed in detail. This challenge may be related to the lack of a mutually agreed upon grounded theory linking independent, covariate, and depending variables. Relatedly, a prominent conclusion when reviewing the study findings is that, with the exception of a few studies (e.g., Branas et al. [34]), there is insufficient work involving the qualitative analysis that might support the development of a unifying grounded theory.

Future studies will have to emphasize the role of confounding variables or package their independent variables using the concept of bundles, an approach borrowed from medicine, in which a variety of variables are clustered to achieve greater efficiency [63]. In this approach, multiple environmental attributes are thought to produce an outcome, although the impact of a single contributor might not be clear.

In this context, we recommend a variety of future studies, including future research directions recommended within the papers included in this literature review:

- Meta-analyses that aggregate data from multiple research projects, empirical and quasi-empirical.
- Studies that focus on the mechanisms that may be impacting behavioral responses [37,53,56,64–66].
- Intervention studies at multiple scales (from small green oases to extensive parks and greenways), particularly those that involve longitudinal pre/post field experiments [11,48,49,55,67,68].
- More studies that exploit the benefits of the development of grounded theory and the gathering of qualitative data, particularly survey and interviews [69].
- More studies that focus specifically on the most violent of crimes—gun violence [11].

4.2. Mediators Contributing to the Relationship Between Greenspace and Violent Crime

As mentioned in the previous section, one of our recommendations involves a more thorough understanding of the mediating variables in the interest of determining causality. We assume that the positive impact of green spaces on crime reduction is attributable to the co-presence of multiple factors that can be divided into physical features (places for community interaction and places for exercise) and qualities (biophilic support, territorial definition, community enfranchisement, and climate moderation; see Figure 2). There are undoubtedly additional factors, but these clusters were most prevalent in the literature and are discussed in the following section.

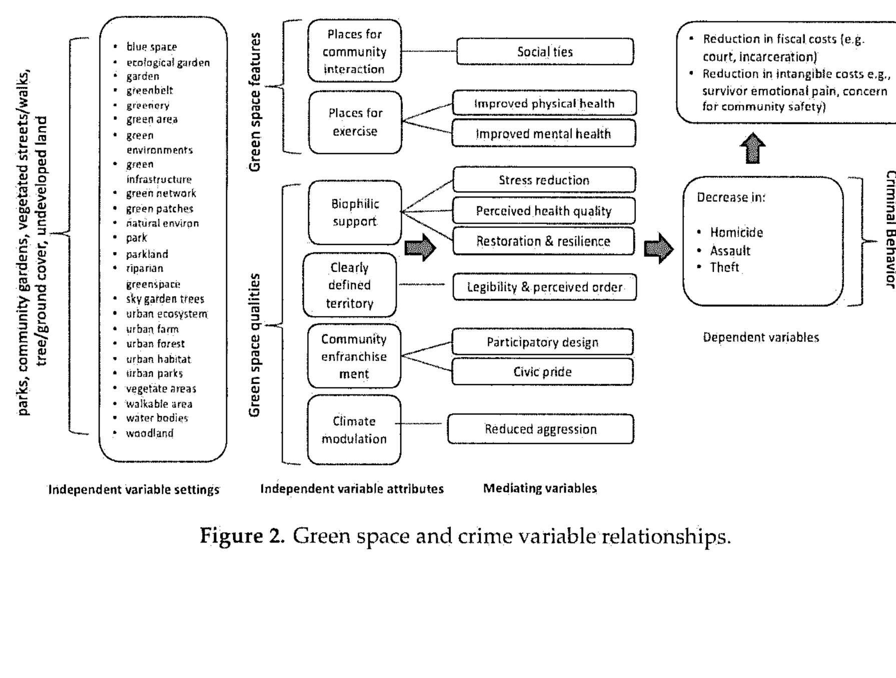

Figure 2. Green space and crime variable relationships.

4.2.1. Places for Community Interaction

Social ties. Outdoor gathering spaces provide the opportunity for interaction among neighborhood members, which increases familiarity and mutual investment in well-being. In keeping with the theory of collective efficacy, greened lots may promote social cohesion and, as a result, the interest in acting for the common good, thereby normalizing healthy behavior in these spaces [70].

Kuo et al. [71] explored the issue of how individuals' natural environments relate to their tendency to establish neighborhood social ties. Their study focused on Chicago public housing units that had direct access to common spaces with varying levels of vegetation. The researchers found a correlation between resident perception of "greenness" and strong neighborhood social ties. In addition, Kuo et al. found that "greenness" of common spaces was associated with perceived neighborhood safety.

With specific regard to children and adolescents, readily visible outdoor recreational spaces provide the opportunity for youth activities and potentially deter gang violence. Researchers have found that the presence of recreational amenities geared toward youth reduces the frequency of criminal activities in this age group [72]. Similarly, playgrounds can provide the opportunity for children to learn social and developmental skills [73], which may help them function more effectively in groups, and ancillary parent interaction has the potential for community adhesion through shared childcare activities.

4.2.2. Places for Exercise

Improved physical health. Parks provide the opportunity for exercise, which may enhance mental acuity [74] and reduce obesity [75]. Improved cognitive skills and health may enhance judgment. Lack of safety, however, may inhibit physical activity and is associated with fear of violence, presence of concerning behaviors, lack of maintenance and good lighting, and the presence of traffic [76]. Han et al. note that gun crimes are associated with long-term negative impacts on health due to reduced use of parks, in addition to the short-term impacts on public safety [77].

Improved mental health. Urban life may be a source of high stress levels [78], and stress and depression are related [79]. The associated mental illness may result in violent behavior. However, exercise is known to produce serotonin and as a result, act as a stress reducer [80]. Parks and other green spaces provide the opportunity for physical activity, including walking, jogging, and playing sports, and, therefore, may contribute to improved mental health.

4.2.3. Biophilic-Related Support

Stress reduction. Nature, in and of itself, may have a calming impact on human psychological and emotional state and cognitive functioning. Higher cortisol levels have been reported in urban areas with a higher percentage of green space [81].

Perceived quality of life. The presence of parks may increase the perceived quality of life [82], particularly as quality of life concerns the provision of perceived choice and control. Reduced lack of choice and control may mitigate the need to strike out against society and engage in violent activities.

Restoration and resilience. Kaplan [83] and others have demonstrated the impact of experience in nature on mental restoration. The resulting ability to make healthier and more productive decisions may be improved by interactions with nature. These interactions may also result in greater resilience [84].

4.2.4. Clearly Defined Territory

Ownership legibility. Clearly defined territories lead to less ambiguity of ownership. Replacement of underdeveloped sites with green spaces is a way to establish territorial markers. The simple act of replacing a run-down, unsupervised lot with a community-developed green space may force sites that previously afforded unhealthy activities to relocated or diminish. The lack of "intrinsic ownership" blurs accountability for maintenance and guardianship [85].

Perceived order. Wilson and Kellings' (1982) theory of "broken windows" suggests that minor cases of disorder create a foundation for more serious crime [86]. This disorder might express itself in the form of visual chaos (garbage, graffiti, abandoned cars) [87]. Several studies associate perceived disorder to physical decline, depression, psychological distress, and perceived powerlessness (e.g., Geis and Ross [88]). The implication is that residents see disorder as an indication of a more problematic neighborhood condition with the potential of compromising health [87]. (The socially controversial underside of this approach is linked to philosophies of crime control that recommend the aggressive arrest of individuals for minor infractions.) At the same time, there is considerable concern around gentrification. Upgrades should be supported and developed by the community and in keeping with local cultural aesthetics [11].

4.2.5. Community Cohesion

Community enfranchisement. Design researchers have known for many years that the participation of users (community members and clients) in the development of guidelines for the physical environment results in greater acceptance of the space and higher levels of maintenance. User participation has been noted for its particular effectiveness in urban settings [89] and provides opportunities for community members to coalesce around common goals. Community cohesion is a primary predictor of reductions in violent crime [90].

Civic pride. Another factor that may contribute to crime reduction is the impact of presence of parks on civic pride [91]; communities that are provided green space amenities may interpret this intervention as an act of respect and collaboration from civic governments. With regard to the duration of exposure, the impact is likely to occur even after short daily interactions with nature [92]. Quality parks may help motivate community members to protect and care for these spaces and reduce the need to erode the physical quality of these facilities as an expression of frustration.

4.2.6. Climate Modulation

Reduced aggression. Among the many ecological benefits of trees and other green features is the reduction of the heat island effect [93]. At the same time, researchers have provided evidence that aggression increases in higher ambient temperatures up to certain levels (i.e., 90 degrees Fahrenheit) [94]. The heat-reducing impact of green space, therefore, may result in reduced crime.

4.3. Limitations

The initial literature search yielded a substantial number of results (14,520 titles reviewed) due to the nature of the language used in the search. Keywords like "green" and "environment" are used broadly outside of the focus topic. To ensure an inclusive set of studies, the researchers relied on manual weeding (title reviews), potentially introducing researcher bias. This will likely continue to be a significant challenge for other researchers seeking to find articles on the topic of violence and green space within such a large collection of literature.

While the search was comprehensive, it was limited to articles written in English and research that took place in the United States. However, corroborating results have been found in other countries, such as Australia and the United Kingdom [92,95]. The researchers were also challenged by the differing definitions of green space and lack of common methods for calibrating green content. We were also unable to incorporate unreported or in-progress studies.

Discerning the impact of confounding variables posed another challenge, particularly in considering the role of maintenance. Beyond the green features of a space, the design and maintenance of a space can also influence its use and perceptions of safety [96]. The presence of green space has the potential to reduce urban crime, but these findings may be substantially moderated by good design and consistent maintenance.

5. Conclusions

Based on the 45 quantitative and qualitative papers summarized here, we can deduce that the presence of parks and other green space reduces urban crime. In the process of our review, we extracted multiple mechanisms from the literature that may account for the impact of green space on crime, including social interaction and recreation, community perception, biophilic stress reduction, climate modulation, and spaces expressing territorial definition. Among the recommendations for future research are a meta-analysis of existing data and the development of grounded theory through qualitative data-gathering methods.

There are several strategies for reducing crime in the U.S. [97], and the provision of green space is one of them. Good public spaces support desirable behaviors and inappropriate public spaces provide the opportunity for increases in criminal behavior, which can be economically costly to society [11,98]. Additionally, safe, accessible green spaces enhance physiological and psychological human health and well-being [99–101]. By providing evidence that access to nature has a mitigating impact on violence in urban settings, city governments and communities are empowered to support these interventions.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Literature Review Summary Table.

Paper	Study Location; Time	Sample Size; Units	Predictor: Type of Green	Outcome: Type of Crime
Abu-Lughod (2006) [47]	Highest populated cities in US; 2000	n/a	P	H, A, T
Auchincloss et al. (2019) [55]	Philadelphia, PA; 2009–2014	n/a	V	H, A, T
Blair (2014) [35]	Cincinnati, OH; 1997–2011	5 gardens	G	H, A, T
Blair et al. (2017) [64]	Cincinnati, OH; 2013–2014	12 parks and playgrounds; 10 gardens	P, G	H, A, T
Boessen & Hipp (2018) [67]	Nine US cities; n.d.	109,808 blocks	P	H, A, T
Branas et al. (2011) [40]	Philadelphia, PA; 1999–2008	4436 city lots	G	A, T *
Branas et al. (2016) [11]	Philadelphia, PA; 1999–2008	676 buildings	G	A *
Branas et al. (2018) [34]	Philadelphia, PA; 2011–2013	541 vacant lots	G	A, T *
Brown (2018) [102]	Philadelphia, PA and Detroit, MI; 2011–2015	384 and 297 crimes	P	H, A, T
Burley (2018) [65]	Portland, OR; 2011–2015	93 neighborhoods	V	H, A, T
Crewe (2001) [58]	Boston, MA; 1996-1998	2 neighborhoods	V	A, T
Culyba et al. (2016) [41]	Philadelphia, PA; 2008–2014	143 crimes	P, G	H
DeMotto & Davies (2006) [42]	Kansas City, KS; 2002	40 parks	P	H, A *

Table A1. *Cont.*

Paper	Study Location; Time	Sample Size; Units	Predictor: Type of Green	Outcome: Type of Crime
Deng (2015) [68]	Milwaukee, WI; 2005–2010	1 city	T	A, T
Donahue (2011) [59]	New York, NY; 2001–2008	59 NYC communities (and 200+ other cities)	T	H, A, T
Donovan & Prestemon (2012) [103]	Portland, OR; 2005–2007	2813 households	T	A, T
Garvin et al. (2013) [36]	Philadelphia, PA; 2011	21 lots	G	A, T *
Gilstad-Hayden et al. (2015) [104]	New Haven, CT; 2008–2012	106 census tracts	T	H, A, T
Gorham et al. (2009) [69]	Houston, TX; 2005	11 community gardens	G	T
Harris, Larson, & Ogletree (2018-B) [56]	Chicago, IL; 2011-2015	138 (Study 1) and 62 (Study 2) census tracts	V	H, A, T
Harris (2018) [57]	Chicago, IL; 2011–2015	(see above)	V	H, A, T
Heinze et al. (2018) [52]	Flint, MI; 2009–2013	216 treated lots	G	H, A, T
Kim & Hipp (2018) [48]	Southern CA; 2010	218 cities	P	A, T
Kondo et al. (2015) [45]	Philadelphia, PA; 2000–2012	238 census tracts	U	H, A, T *
Kondo et al. (2016) [53]	Youngstown, OH; 2010–2014	5126 crimes	G	H, A, T
Kondo et al. (2017-A) [105]	Cincinnati, OH; 2005–2014	307 blocks	T	H, A, T
Kondo et al. (2017-B) [46]	Philadelphia, PA; 2008–2011	309 (Study 1) 135 (Study 2) individual victims	T	A *
Kuo & Sullivan (2001) [12]	Chicago, IL; n.d.	98 apartment buildings	T	H, A, T
Lee (2013) [106]	Chicago, IL; 2010	150 parks	P	H, A, T
Li (2008) [61]	Oakland, CA; 2006–2007	234 neighborhoods	T	H, A, T
Lim (2005) [60]	Dallas, TX; n.d.	1683 blocks	T	H, A, T
Locke et al. (2017) [39]	New Haven, CT; 1996–2007	1193 blocks	V	H, A, T
Luke (2013) [107]	Cleveland, OH; 2012	105 gardeners; 92 non-gardeners; 3 community gardens	G	Safety; sense of community
McCord & Houser (2017) [49]	Philadelphia, PA and Louisville, KY; 2005–2010	307 parks	P	H, A, T
Nitkowski (2017) [108]	Milwaukee, WI; 2013–2015	210 census tracts	P	H, A, T
Sadler et al. (2017) [54]	Flint, MI; 2005–2014	1800 lots	G	H, A, T
Schusler et al. (2018) [66]	Chicago, IL; 2009–2013	801 census tracts	T	H, A, T
Seymour et al. (2010) [109]	Los Angeles, CA; 2007	39 individuals	G	Utilitarian relationships with green alleys
Snelgrove et al. (2004) [110]	Austin, TX; 1995	1170 crimes	T	H, A, T

Table A1. *Cont.*

Paper	Study Location; Time	Sample Size; Units	Predictor: Type of Green	Outcome: Type of Crime
Sparks (2011) [62]	San Antonio, TX; 2003–2006	235 census tracts	U	H, A
Stodolska et al. (2011) [111]	Chicago, IL; 2007	26 crimes	P	Benefits, concerns of parks
Troy et al. (2012) [43]	Baltimore, MD; 2007–2010	1208 census tracts	T	H, T *
Troy et al. (2016) [44]	Baltimore, MD; 2007	999 households	T	H, A, T *
Wilcox et al. (2003) [112]	Seattle, WA; 1989–1990	100 census tracts	G	Impact of parks and playgrounds on crime perceptions
Wolfe & Mennis (2012) [37]	Philadelphia, PA; 2005	363 census tracts	T	A, T

TYPE OF GREEN: ^{P} Parks (larger than community or neighborhood), ^{G} Community greening (alleys, urban gardens, small green space, greening vacant lots), ^{V} Vegetated streets and walkways (elevated trails and street tree planting), ^{T} Trees and ground cover (grass, tree upgrades), ^{U} Less developed green areas (stormwater upgrades, croplands, wetlands, natural spaces, diverse landscaping); TYPE OF CRIME: ^{H} Homicide—General, ^{A} Assault, Sexual Assault, ^{T} Theft, Robbery, Burglary, * Specifies gun crimes.

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PEOPLE NATURE

REVIEW AND SYNTHESIS

Denser and greener cities: Green interventions to achieve both urban density and nature

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Abstract

1. Green spaces in urban areas—like remnant habitat, parks, constructed wetlands, and street trees—supply multiple benefits.
2. Many studies show green spaces in and near urban areas play important roles harbouring biodiversity and promoting human well-being. On the other hand, evidence suggests that greater human population density enables compact, low-carbon cities that spare habitat conversion at the fringes of expanding urban areas, while also allowing more walkable and livable cities. How then can urban areas have abundant green spaces as well as density?
3. In this paper, we review the empirical evidence for the relationships between urban density, nature, and sustainability. We also present a quantitative analysis of data on urban tree canopy cover and open space for United States large urbanized areas, as well as an analysis of non-US Functional Urban Areas in OECD countries.
4. We found that there is a negative correlation between population density and these green spaces. For Functional Urban Areas in the OECD, a 10% increase in density is associated with a 2.9% decline in tree cover. We argue that there are competing trade-offs between the benefits of density for sustainability and the benefits of nature for human well-being. Planners must decide an appropriate density by choosing where to be on this trade-off curve, taking into account city-specific urban planning goals and context.

[Corrections added on 1 February 2023, after first online publication: In the Abstract, the text 'a doubling of density' has been changed to 'a 10% increase in density'].

5. However, while the negative correlation between population density and tree cover is modest at the level of US urbanized areas ($R^2 = 0.22$), it is weak at the US Census block level ($R^2 = 0.05$), showing that there are significant brightspots, neighbourhoods that manage to have more tree canopy than would be expected based upon their level of density. We then describe techniques for how urban planners and designers can create more brightspots, identifying a typology of urban forms and listing green interventions appropriate for each form. We also analyse policies that enable these green interventions illustrating them with the case studies of Curitiba and Singapore.
6. We conclude that while there are tensions between density and urban green spaces, an urban world that is both green and dense is possible, if society chooses to take advantage of the available green interventions and create it.

KEYWORDS
ecosystem services, energy use, land sharing, land sparing, landscape architecture, sustainability, tree canopy cover, urban planning

1 | INTRODUCTION

Urban growth is occurring faster than has ever been experienced in human history, with an additional 2 billion people expected in urban areas by 2050 (UNPD, 2018). In the next couple of decades, more homes will be built in cities around the world than currently exist in all of Europe (McDonald, 2008). The form of those new urban neighbourhoods has implications for numerous aspects of sustainability, from resource use to material efficiency to greenhouse gas emissions. This paper looks at the potential role of nature in urban neighbourhoods, and how different urban forms allow for different amounts of nature and sustainability. We ask how urban neighbourhoods can be designed to be both full of green spaces, for biodiversity and ecosystem service benefits, while also dense enough to confer some of the sustainability benefits of a more compact city. We primarily focus on urban density in this manuscript, but acknowledge that there are other aspects of urban form that are also important for sustainability and present a typology of urban forms relative to different kinds of green spaces.

While there have been reviews about the state of scientific knowledge for specific topics, this review attempts to synthesize results from what are arguably several distinct areas of study now: urban biodiversity and urban form; urban ecosystem services and urban form; urban sustainability and urban form; and discussion of specific types of green intervention to increase urban nature. Moreover, we have tried where possible to draw from quantitative assessments of how density relates to these different goals, to provide context and specificity for the literature review. To our knowledge, there are no other similar paper that quantitatively synthesizes these distinct areas of study.

In this paper, our overarching research question is: How can urban areas be both dense and green? We first review the scientific literature (Section 2) to understand the quantitative relationships between green spaces and the amount of biodiversity or ecosystem service provision in urban areas. Next (Section 3) we review the empirical data on the relationship between human population density and sustainability. In Section 4, we quantitatively analyse two recently published datasets from the United States, to determine if there is, on average, a trade-off between human population density and the number of green spaces. We also analyse trends for non-US cities using data from OECD countries. Next (Section 5) we investigate brightspots, defined as neighbourhoods that have at least three times more tree canopy than would be expected based upon their level of density. We identify a typology of urban forms and describe how they relate to possible green interventions that can increase green spaces (Section 6). Finally, we describe policies that enable these green interventions using two case studies: Curitiba and Singapore (Section 7).

1.1 | Defining urban population density

In this paper, we define 'urban form' as 'the physical characteristics that make up built-up areas, including the shape, size, density and configuration of settlements' (Redbridge Government, 2014). Urban density is one component of urban form, the concentration of people or building infrastructure within a certain urban area (Ng, 2009). It is a common measure in urban planning and landscape architecture, which is why we have chosen to focus on it here. Other components of urban form are discussed in more detail in Section 6.

In this paper we measure urban density as the number of people per square kilometre within an urban area. Definitions of urban vary between different databases and scientific papers use different definitions of urban depending on the context (Bay & Lehmann, 2017). In this paper, we generally follow the Functional Urban Area (FUA) definition, which defines a core area surrounded by a commuting zone (Dijkstra et al., 2019). However, for cities in the United States, in order to align spatially with census data, we follow the definitions of the U.S. Census Bureau (2010), which delimits core 'urbanized areas' surrounded by a commuting zone (Metropolitan Statistical Areas). Note that urbanized areas are not arbitrary political units, but are based on the density of human settlements, similar but not identical to the delineation of a core FUA.

Our paper discusses density and nature at three different scales: (1) the entire FUA or Metropolitan Statistical area, (2) the core FUA or urbanized area, (3) and the neighbourhoods scale (defined in the US as census blocks). For the US, we consistently present data using the urban area concepts defined by the US Census Bureau, whereas for other countries we present data using the FUA concept. Sections 2–4 focus primarily on scales #1 and #2, as that is scale at which overall relationships between urban density and sustainability has been most frequently studied. Sections 5 and 6 focus on green interventions at the neighbourhood scale (scale #3), as that is the scale at which landscape architects and urban planners often work when designing new developments. Sections 7 discusses policy options across these three scales.

Readers are cautioned that density statistics may look very different across these three scales, and depending on the urban area definition used. For instance, in 2010 the US Census Bureau estimated the density of the New York Metropolitan Statistical area (New York–Newark–Bridgeport, NY, NJ, CT, PA) was 1085 people/km^2, that of the New York City urbanized area was 2053 people/km^2, while specific neighbourhoods (US census blocks) in Manhattan like the Upper East Side exceed 50,000 people/km^2 (McDonald et al., 2021). For comparison, the OECD estimated the density of the New York City FUA as 829 people/km^2, while the core FUA population density was 1431 people/km^2 (Brezzi et al., 2012; OECD, 2021).

2 | URBAN GREEN SPACES, BIODIVERSITY AND HUMAN WELL-BEING

There are multiple types of nature in cities, which we will refer to collectively as green spaces. Our definition of 'green spaces' follows Aronson et al. (2017), and includes vegetated natural, semi-natural, and artificial ecological systems within and around a city. Some green spaces are not human creations, such as remnant patches of habitat in or near urban areas. Other green spaces are anthropogenic, such as parks, gardens, and vegetation planted along city streets. Note that in arid or semi-arid landscapes, green spaces may have vegetation that is appropriate to these climatic zones and may thus appear less green in colour. As will be discussed in more detail below, different kinds of green spaces support biodiversity and provide ecosystem service in different amounts and ways (McDonald, 2009).

2.1 | Urban nature and biodiversity

In this subsection, we briefly review the literature on the relationship between urban form and biodiversity, with a goal of identifying what density and urban form seem most able to support biodiversity.

It is helpful for purposes of analysis to divide the taxa present in urban areas into three groups (Fischer et al., 2015). *Urban avoiders* are species, often native to a location, which are unable to survive in urban areas due to habitat requirements or other susceptibility to the changes in conditions (abiotic and biotic) within urban areas. As a city expands, then, urban avoiders in general decline in abundance, or may be driven locally extinct. *Urban utilizer species*, can survive in urban areas, whether due to a wide range of possible habitat or due to behavioural adaptability. As an urban area expands, urban utilizers will persist locally or even increase in abundance. Finally, *urban dwelling species* are those that tend to arrive with human settlement and habitation and are often well-suited to life in an urban environment. As an urban area expands, the species richness and abundance of urban dwellers tends to increase. The overall change with urban growth in total species richness depends on the relative species richness in each group. In some cases, total species richness at the city scale may even increase with urban growth (Spotswood et al., 2021), if gains in urban dwellers outweigh losses of urban avoiders. However, at a global scale, because the species richness of urban avoiders generally declines with habitat destruction, urban growth has a net negative effect on global biodiversity (McDonald, M'Lisa Colbert, et al., 2018).

One key finding of studies of urban biodiversity is that remnant habitat—vegetation native to the region that remains after urban expansion—is one of the most important type of green spaces for increasing and maintaining biodiversity (Figure 1). Other green spaces such as street trees, parks, or habitat on residential properties can also harbour important elements of biodiversity, so these other features are also important in determining urban biodiversity (Belaire et al., 2014; Daniels & Kirkpatrick, 2006; Lerman & Warren, 2011; Smith et al., 2014). A larger extent of habitat predicts a more diverse flora and fauna (Aronson et al., 2014; La Sorte et al., 2020). This is consistent with the often-studied species-area relationship in ecology, with more habitat area allowing the maintenance of a greater number of species.

Remnant habitat is often converted to urban land uses as urban areas grow. One debate in the literature has been framed as 'land sparing versus land sharing' (Soga et al., 2014). Land sparing in an urban context would be concentrating and limiting urban development, often by having greater human population density, thus sparing habitat on the fringes of the urban area. Land sharing would be interspersing urban areas with green spaces, and thus the total amount of urban area being greater and human population density being lower. In general, most urban studies find that land sparing produces higher total biodiversity than land sharing. Higher biodiversity or biomass was found to occur with land sparing for birds in a set of 9 European cities (Jokimäki et al., 2020), for trees in the UK (Collas et al., 2017), for insects in Japan (Soga et al., 2014), and for birds and bats in Australia (Caryl et al., 2016; Geschke et al., 2018; Sushinsky et al., 2013; Villasenor et al., 2017). There are exceptional cases where land sharing is better, however, such as for overwintering birds (Ibáñez-Álamo et al., 2020). Moreover, there are instances where other anthropogenic green spaces are crucial for supporting some taxa (Spotswood et al., 2021).

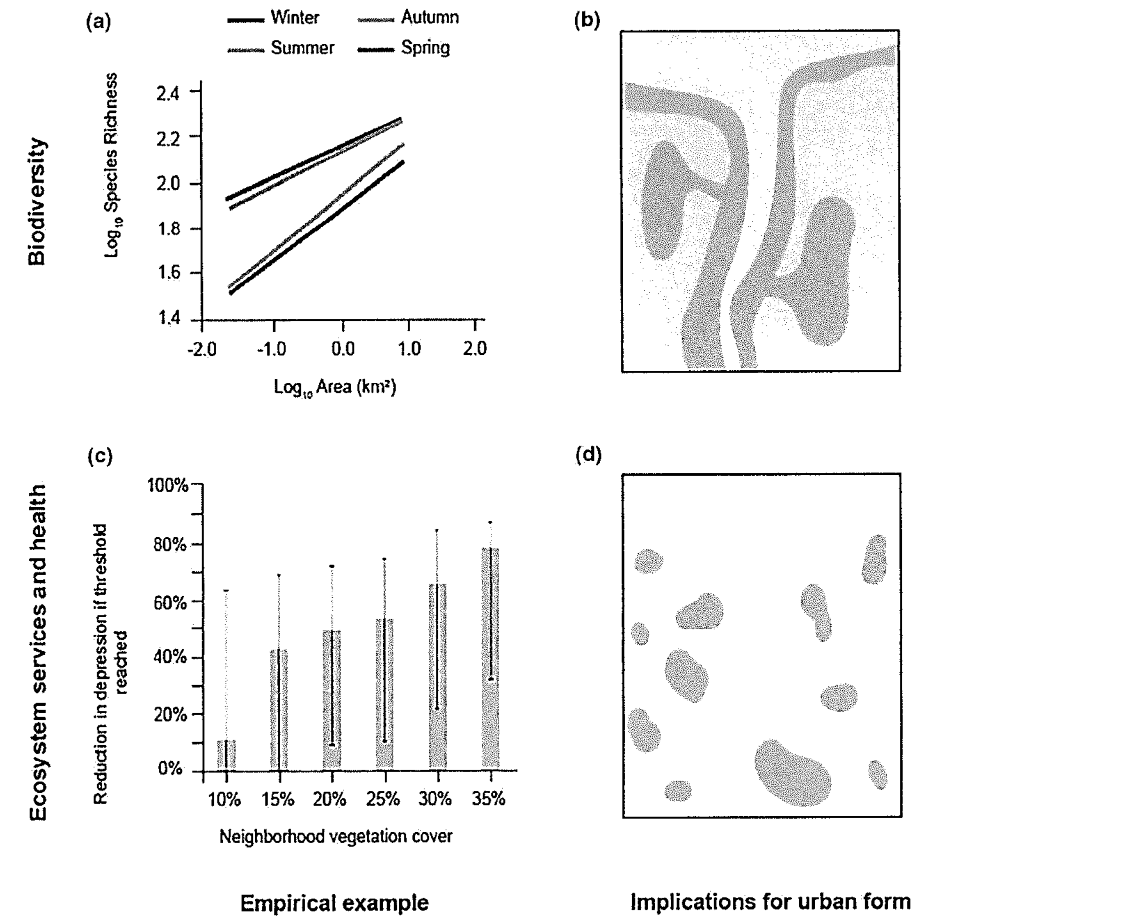

FIGURE 1 Relationship between nature, biodiversity, and ecosystem provision. (a) The relationship between habitat area and avian species richness in New York City (La Sorte et al., 2020). (b) Conceptual drawing of urban development (grey) near a waterbody (blue) in a matrix of remnant habitat (green), with important biodiversity areas protected with corridors between them (McDonald, 2015). Note that small green spaces within the urban area (not shown) can improve matrix quality and help maintain biodiversity as well (Forman, 2008). (c) Neighbourhood vegetation cover and the odds of having depression, from a study in southern England. Shown is the reduction in the odds of having depression, relative to the base case, if a vegetative cover threshold is exceeded (Cox et al., 2017). (d) Conceptual drawing of urban development (grey) near a waterbody (blue) in a matrix of green spaces (green), where each urban neighbourhood is surrounded by green spaces that can provide benefits to residents (McDonald, 2015).

Of course, other components of landscape structure also play a role in determining biodiversity (Fahrig, 2003). Edge effects between remnant habitat and urban areas significantly alter abiotic and biotic conditions (Cadenasso et al., 1997). Edge effects can be minimized by having larger patches of remnant habitat that have lower edge: area ratios (Woodroffe & Ginsberg, 1998). Fragmentation of remnant habitat into multiple patches may reduce connectivity between patches (Fagan, 2002). Loss of connectivity can be minimized by maintaining corridors between patches, although what is a viable corridor is taxa specific (Tischendorf & Fahrig, 2000).

Finally, the dominant paradigm of island biogeography (islands of habitat surrounded by an inhospitable matrix) does not reflect the reality of urban ecology. The quality of the urban matrix matters for determining what urban biodiversity can survive (Spotswood et al., 2019), and should be accounted for in urban biodiversity planning. All else being equal, an urban area that has anthropogenic features such as street trees, green facades and green roofs will have more biodiversity than an urban area without these green spaces. Urban green spaces can thus play an important role in improving matrix quality, and incentives and programs that increase vegetation on otherwise developed parcels can be green interventions with significant biodiversity benefit. Matrix quality can be measured in terms of how it enables connectivity (Ricketts, 2001) or in terms of providing habitat and resources to some taxa (Ruffell et al., 2017).

In sum, the literature suggests that the ideal urban form to maintain biodiversity globally is a compact, high-density city that minimizes remnant habitat conversion (Gagné & Fahrig, 2010; Jokimäki et al., 2020; Sushinsky et al., 2013). Large patches of remnant habitat should be maintained in and near urban areas, with corridors to connect these large patches when possible, while green spaces should be present in the urban matrix to improve matrix quality as much as possible (Forman, 2008).

2.2 | Urban nature and human well-being

There are a wide variety of ecosystem services which are important in urban contexts (Keeler et al., 2019; McDonald, 2015; Souza et al., 2021). Ecosystem services tend to be preferentially provided by certain types of green spaces (de Macedo et al., 2021). For instance, urban tree canopy cover is the green space most involved with air temperature regulation (Kroeger et al., 2018; McDonald et al., 2020). Stormwater mitigation is most associated with wetland features, whether constructed or natural, as that is where rainwater can collect and infiltrate into the soil (Venkataramanan et al., 2019). Recreation value requires people to visit a green space, which often requires substantial areas of anthropogenic land-uses such as walking trails and playing fields (McCormack et al., 2010).

Ecosystem services also occur at particular spatial scales (McDonald, 2009). The scale of an ecosystem service determines where green spaces must be present to help a particular beneficiary group. Some services like carbon sequestration are effectively global, for a tree planted anywhere ultimately reduces the carbon dioxide concentration of the atmosphere globally. Other services play out in watersheds, such as the way vegetation can prevent erosion and the transport of sediment into the stream (Romulo et al., 2018; Vogl et al., 2017). At the other extreme, some ecosystem services must be provided locally. For instance, the area of temperature mitigation typically extends a few hundred meters from vegetation (McDonald et al., 2016).

One particularly important group of ecosystem services are those related to human health. Multiple epidemiological studies show a strong overall correlation between nature exposure and human health (Rojas-Rueda et al., 2019). For example, one long-term cohort study found 12% lower all-cause mortality among female nurses with greater NDVI (a commonly used remotely sensed index related to vegetative greenness) within 250 m than those nurses with less greenness (James et al., 2016). Greater NDVI exposure has also been found to reduce stress and the incidences of certain diseases such as cardiovascular diseases.

Researchers have proposed three key dimensions of nature exposure (Shanahan et al., 2015). The *Intensity* of the exposure might be affected by the amount or quality of nature, with seeing one single tree less intense than being surrounded by a dense tree canopy on all sides. The *frequency* of the exposure might be affected by the location of green spaces, with those with much more nature nearby their home and work more frequently interacting with it. Finally, the *duration* of nature exposure describes how long an individual typically spends interacting with nature in each session, with longer duration exposures expected to have a greater effect on human health. Taken together, these three dimensions describe the 'dose' of nature an individual receives. The dose–response curve of nature exposure is clearly positive (greater dose, greater health) although the exact functional form of this relationship is unclear.

The ideal urban form with respect to many aspects of ecosystem service provision (Figure 1) is thus different than was the case for biodiversity (Sushinsky et al., 2013), particularly where proximity and interaction is required for service delivery (McDonald, 2009; Tallis & Wolny, 2011). Many small clumps of green spaces, interspersed in the urban fabric (Stott et al., 2015), enable a greater and more equitable ecosystem service provision (Bratman et al., 2019; McDonald, 2015). Since different green spaces are best suited to different ecosystem services, a variety of types of green spaces will better meet human needs (Keeler et al., 2019). Ideally, these green spaces should be placed to deliver key ecosystem services to those beneficiaries who need them (Kremen, 2005). Similarly, green spaces should be placed to promote more intense, frequent, and long-duration exposure to nature (Shanahan et al., 2015).

3 | RELATIONSHIP BETWEEN DENSITY AND URBAN SUSTAINABILITY

This manuscript discusses how to reconcile green spaces in urban areas, and their many benefits to human well-being and health, with the other human needs determining urban density. Globally, an increasing fraction of humanity lives in urban areas, and one driver of this urbanization is the benefits of living at higher densities in cities rather than in rural areas (Knox & McCarthy, 2005). As discussed further below, urbanization increases economic productivity and innovation, and brings substantial benefits to those living in cities. Higher population density of urban areas, therefore, can bring with it many benefits. In this section, we explore these benefits of a dense urban lifestyle, contrasting not just rural versus urban areas but also denser urban neighbourhoods with less dense urban neighbourhoods.

3.1 | Benefits of density

Higher densities and an urban pattern of settlement are associated with greater economic productivity (Figure 2a). For instance, an analysis of European subnational regions found that greater population is associated with greater economic productivity (Pan et al., 2013). In this paper, we run a parallel analysis for all OECD FUAs, using the most recent economic and population data, focusing the statistical analysis on the relationship between population density and per-capita economic productivity (Brezzi et al., 2012; OECD, 2021). We find an equivalent relationship, with greater population density associated with greater per-capita economic productivity (Figure 2a). In US cities, a 10% increase in population density is associated with a 1.7% increase in per-capita GDP, while in other OECD countries it is associated with a 2.1% increase in per-capita GDP.

Density increases proximity among individuals and among firms, and proximity has several social and economic benefits to production (McDonald & Beatley, 2020). These benefits are sometimes classified as sharing, matching and learning (Andersson et al., 2007; Duranton & Puga, 2004). *Sharing* of infrastructure like roads or ports is easier when multiple users are in proximity.

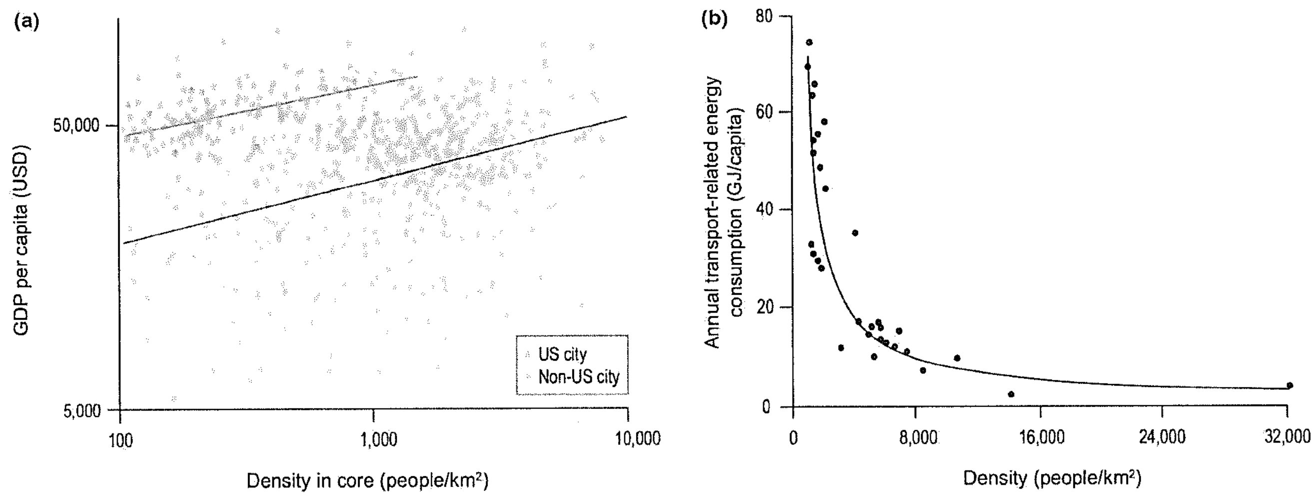

FIGURE 2 Relationship between density and sustainability. (a) Greater population density in OECD functional urban areas (FUA) is associated with greater per-capita economic activity. Shown here are the OECD data, which lists the core FUA population density (OECD, 2021). Our analysis methodology follows Pan et al. (2013), except we have subdivided US and non-US FUAs. (b) Greater population density in cities is associated with less transportation-related energy use, as the use of the private automobile per-capita declines (Newman & Kenworthy, 1989).

The proximity of people and firms also speeds up *Matching*, when two actors find a mutually agreeable collaboration (Andersson et al., 2007; Venables, 2010; Wheeler, 2001). Finally, the increased interaction in urban areas between individuals leads to *Learning*, the sharing of information.

Urban density is negatively correlated with vehicle miles travelled (Figure 2b). In low-density urban settlements, automobiles are often required for getting between destinations, which are often far apart, whereas in higher-density neighbourhoods, particular those oriented toward public transit, it is more possible to travel without car, and travel distances are shorter (Park et al., 2018). Fewer vehicle miles travelled leads to less energy for transport and fewer greenhouse gas emissions from internal combustion engines (Ewing et al., 2003), while more active transport leads to better health outcomes (Hamidi et al., 2018). For instance, Newman and Kenworthy found a negative relationship between urban density, measured at the municipal level, and transportation energy use (Newman & Kenworthy, 1989). Fitting a regression line to the data, we find that a 10% increase in urban density in their sample is associated with around an 8% decrease in transportation energy use. Thus, there is an important sense in which designing new neighbourhoods to be dense can be an important climate mitigation strategy for urban areas.

Importantly for the goal of maintaining remnant habitat, denser cities tend to be 'land sparing.' That is, the greater density leads to less land converted to urban land uses, all else being equal, and this can lead to less habitat loss. Specifically, compact cities need less land area per capita devoted to the road network, reducing total road area needed to support a given population. Similarly, there is less of a building footprint per capita, reducing the total building area needed to house a given population. Of course, other aspects of urban form relate to the degree of 'land sparing', such as the spatial configuration of road and building areas.

The characteristics of urban form essential to a well-functioning city go beyond just population density. One theory (Burton et al., 2003) that tries to enumerate these other characteristics is compact city theory. This theory argues that a compact city can promote beneficial interactions among residents and deliver several environmental benefits. Compact cities are generally at relatively high population density, but also support a mixture of land-uses and building types. There are other theories with similar but not identical goals, including 'green urbanism', 'new urbanism', and 'smart growth'. Recently the idea of the walkable city has become popular, such as the 15-min or 20-min city (Moreno et al., 2021). This is the length of time a short walk from one's house would take, and the idea is that all basic needs should be obtainable within this distance. We cannot in this short section cover this whole rich topic within urban planning but acknowledge that while density may be a necessary part of these urban planning paradigms, they also aim to influence other aspects of urban form.

3.2 | Some challenges with density

Dense neighbourhoods also have some less desirable attributes. We discuss the potential trade-off between density and green spaces in detail in the next section, but in this section our goal is to acknowledge the existence of a few other trade-offs. One common criticism of dense cities is that the cost of renting or buying a home is often greater than in less dense cities (Rérat, 2012). While the causal mechanisms behind this correlation are complex, part of it seems to be that the supply of housing in dense cities does not keep up with demand, raising prices. However, other studies have critiqued low-density suburbs for being exclusionary and unaffordable (Jackson, 1985), so being dense per se is not a sole determinant of the price of housing.

Density can also have some negative effects on quality of life (Cramer et al., 2004). A greater density is often correlated with greater exposure to air pollution from traffic (Davies et al., 2009). Of course, there are solutions to this environmental problem, such as emission controls or zero-emissions vehicles or increased mass transit. Dense cities also tend to have more noise pollution, from more traffic but also from the industrial and commercial land uses (Yuan et al., 2019). Again, other mitigation measures are imaginable, such as sound barriers.

Finally, the increased crowding and interaction in dense cities seems to pose a mental health strain. McDonald and Beatley (2020) refer to this as the urban psychological penalty, the tendency for certain mental health disorders to increase with density. For instance, there are greater rates of stress in urban settings, whether measured with surveys or with cortisol levels (Hartig et al., 2014). Several diseases such as schizophrenia are more prevalent at high densities (Lewis et al., 1992). While other aspects of urban form, including the presence of green spaces, can mitigate these benefits, it is fair to say that for some individuals, life in a high-density city may pose some mental health challenges.

4 | TRADE-OFFS BETWEEN DENSITY AND NATURE PROVISION

In Section 2, we described how having an abundance of green spaces within and near urban areas helps maintain biodiversity and provides important ecosystem services. A separate body of research into urban sustainability suggests that having dense cities delivers, on balance, multiple benefits for sustainability (Section 3). The ideal urban neighbourhood then should have an abundance of green spaces, within and nearby, and be dense. But is this ideal possible?

There are potential trade-offs between human population density and the number of green spaces. For instance, Westerink et al. (2013) present data suggesting that some compact cities in Europe have less accessible open space. They found that people were willing to live in the less dense suburbs and accept a longer commute if it afforded them access to more open space and parks. Moreover, this potential trade-off between density and remnant habitat is implicit in the 'land sparing versus land sharing' formulation (Soga et al., 2014). Denser, 'land sparing' development is assumed to reduce biodiversity within the urban area but help avoid habitat loss at the urban fringes.

In order to assess the extent of this trade-off empirically, we estimated tree cover and population density, utilizing an already published dataset of urban tree canopy cover at 2 m resolution for the 100 largest urbanized areas in the United States, which contain 167 million people in 5723 municipalities and communities (McDonald et al., 2021). Climate plays a role in determining tree canopy cover and ecosystem service provision (cf. Richards et al., 2022), and in our dataset for the US, cities in humid locations have more tree cover than cities in drylands (arid or semi-arid climates) (Figure 3a). For urbanized areas in humid climates, there is a negative association between density and tree canopy cover ($R = 0.47$). This trend presumably occurs because at higher population density there is more impervious surface cover of things like pavement and concrete, which limits the possibilities for planting trees in soil. Note that for urbanized areas in drylands, there is no statistically significant relationship between density and tree canopy cover.

Another important kind of green space is the amount of open space near residents, particularly the amount of publicly accessible parks (Figure 3b). We draw data from Spotswood et al. (2021), which integrated several data layers to map protected areas across all US urbanized areas. To estimate the fraction of the land that is in an undeveloped land cover, we use the United States National Land Cover database of 2016. Human population density and the fraction of land that is open space are negatively associated. Interestingly, the fraction of open space that is protected increases with population density. In denser city centers, a large fraction of open space is protected, while in lower density suburbs, there is a greater amount of open space that is disproportionately on non-protected lands.

Our sample of cities with high-resolution tree cover was from the United States. To assess where similar trends hold for a global sample of cities, we used data on OECD FUAs (excluding US cities, to avoid double counting). Trends for tree cover are similar to the US urbanized area sample (Figure 4). Density in core FUAs is negatively associated with tree canopy cover ($R = 0.33$), with a 10% increase in density associated with a 2.9% decrease in tree cover. There is no significant association between density and percent protected area in OECD FUAs.

Available studies from the literature show a similar trend with density. A study of 386 European cities found a decrease in per-capita green space provision at higher population densities (Fuller & Gaston, 2009), and a study of 111 Southeast Asian cities found that cities with higher population density have lower absolute and per-capita green space (Richards et al., 2017). Other studies have examined other potential explanatory variables related to urban green space, including level of economic development among countries (Huang et al., 2021) and within a country, China (Chen & Wang, 2013; Zhao et al., 2013), as well as change in green space provision over time (Huang et al., 2017; Zhao et al., 2013).

Thus, at the urbanized area or FUA level, higher human population density is associated with less tree cover and (at least for US cities) less percent open space. The competing desires—for nature but also for the benefits of biodiversity—suggests that there may be on average a trade-off between these two objectives. Three caveats are in order however.

First, the scientific knowledge of the shape of this trade-off curve remains imprecise. While there have been many papers that have examined aspects of this trade-off between nature and density, there are relatively few quantitative results. One partial exception is a qualitative study by UN-HABITAT that considered trade-offs around density, urban sustainability, and quality of life and suggested

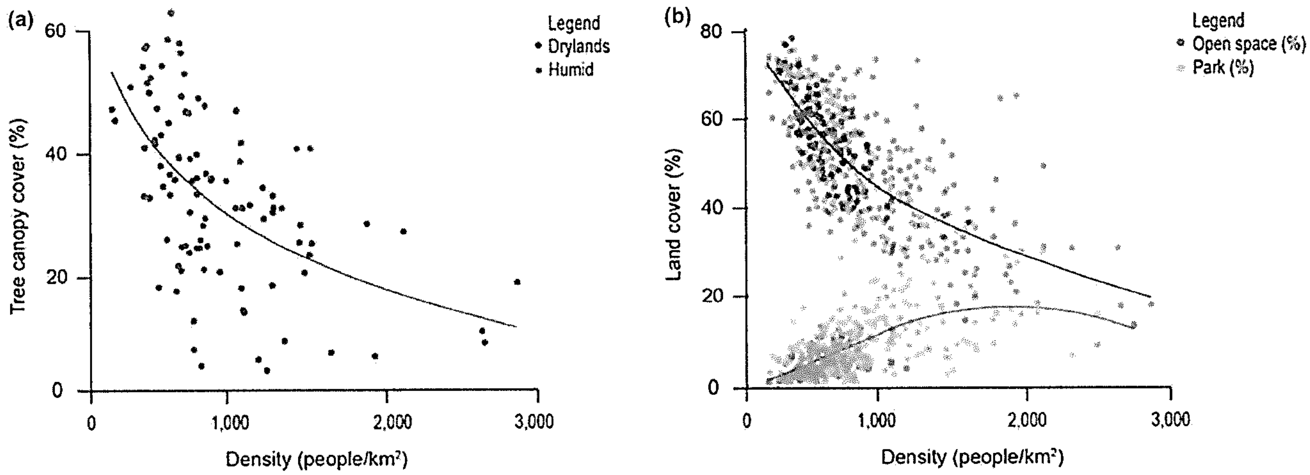

FIGURE 3 Trade-offs between density and nature in U.S. urbanized areas. (a) Population density in the 100 largest urbanized areas (U.S. Census Bureau, 2010) is negatively associated with tree canopy cover. Urbanized areas are divided into two climate types, based on their scores on the aridity index. Best-fit line is a log-linear regression. Data adapted from McDonald et al. (2021). (b) Population density in US urbanized areas is negatively associated with the amount of undeveloped 'Open space' nearby. However, the amount of publicly accessible protected area ('Park') appears relatively uncorrelated with density. Denser urbanized areas therefore have less open space but a greater fraction of it is publicly accessible. Best-fit lines are smoothing splines. Data adapted from Spotswood et al. (2021).

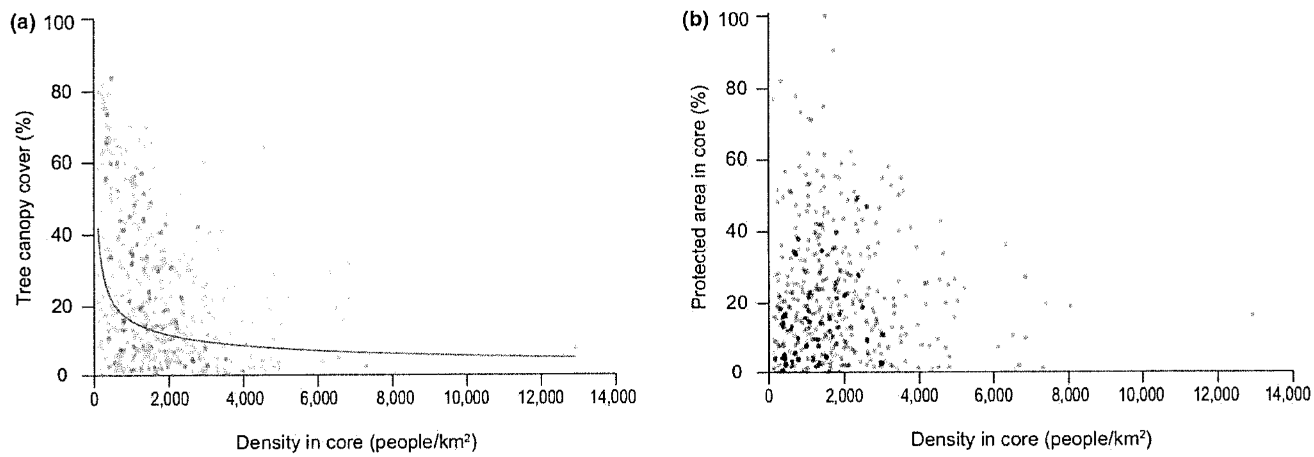

FIGURE 4 Trade-offs between density and nature in OECD functional urban areas (FUAs). (a) Population density is negatively associated with tree canopy cover. Best-fit line is a log–log regression. Data from the OECD atlas of regions and cities (Brezzi et al., 2012; OECD, 2021). (b) Population density in core FUAs is not significantly associated with the percent protected area in core FUAs.

1500–4500 people/km^2 as a reasonable compromise among trade-offs (UN-HABITAT, 2012).

Second, in different planning contexts and different urban areas, the relative importance of different benefits would vary, shifting the optimal solution. For instance, in a planning context that puts strong emphasis on greenhouse gas mitigation there may be a push toward greater urban area density, even at the expense of green spaces.

Third, when planners choose where to be along this trade-off curve between density and nature, it is important to keep in mind the issue of spatial scale. The distribution of green spaces within a city is also important. For any FUA at a given target density, there must be neighbourhoods and buildings that are greater than this density, often by orders of magnitude, to make up for areas within the FUA that are more sparsely settled or left as open space. An important consideration, in practice, then is who has closest access to urban nature, who might benefit most from it, and ultimately how equitable this is across society. These are city-level factors that must be considered by urban planners to ensure the best outcomes are achieved for both people and nature.

5 | DENSITY IS NOT DESTINY

By creative green interventions at the neighbourhood scale, one can avoid a strict trade-off between density and green space amount at the urbanized area or FUA level. The trade-off curves shown in Figures 3 and 4 are only the average relationship at the urbanized area level of analysis. There is significant variation around this mean at the level of neighbourhoods. For instance, Figure 5 shows the census block-level variation in urban tree canopy cover versus population density for one US city, San Francisco. At the US census block scale, while there is a statistically significant relationship between population density and urban tree canopy cover, the R^2 is only 0.05, implying that 95% of the variance in tree cover is not explained by density. The trade-off between population density and urban tree canopy cover at the US block-level is perhaps best thought of as variation in the range of possible urban tree canopy covers. At low densities (0–2000 people/km^2), the range of possible tree covers is quite wide, with observed values of 0% to above 85% urban tree canopy covers. Conversely, in very dense blocks (>10,000 people/km^2), blocks are observed with canopy covers ranging from 0% to 40%. While US block-level human population density does impose some constraints on the amount of tree canopy cover, there is a large window of possibilities. Similar arguments could be made for the relationship of other types of green spaces to density.

We assembled information on urban form, density, and green space for a few core FUAs (Figure 6). It is apparent that density is not destiny. Victoria-Gasteiz, for instance, has 1/7 the density of Barcelona but similar green space and tree canopy cover. There are also different patterns for green space and tree cover. Barcelona, for instance, which has the highest density of this small set of cities, has an urban tree canopy cover that exceeds that of London, the next most dense city. Washington, DC has the highest tree canopy cover of this sample of cities (43%), but significantly less green space than Vitoria-Gasteiz, a city of similar density.

Given the large variation in observed patterns of urban form, density, and green space, one question for those planning and designing at the neighbourhood scale thus becomes: How does one maximum the number of green spaces at a given density?

An examination of the outliers in Figure 5 is instructive. We define *brightspot* neighbourhoods as those that contain more green spaces given their density than at least three times the average tree canopy cover of other neighbourhoods of that density. Examination of brightspot neighbourhoods suggests there are two main pathways to creating a brightspot, which are not mutually exclusive.

First, brightspots often have a low built-area ratio for their population density. This can happen for a variety of reasons, and we discuss below specific interventions that can achieve this goal. But all

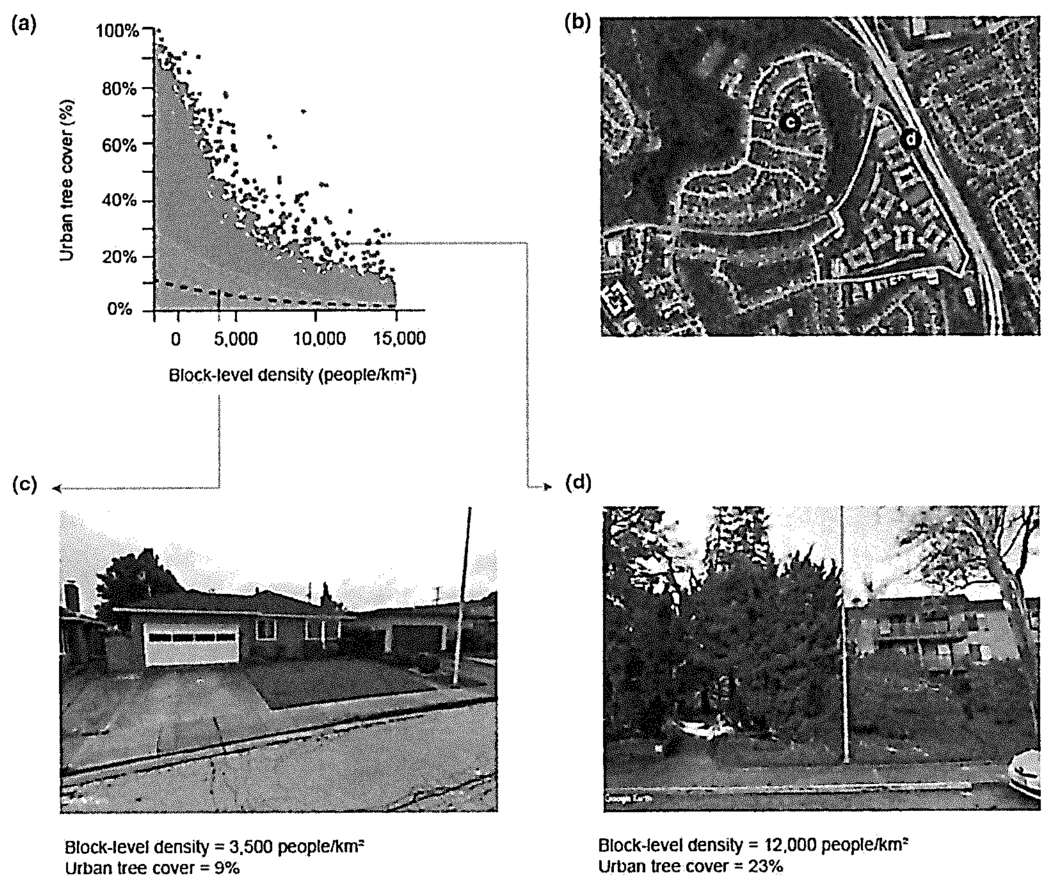

FIGURE 5 San Francisco urbanized area brightspots. (a) While urban tree cover is negatively correlated with population density, at the US Census block scale this correlation is weak. Of interest are brightspots, areas of relatively high density and urban tree canopy cover. Brightspots are shown in orange and are defined as blocks that have more than three times the urban tree canopy predicted given their density, using a log-linear regression. (b) An aerial photo of one brightspot (outlined in green, and labelled with 'd'), which lies next to a typical neighbourhood (labelled with 'c'). (c) Street view of typical neighbourhood. (d) Street view of brightspot.

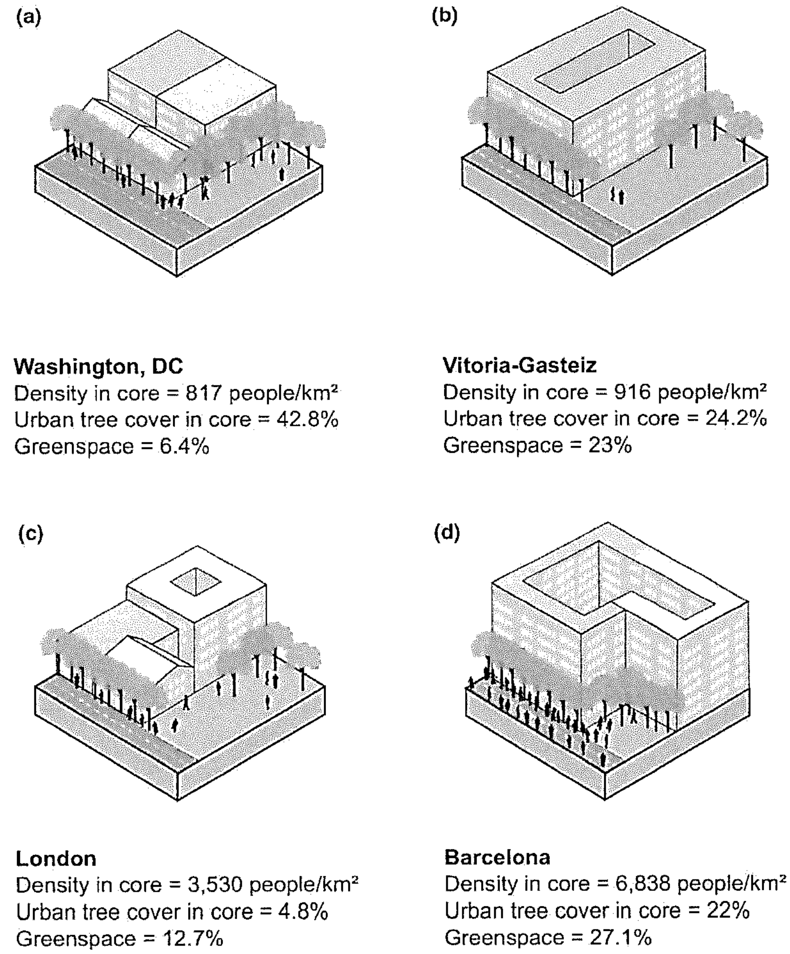

FIGURE 6 Global examples of different urban forms. Schematic drawings illustrating the urban form typical of a few cities, and the corresponding population density (core of functional urban area, FUA), percent greenspace (i.e. protected area), and percent tree canopy (core of FUA). Numerical data taken from OECD data (2021). These examples are not meant to be a statistically representative sample of cities, merely to illustrate a variety of urban forms and green space configurations.

else being equal, neighbourhoods with a lower built area ratio have more residential space for green spaces such as parks. Conversely, neighbourhoods with a higher built-up ratio use much of their land surface on human-dominated uses and have less space for nature. The first overarching pathway, therefore, to being a brightspot is to shrink the overall footprint of built-up area within a neighbourhood. Following the literature, we will call this the 'land sparing' strategy, since land must be spared from development to allow space for nature.

Second, brightspots sometimes incorporate green spaces that are on top of (or overhanging) built-up areas. Street trees for instance can be planted in a small strip of permeable surface but can substantially overhang pavement and other developed land. Green roofs are directly on top of a developed surface, by definition. This vertical stacking of nature on top of built-up area avoids a strict trade-off between more built-area-ratio (BAR) and more green spaces. Similarly, if for whatever reason there are vacant parcels that are undevelopable in the current neighbourhood context, restoring these to be green spaces does not compete with development for space. The second overarching pathway, therefore, is to maximize the sharing of space between nature and developed areas as much as possible. Following the literature, we call this the 'land sharing' strategy, since land is shared between nature and developed areas.

6 | URBAN FORM DETERMINES WHAT IS POSSIBLE AT THE NEIGHBOURHOOD AND PARCEL SCALES

One main reason for the large variation, at any given density, in US Census block-level tree canopy cover and open space is the variation in urban form. There are many different typologies and ways of measuring urban form (Redbridge Government, 2014). There is the *Intensity* of development, which can be measured by population density but also other measures such as floor-to-area ratio (FAR) or built-area-ratio (BAR). There is the *Scale* and *Grain* of development, such as the size of city blocks or buildings and the scale at which they recur. There are measurements of *Land use*, such as the relative proportion of residential versus commercial or industrial buildings at a site. *Transport* networks can take various shapes, and these shapes also play a crucial role in determining urban form.

One important dimension of *Land use* is building type(s). Again, this dimension can be classified in many ways, and we use a relatively simple terminology in this paper. Single-family detached homes use the most space per-capita of any building type but are commonly found in city suburbs and exurbs. Single-family attached homes (e.g. row houses) are a slightly denser pattern of residential settlement, often with characteristic small lawns and other open space immediately behind the row of buildings. Multi-unit apartment buildings have the greatest density and can be many stories tall in some cases. Multi-family buildings can take several forms (Per & Mozas, 2015): they can be point buildings, organized primarily around their vertical circulation with open space on all sides; they can be bar buildings, organized around a linear hallway on every floor; they can be towers (essentially point buildings above a certain height); or can be residential towers atop a multistory plinth that contains commercial or other uses. Commercial land-uses can similarly be found in large, multistory buildings, especially in the central business district, whereas industrial buildings tend to be massive flat single-story buildings or complexes of buildings.

Each of these building types can be arranged in a variety of urban forms. Zoning codes influence the way buildings on adjacent lots interact to form an urban block: when buildings are built such that similarly-sized abutting buildings enclose a shared set of open spaces in the block's interior, they may collectively form areas for green spaces around buildings (Bürklin & Peterek, 2017). Thus, for each of the building types there is a broad range of population densities and configurations that are possible. For instance, a single-family detached home with five residents could be placed on a large lot (e.g. $500\,m^2$) or a small lot (e.g. $150\,m^2$). These lot sizes imply a population density, at this parcel scale, of 100 people/ha and 333 people/ha, respectively, a difference of more than a factor of three. Commercial or industrial buildings do not have a direct link to residential population density, but the intensity of built form can be assessed in other ways such as FAR or BAR.

Of special importance in determining urban form and the residual space left for green spaces is the *Transport* network, and specifically the amount of road area. In older cities where the transport network was developed primarily to support walking or horse-drawn vehicles, the amount of road is relatively little. London, for instance, has on average 1.5 m of road per inhabitant (Dingil et al., 2018). Conversely, in cities that were designed with a large transport network, often created with the personal automobile in mind, this factor can be much larger. Atlanta, for example, has on average 8 m of road per resident (Dingil et al., 2018). Parking spaces for cars are also an important aspect of urban form. In many parcels, the inclusion of parking lots near multi-family apartments can consume a significant fraction of the parcel.

The *Intensity* of development, along with its *Scale* and *Grain* and the shape of the *Transport* network, determine the opportunities for green spaces that are independent of building typology—parks, riparian corridors and vacant lands. Such green spaces are possible to introduce in new districts but difficult to shoehorn into existing districts, simply because it is costly to remove buildings and transport infrastructure once constructed. Other green interventions such as green roofs are possible to add even within existing urban districts, both as retrofits to existing buildings and when doing new construction. Green roofs have additional benefits beyond biodiversity, including stormwater mitigation and energy efficiency (McDonald, 2015).

7 | INTERVENTIONS TO BECOME DENSE AND GREEN

In the previous section, we discussed the various urban forms, and how these forms shape the potentialities for green spaces in and near urban areas. We also began discussing a few green interventions that might add more green spaces to new and existing neighbourhoods. In this section, we more formally present a broader set of green interventions (Table 1), identified during our review of the literature on urban form and green spaces (Section 6). Key citations are included during the description of each green intervention below. The feasibility of each green intervention varies by the urban form typology presented in the previous section, with some green interventions only being possible for certain urban forms.

Below, we discuss each green intervention in turn, illustrating the use of green interventions with two contrasting case studies, Curitiba and Singapore. Both have been written about frequently in the planning literature (see citations below), but we wanted to suggest an interesting distinction between them. From Curitiba we highlight the use of green interventions that spare space for nature, in the sense that development opportunity is foregone on a site or neighbourhood to allow green spaces. From Singapore we highlight the use of green interventions that share space between people and nature, in the sense that these interventions increase green spaces without necessarily limiting the footprint of the developed area. While this dichotomy is useful for presenting the types of green interventions, we acknowledge that reality is considerably more complex, with both case study cities using a broad mix of the green interventions shown in Table 1.

7.1 | Curitiba: Innovative planning that spares space for nature

Curitiba is the largest city in southern Brazil. It is known for urban innovations that have been later adopted by other cities around the world, such as Bus Rapid Transit (BRT). The city has faced a dramatic urban growth since the 1970s, when the population was only 600,000, increasing to a population of approximately 2 million in 2020. Curitiba has a strong planning tradition with integration of land use with urban services, such as housing, green areas and especially transportation. The city has a radial growth along the arteries of Bus Rapid Transit (BRT) coupled with avenues.

Curitiba has well-integrated and functional green and blue urban infrastructure. The planning of Curitiba set aside land for natural parks ('Preserve remnant patches' and 'Create managed parks' strategy in Table 1), and as a result has 35 parks and more than 1000 conservation areas (Gustafsson & Kelly, 2016). The Curitiba urban plan aims at a gradual decline in density as you move away from the transportation arteries, but parks and other green areas cover a large part of the city with easy access through the efficient urban transportation system.

TABLE 1 Urban forms and green interventions

Green intervention	Single-family detached	Rowhouse	Multi-unit	Multi-unit over plinth	Industrial	Transport
Land sparing interventions (interventions generally take space from development)						
Preserve remnant patches	Low[a]	Low[a]	High	Medium	Medium	Medium
Maintain riparian corridors	Low[a]	Low[a]	High	Medium	Medium	Medium
Create managed parks	Low[a]	Low[a]	High	Medium	Medium[b]	Low
Build home gardens/backyards	High[c]	Medium[c]	Low	Low		
Create stormwater GI	High	High	Medium	Low	Medium	High[d]
Land sharing interventions (interventions do not generally take space from development)						
Greening vacant lands	High	Medium	Low	Low	Medium	
Instal green roofs/facades	Low[e]	Low[e]	Medium	Medium	High[f]	
Increase vegetation around perimeter	Low	Low	Medium	Low	Low	
Increase vegetation along streets/ROW						High

[a]Constrained by available space.
[b]Occasional opportunities to convert large industrial areas to parkland.
[c]Setbacks already set; available space gets smaller over time.
[d]Opportunity for widespread deployment; constrained by maintenance.
[e]Constrained by roof shape & structural limits of existing roofs.
[f]Typically large roof areas substantially increase potential benefits.

Within different urban forms, there are different green intervention types that are possible. This table shows a simple typology of urban forms (columns) crossed with a typology of possible green interventions (rows). The rating (high/medium/low) describes the degree to which that green intervention is possible with that urban typology class. Cells that are blank are where a green intervention is generally not possible or applicable within a typology class.

The city government has innovated and used green and blue infrastructure for other strategic functions, such as flood prevention, biodiversity protection, water quality conservation and carbon reduction. Public parks and lakes were planned along the rivers and lowlands ('Maintain riparian corridors' strategy in Table 2) which protect the city from risks of flooding during the heavy rains, common in many Brazilian cities during the rainy season. Curitiba has also created several incentives for greening private land. It has a system of Transferable Development Rights (TDRs) for protection of green areas in private land, besides social housing and heritage conservation. The TDRs make possible a good balance between density and green areas. The city also provides incentives for the creation of private natural heritage reserves (RPPN), and Curitiba is the city in Brazil with the largest number of RPPNs.

7.2 | Land sparing green interventions

For biodiversity preservation, maintaining remnant habitat patches over time is one key step (Table 1), especially for cities with sufficient governance capacity to plan and regulate land-use (Huang et al., 2018). This is especially true for urban avoider species, which may have been endemic to a particular locality and might be lost with the expansion of urban habitat (McDonald, M'Lisa Colbert, et al., 2018). Strategies to maintain remnant habitat patches (Table 2) can involve an outright ban on the conversion of nature habitat or implemented through zoning codes or development permitting regulations. Such a ban can be controversial politically, and more commonly, the public sector is involved in purchasing or setting aside land for public parks. For instance, in Curitiba, forest patches such as Bosque do Barigui (Lat −25.4167°, Long −49.3070°) were protected, providing relatively large patches of habitat within the urban fabric. Another way to finance land protection is through the sort of TDR system used in Curitiba, which discourages land conversion on some privately held land while compensating landowners through the creation of development rights with monetary value elsewhere.

Another important step for maintaining biodiversity is maintaining corridors of habitat in riparian areas (Table 1). These riparian areas are relatively high in biodiversity, often harbouring rare flora or fauna, and are long linear features that can be important for connectivity, for people and biodiversity. In many cities, various building and zoning codes prevent development near rivers (Table 2), while flood insurance programs theoretically make development in flood prone areas more expensive. These policies have the net effect of maintaining riparian habitat and reducing flood risk for people and property. Urban planners therefore often think of riparian corridors as linear features that can connect a row of parks or protected areas with walkways. For instance, Parque das Águas (Lat −25.4391°, Long −49.1464°) and other parks form a chain along the Iguaçu River in Curitiba, maintaining this river corridor and avoiding development in a flood prone area.

Another type of green intervention is to plan for and create parks and other green spaces, even on land that has been cleared and no longer maintains remnant habitat (Table 1). In many cities, setting

TABLE 2 Policies to support green interventions

Green intervention	Site-level policies	City-level policies	Main variables to improve ecosystem function
Land sparing interventions			
Preserve remnant patches	Zoning rules that discourage habitat conversion	Protect habitat in open spaces; tradable development rights.	• Patch size • Habitat quality • Invasive species suppression • Habitat heterogeneity
Maintain riparian corridors	Setback rules to protect riparian areas; building restrictions in floodplains	Protect/restore habitat along river corridors; urban planning to maintain connectivity of riparian corridors	• Width • Connectivity • Natural banks rather than channelized • Water quality
Create managed parks	Requirement for developers to set aside land for public parks	Urban planning to create public park network throughout city	• Park size • Vegetation type + structure • Intensity of human use + management
Build home gardens/ backyards	Green area fraction or other similar rules that require some portion of parcels to be green	Tree canopy protection ordinances; Programs to promote native plant plantings and high biodiversity gardens.	• Reduction of pesticide/herbicide application • Proportion of native planting • Addition of structural complexity (tree/shrub planting) • Reduction of organic matter removal
Create stormwater GI	Zoning and building rules that require stormwater capture onsite for new development or redevelopment	Impervious surface fees; municipal rain-garden programs	• Scale of implementation • Vegetation type • Proportion of native planting • Structural complexity
Land sharing interventions			
Greening vacant lands	Zoning and building codes that easily allow vacant/ underutilized lots to be converted to green areas	Public sector funds or private-sector incentives to green vacant lots	• Patch size • Soil type + compaction • Vegetation type + structure • Successional stage
Instal green roofs/facades	Building codes that allow greater density with green features; green area fraction rules.	Public sector funding for the creation of green roofs	• Soil depth (Intensive rather than extensive) • Soil type (influences nesting, stormwater mitigation) • Soil topography (influences habitat, heterogeneity) • Addition of structural complexity (grasses, forbs) • Proportion of native planting, mutualisms

TABLE 2 (Continued)

Green intervention	Site-level policies	City-level policies	Main variables to improve ecosystem function
Increase vegetation around perimeter	Building rules that require vegetation in setbacks and other required perimeter areas around a building; green area fraction	Programs to promote native plant plantings and high biodiversity gardens.	• Reduction of pesticide/herbicide application • Proportion of native planting • Addition of structural complexity (tree/shrub planting) • Reduction of organic matter removal
Increase vegetation along streets/ROW	Programs/incentives to encourage citizen maintenance of vegetation in front of their homes	Municipal tree planting and maintenance programs	• Proportion of native planting • Design of tree pit • Longevity of trees • Degree of replacement upon mortality

This table shows possible policies to promote green interventions, at the site-scale or city-level scale. Note that these are just a selection of some of the most common policies, there are other possible policy routes to achieve the same outcome. Also shown are the main variables that can modulate the biodiversity and ecosystem function of the green intervention.

aside land for a park is a requirement when new neighbourhoods are proposed by developers (Table 2). Similarly, urban planners when creating a new district plan often include space for a park as a matter of best practice. Parks often contain distinct features that reflect the culture and context in which they are located. For example, Curitiba has Praça Osório (Lat −25.4331°, Long −49.2761°) and other plazas, often centered around a pedestrian area or fountain but ringed with trees and other natural features, a common way of constructing plazas in Brazil.

In many cities a large fraction of open space is private, and so the creation of home gardens and backyards on private land is an important way to provide green spaces to individual households (Table 1). This is especially true in suburbs or exurbs at low population density (Figure 3), when the majority of open space may be private. Many cities encourage the creation of gardens and backyards, intentionally or not, by limiting the BAR or FAR on the development of new parcels (Table 2). This forces a lower density pattern of settlement, which often allows more space for gardens and backyards. More directly, some cities have begun setting zoning and building codes around a 'green area fraction', a proportion of a parcel that must be green (including backyards and gardens, but also typically including green roofs). At a municipal level, many cities have tree and other vegetation protection ordinances, which make the clearing of these green spaces more difficult for developers. For instance, Curitiba and many other cities require permits from the city for removal of large, existing trees.

Finally, cities increasingly create stormwater green infrastructure (GI), green spaces that have as one of their primary purposes to encourage rainwater to infiltrate into the soil and thus mitigating the quantity or quality of surface stormwater runoff (Table 1). Stormwater GI may be a part of remnant patches, riparian corridors, or parks. In Curitiba, for instance, many of the protected areas are along riparian corridors, and serve a purpose of helping manage stormwater. Alternatively, it may be in small, constructed wetlands designed primarily to detain stormwater, sometimes in the public right of way such as in sidewalk berms and sometimes in backyards. Construction of such stormwater GI may be required by zoning or building rules or incentivized by the creation of an impervious surface fee or other financial incentives to increase landscape permeability (Table 2).

7.3 | Singapore: A dense city that shares space with nature

The Island City-state of Singapore has long been referred to as a Garden City. Today, Singapore stands out as an example of a high-density city with a focus on green space creation and maintenance. Singapore's current population of 5.5 million occupies a land area of 710 km^2 (essentially the entire island is a part of the FUA), resulting in a density of around 7800 persons/km^2. An estimated 47% of the island nation is in green cover, a percentage that has risen while population growth has increased.

Singapore has invested in nature in many ways and through many different initiatives, including 350 parks and 4 nature reserves; a program for converting engineered hard-surface streams into habitat-rich natural systems (an example of the 'Greening vacant lands' strategy in Table 1), the most notable example being Bishan-Ang Mo Kio Park (Lat 1.364°, Long 103.8441°); extensive tree planting and public landscaping throughout the city ('Increase vegetation along streets/ROW' strategy in Table 1); more than 360 km of pathways and trails in its Park Connector Network; more than 300 km in its Natureways network of wildlife corridors; and more than 1600 community gardens through its Community in Bloom program. A recently adopted Green Plan 2030 lays out ambitious plans and targets for the future, including new therapeutic gardens and a million tree-planning goal, among others (Choo, 2017).

Singapore has been especially noted for its innovations in vertical greenery, as most new growth and development in the city happens through high-rise towers. Through its Landscaping for Urban Spaces and High-Rises (LUSH) program, new buildings must replace ground-level nature with nature in the vertical spaces above. Many high-rise buildings commonly include sky parks, greenwalls and rooftop gardens and trees ('Install green roofs/facades' in Table 1). Under its landscape replacement policy developers must at least replace the nature one-for-one, but increasingly new green buildings in the city are including much more than that. Recent examples include the ParkRoyal Hotel (Lat 1.2858°, Long 103.8461°), providing 200% replacement nature, and the Oasia Downtown Hotel (Lat 1.2759°, Long 103.8442°), which replaces ground level nature by some 1200%, including through a living facade that boasts 14 varieties of flowering vines. Singapore NParks has a Skyrise Greenery division to support vertical greening. There are financial subsidies and annual Skyrise Greenery Awards to recognize design innovation and industry leaders.

7.4 | Land sharing green interventions

Often cities have lands that are underutilized and that can be converted into a green space without directly competing with development (Table 1). This kind of vacant land is not common in a densely settled city like Singapore, although the restoration of streams that were previously lined with concrete like in Bishan-Ang Mo Kio Park is one example. Another example in Singapore is reclaimed land, which may be allowed to naturally reforest for several decades even if it is ultimately slated for development for housing (Gaw & Richards, 2021). In many shrinking or deindustrialized cities like Detroit, there is more vacant land that can be reused. In these cities, there are often public sector funds and incentives for the private sector to green vacant lots, as well as changes to the zoning and building codes that make creative reuse of previously developed sites possible (Table 2).

Green roofs and facades are a straightforward example of sharing space between human development and green spaces, in the sense that a square meter of green roof or green facade does not reduce developable area in a city (Table 1). Singapore has a strong system of incentives for creating green roofs, using a combination of regulatory mandates as well as public sector financing. Some cities use the zoning and building code to create value in green roofs, rather than using public sector financing (Table 2). For instance, in Chicago developers that construct a building with a green roof get an increase in the FAR allowed by regulations, increasing the amount of developable space and providing a real monetary benefit to developers, which often outweighs the cost of green roof construction.

Another example of sharing space between human development and green spaces is the maximization of vegetation around the perimeter of buildings and other developed features on a parcel (Table 1). Taken to an extreme, building and zoning codes that require large setbacks and create large perimeter spaces may decrease developable space, but even in dense urban areas there tend to be perimeter spaces that can become green spaces that provide significant benefits to those living in and using a building. Cities often require building perimeters to be properly landscaped or set requirements for the green area fraction required when developing a parcel (Table 2). Municipal programs, or those of non-profit groups, can seek to promote native plantings and increase the biodiversity value of these perimeter areas.

One of the most important ways to increase green spaces in a city is to increase vegetation along streets and other parts of the public right of way (Table 1). This is particularly important for urban tree canopy cover, which can overhang over impervious surfaces like concrete and pavement, leading to a straightforward example of sharing space between human development and green spaces. This shading of impervious surfaces by trees also has important benefits for reducing the urban heat island effect and helping mitigate the flow of stormwater into stormwater systems. A substantial fraction of the area of a city can be in the public right of way of the Transport system. For instance, Manhattan in New York City has around 36% of its area in the public right of way, and an UN-Habitat report suggests new neighbourhoods have at least 30% of their area in the public right of way to ensure adequate transport (UN-Habitat, 2013). As this land is already publicly owned, it represents an enormous opportunity for green spaces, if they can be made consistent with the other transportation needs of the right of way. In most cities, tree planting in the right of way is the responsibility of the public sector (Table 2). For instance, in Singapore there is now a goal of planting an additional 1 million trees, many (but not all) along roads. The maintenance of tree canopy cover, however, varies, with some cities placing this under municipal control, while others try to enlist volunteer nearby private landowners to help maintain trees in the public right of way.

8 | TOWARD A DENSER AND GREENER URBAN FUTURE

Our research found evidence, both in the literature and in empirical data for the United States and the OECD, of a negative association between human urban population density and the number of green spaces. This negative association with density appears to occur for urban tree canopy cover as well as (for the US) open space. The association is at moderate strength at the FUA or urbanized area scale but is relatively weak at the US Census block (neighbourhood) scale. We emphasize therefore that this association is not a strict trade-off at the neighbourhood scale, and there are neighbourhoods that contain more or less nature for a given population density.

There are countervailing relationships that one could use to argue for or against urban population density. Urban planners must of course consider the unique local goals and context when evaluating the appropriate target population density for a project. Different local goals or preferences might lead to different selected target population densities. Finally, significant variation in density at the neighbourhood scale leaves many opportunities for green spaces even in urbanized areas with relatively high urbanized-area population density.

We listed in this paper multiple green interventions, ways to create neighbourhoods that are dense and green. These are proven interventions, implemented in multiple places around the world. The interventions that are applicable in each neighbourhood or parcel depends on the urban form as well as the political, social and economic context. Planners and policymakers can choose which specific green interventions make sense, given that local context (Mansur et al., 2022). There is also significant scope for new, yet undiscovered innovations that could promote both biodiversity and human outcomes. In a sense, there can be no excuse for designing neighbourhoods that lack abundant nature: the tools are out there to create dense and green spaces to live in.

Nevertheless, many urban areas are not achieving this potential. For instance, one global study suggested only 13% of urban dwellers have enough urban tree canopy near their homes to achieve mental health benefits (McDonald, Beatley, et al., 2018). This relatively low amount of urban nature persists despite a global trend toward less dense urban areas since the 1970s (Güneralp et al., 2020). Given the clear importance of urban density toward sustainability and reducing greenhouse gas emissions, this is a worrying trend. There is thus an urgent need for cities to create urban neighbourhoods that are both dense and green. Indeed, encouraging data from Denmark show it is possible for cities to increase both in density and greenness over time, with the right urban planning policies (Samuelsson et al., 2020). Humanity is building the urban neighbourhoods of the future, today. As a species, we will choose the future urban world we get. Another urban world, both verdant and lively and dense, is possible, if we choose to take advantage of the available green interventions and create it.

AUTHOR CONTRIBUTIONS

Robert I. McDonald, Erica Spotswood and Erin Beller conceived of the project, and organized a working group of all co-authors; Robert I. McDonald and Erica Spotswood led the project; Myla F.J. Aronson and Nicholas Pevzner created Tables 1 and 2; Timothy Beatley and José Antonio Puppim de Oliveira created case studies of Singapore and Curitiba, respectively; Lauren Stoneburner and Stephanie Panlasigui analysed data in Figures 4 and 5; Micaela Bazo and Joe Burg designed the figures; and all co-authors participated in the writing of the manuscript.

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CONFLICT OF INTEREST

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DATA AVAILABILITY STATEMENT

All data shown in this paper are derived from previously published datasets, as listed in the methodology. Copies of all derived datasets we used in our analysis can be found on Dryad Digital Repository https://doi.org/10.5061/dryad.s4mw6m99g.

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RESEARCH Open Access

Homicide rates are spatially associated with built environment and socio-economic factors: a study in the neighbourhoods of Toronto, Canada

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Abstract

Objectives: Homicide rate is associated with a large variety of factors and therefore unevenly distributed over time and space. This study aims to explore homicide patterns and their spatial associations with different socioeconomic and built-environment conditions in 140 neighbourhoods of the city of Toronto, Canada.

Methods: A homicide dataset covering the years 2012 to 2021 and neighbourhood-based indicators were analysed using spatial techniques such as Kernel Density Estimation, Global/Local Moran's *I* and Kulldorff's SatScan spatio-temporal methodology. Geographically weighted regression (GWR) and multi-scale GWR (MGWR) were used to analyse the spatially varying correlations between the homicide rate and independent variables. The latter was particularly suitable for manifested spatial variations between explanatory variables and the homicide rate and it also identified spatial non-stationarities in this connection.

Results: The adjusted R^2 of the MGWR was 0.53, representing a 4.35 and 3.74% increase from that in the linear regression and GWR models, respectively. Spatial and spatio-temporal high-risk areas were found to be significantly clustered in downtown and the north-western parts of the city. Some variables (e.g., the population density, material deprivation, the density of commercial establishments and the density of large buildings) were significantly associated with the homicide rate in different spatial ways.

Conclusion: The findings of this study showed that homicide rates were clustered over time and space in certain areas of the city. Socioeconomic and the built environment characteristics of some neighbourhoods were found to be associated with high homicide rates but these factors were different for each neighbourhood.

Keywords: Spatio-temporal analysis, Homicide, Socio-economic, Built environment, Toronto, Canada

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Introduction

Homicide is a global public health issue [1]. The rates of homicide, one of the most severe types of violent crime, are considered around the world as a benchmark to assess the level of violent activity [1–3]. For example, Canada's homicide rate increased from 1.83 per 100,000 population in 2019 to 1.95 per 100,000 population in 2020, which indicates a 7% increase of violence for that year [4]. The metropolitan city of Toronto, located in southern Ontario, Canada, is rapidly approaching the status of megacity [5]. The levels of violent crime and homicide are both high in many of Toronto's neighbourhoods [6, 7]. Its police service [8] has reported that the annual number of homicides in the city increased from 57 in 2012 to 84 in 2021, with 105 homicides in 2020; the metropolitan area had the highest homicide level in Canada [9, 10]. As security is an important component of achieving sustainable and healthy cities [11, 12], high crime rates amount to a strong threat to the health of local communities [13–16]. In fact, no city can be regarded as sustainable and healthy if the occupants in their neighbourhoods lack safety [17].

The association between violent crime and communities has long been a focal point of criminological and sociological investigation [18]. High violent crime rates in cities are associated with various individual, socio-economic and environmental factors [19, 20]. The areas with less educated people are associated with more 'criminogenic' compared to those with higher education; specifically, areas with a low rate of people with high-school diplomas are more likely to also have many formerly incarcerated people [21, 22]. Other individual factors associated with the occurrence of violent crimes are age and gender [23]. Individuals in the 15 to 30 years age group, males in particular, run a higher risk of being involved in violent crimes [24, 25]. Socio-economic and environmental factors add to space-time clusters of violent crimes, such as homicide incidents, in urban areas that often are unevenly distributed over space and time [26–28]. Characteristics of urban neighbourhoods environment may associate with some of these spatial variations [29]; hence identifying factors that correlate with more crime in urban neighbourhoods is a central focus of this research [7, 21, 23, 24, 30, 31]. For example, socioeconomic and demographic characteristics, such as poverty, residential mobility and ethnic heterogeneity within a neighbourhood, are strongly associated with above average levels of violent crimes and urban security [15, 32, 33]. According to social disorganization theory [34], the occurrence of crime is correlated with socio-economic and demographic variables indicating lack of cohesion, e.g., family disruption [30, 35]. For example, a neighbourhood with proportionally more poor, unemployed and low-income residents is more likely to have a higher crime rate than other neighbourhoods [36, 37]. Some studies confirm a significant correlation between median household income inequality and rental housing rate on the one hand and the rate of violent crimes on the other [32, 37]. According to Lens [38], the general incidence of violent crimes among tenant households is higher than that among homeowners, and the results of Lam's research in Toronto [39] show that homicide among minorities and new immigrants is higher than that in the majority groups. Other research has identified population density and economic activity as associated factors with high crime rates in some urban neighbourhoods [40]. Further, studies have found that built-environment characteristics, such as commercial establishments, sports places, places of interest, poor housing situations (large poorly designed buildings) and road intersections, are associated with increased homicide rates in urban areas [41–45].For example, in New York City most homicides occur in areas where many neighbourhoods intersect [44]. Further, the concentration of secondary schools in particular areas has been reported as one of many important factors correlating with increased rates of violent crime [19, 46–48].

This study pursued two main objectives. First, it attempted to identify and analyse spatial and temporal patterns of homicide rates in Toronto during 2012-2021 at the level of 140 Toronto neighbourhoods. Second, it focused on exploring the correlation(s) between the level of homicide rates on the one hand and economic, social and built environment factors on the other.

Methodological literature review

In recent years, the fields of crime analysis, crime mapping, and environmental criminology have grown in prominence [49–52]. As a result, numerous analytical studies have been conducted with regard to various types of crimes [53, 54]. For years, spatial analysis of homicide rates has also come to the attention of crime analysts [55]. In this study, we focused on research on homicides in recent years, examining the spatial aspects of homicides in association with specific social economic and built environmental circumstances.

Graifand Sampson [56], studied the association between immigration and diversity with the homicide rate in Chicago using geographically weighted regression (GWR). They found that the association of neighbourhood characteristics with the homicide rate varied across the city, indicating a process of "spatial heterogeneity" and that immigrant concentration is either unrelated or inversely related to homicide. The GWR is commonly used to determine the spatial association among explanatory variables. Thompson & Gartner [7] used ordinary least squares (OLS) methodology and negative binomial models to explore the association between neighbourhood characteristics and homicide rates in the city of Toronto finding higher rates of violent crime and homicides in neighbourhoods where the ratios of youth and black people were higher and where the average household incomes were lower. The OLS method was used to find the best linear fit among socio-economic factors and homicide rates; however, as the explanatory factors manifested spatial variations among different neighbourhoods, the researchers suggested using a GWR model to take into account the spatial phenomena in future research [7]. A Brazilian study [57] reported higher homicide rates in communities where the majority were poor blacks with low life expectancy; using the generalized incremental regression model based on time series analysis and spatio-temporal approach they revealed an increase in homicide rate from 2000 to 2016 in the black society. Wang & Williams [30] analysed violent crimes in Toronto's 140 neighbourhoods considering the individual factors of offenders and four dimensions of the Ontario-Marginalization Index using OLS and GWR models, showing that violent crimes were clustered in the central areas of the city. Instability and deprivation indices were used to associate with high rates of homicides in high-risk neighbourhoods. Ingram & Marchesini [58], in their analysis of homicide in Brazilian cities using geographical information system (GIS) and crime mapping, concluded that homicide occurred mainly in poor and overcrowded neighbourhoods with high unemployment rates and poor housing conditions. They also found that violent crime rates were high in neighbourhoods with high ethnic and minority diversity. The GWR-SL approach provided a framework to add unpredictable spatial interference variables to spatial variables [58].

A study in Kentucky, USA, examined the homicides rates at the county level and showed that homicide rates were higher in areas with high alcohol sales. The multilevel logistic regression was performed using clustered and non-clustered homicide areas as the binomial dependent variable; however, if the researchers had used the GWR method, the spatial association between homicide rates and independent variables would have been obtained [59]. Another study based on GIS and spatial analysis [60] showed that violent crimes and homicide rates were higher in areas where secondary schools and sport places were concentrated. Due to the scattering and excessive fragmentation of data, the negative binomial regression method was used to investigate the spatial association between homicide rates and the explanatory variables [60]. In a similar study conducted by de Miranda & de Figueiredo [43], homicide rates were higher in neighbourhoods where crowded and large buildings were concentrated and where most residents were tenants. The spatial autocorrelation methods, including hotspot analysis and Local Moran's I were used to identify the area where both homicide rate and at least one explanatory variable formed hotspots. Onifade [61], studied the associations between green-space areas and street crimes in Toronto concluding that violent crimes were more prevalent in areas where the density of road intersection was higher. The spatially weighted regression used in the study helped the researchers model the space-affected associations to obtain reliable results. South et al. [62], performed GWR to examine the association between structural housing repairs for low-income homeowners with neighbourhood crime in Philadelphia City, PA, USA. Here, major repair rates in low-income households were significantly associated with higher homicide and violent crime rates echoing the results of a Brazilian study using a spatial autocorrelation method conducted in João Pessoa/Paraíba [63] where the spatial patterns of intentional homicides were shown to be higher in poor districts compared to others.

Most previous studies have attempted to examine the association between homicide incidents and a specific type of variable, such as individual [7, 21, 31, 58], socio-demography [24, 30, 35, 40], economy [30, 36, 37] or built environment [43, 60, 61], separately. However, given the number of indicators available, the present study represents an attempt to assess the association between the all the different socioeconomic and built environment factors on the one hand and homicides on the other. This was done, since we feel that a comprehensive analysis of the role of each indicator can be determined more accurately by considering a large number of potential factors together. Furthermore, in terms of analytical approach, previous research studied homicide from a purely spatial aspect [6, 7, 19, 28, 30, 64] or a purely temporal one [27, 35, 39]. In this study, homicide data have been analysed from temporal, spatial and spatio-temporal point of view. The fundamental hypothesis is that the 'where and when' crimes are committed are not random but follow a clustered pattern [65, 66] concentrated on a small proportion of places [67]. Therefore, GIS provides a powerful tool to identify existing patterns of crimes and their spatio-temporal patterns (high-risk areas), something which is essential for the development of strategies for reducing crime [68–72]. It also assists criminal justice in improving law enforcement and implementing social and economic measures to reduce and prevent various types of crime [64, 73, 74]. Finally, previous studies rely more on traditional statistical analysis such as regression analysis [37, 40, 69] and only a few studies examined local variations or spatio-temporal patterns of homicides using location-integrated statistical analysis such as multiple GWR (MGWR) and Kulldorff's space-time methodologies. The literature has acknowledged the neighbourhood as an appropriate scale for spatial analysis of crime incidents and useful for the determination of the association between crime rates and socio-economic and built-environmental variables [30, 47, 48, 75].

Research methodology

Study area

Toronto, the capital of Ontario Province, is a major Canadian city along Lake Ontario's north-western shore. The city covers an area of 630 km^2 (243 mi^2) and its population in 2020 was about 2,820,000 people with a density of 4,476 people per/km^2 [76]. Toronto has 44 wards, 140 social planning neighbourhoods [77] and 29 police service divisions [78]. Figure 1 shows the homicide incidents by type between 2012-2021 in the city in relation to its spatial divisions. Further, the population density per km^2 at the neighbourhood scale, i.e. the level at which our research was carried out.

Datasets and selection of variables

In a first step, a literature search identified 25 indicators related to socioeconomic characteristics and the built environment (Table 1). Pearson's correlation was used to

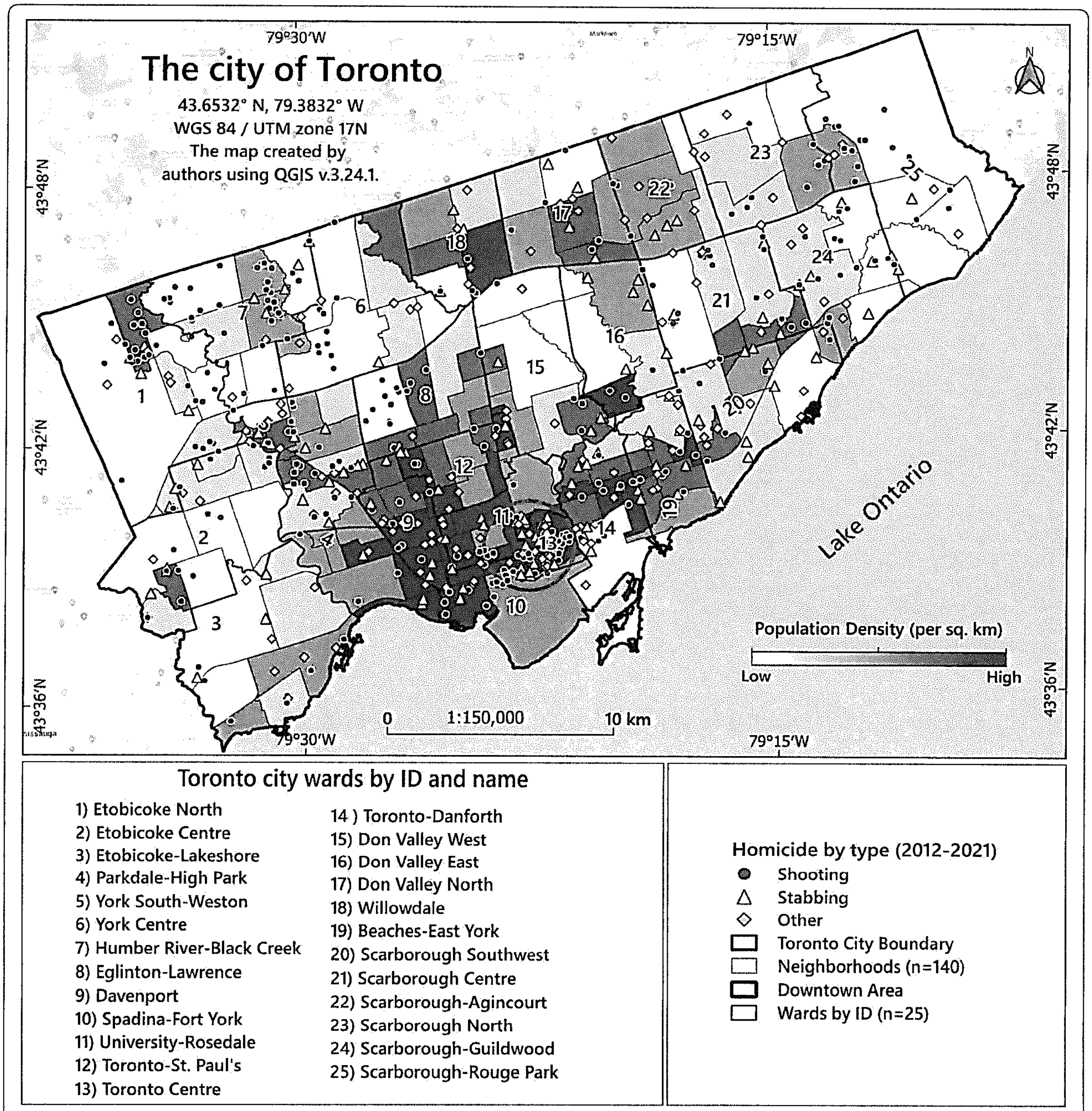

Fig. 1 Geographic location of homicide incidents and population density in Toronto

Table 1 Built environmental and socio-economic factors used to explore association between homicide rate and neighbourhood characteristics in Toronto 2012-2021

Dimension	Indicator	Description	Rationale	Status	Data source(s)
Socio-economic (N = 15)	V1: Population density	Dividing the total number of people by the total land area (km^2)	Population density can be associated with high rates of violent crime in urban areas [40]	5	1
	V2: Average household income	Average after-tax income of households ($)	Low income and income poverty can play an important role in the occurrence of violent behaviour and crime [37]	3	1
	V3: Unemployment rate	Unemployed population/total population in the labour force aged 15 years and over × 100	There is an association between unemployment rates and the occurrence of violent behaviour, such as homicide [36]	4	1
	V4: Rate of adults lacking tertiary education	Population lacking tertiary education/total population aged 15 years and over × 100	Lack of tertiary education can associate with many crimes, including violent ones and homicide [31]	2	1
	V5: Visible minority rate	Total visible minority population/total population × 100	Some studies [7, 39] have shown that violent crimes rates are higher among ethnic and racial minorities	3	1
	V6: Sex ratio	Total number of males/total number of females × 100	Evolutionary behavioural models suggest that when the sex ratio is high (more available men than women), violence against women is more likely to occur [81]	4	1
	V7: Residential instability	This measure refers to area-level concentrations of people who experience high rates of family or housing instability, weighted average residential instability score - higher values mean more instability	Social disorganization theorists argue that residential instability can associate with the local violence crime rate by disrupting residential networks that are protective factors against crime [18]	2	2
	V8: Material deprivation	Material deprivation is closely connected to poverty and it refers to inability for individuals and communities to access and attain basic material needs. The indicators included in this dimension measure quality of housing, educational attainment and family structure characteristics [82]. Weighted average residential instability score – higher values mean more instability	Some studies have shown that homicide rates were higher in urban areas with higher material deprivation [83]	5	2
	V9: Ethnic concentration	Proportion of the population who self-identify as a visible minority, weighted average material deprivation score – higher values mean more deprivation	Some studies revealed that ethnic concentration exhibits a significantly positive but spatially different association with violent crime rates [30]	2	2
	V10: Dependency ratio	Dependency ratio (total population 0-14 and 65+ / total population 15 to 64), weighted average dependency score – higher values mean more dependency	Some studies have shown that in urban areas with high dependency rates, violent crime rates are also high [84, 85]	1	2
	V11: Mobility status	Mobility status 5 years ago – 25% sample data= total movers/total population × 100	High rates of geographic mobility (movement over time), High rates of geographical displacement in urban neighborhoods, while disrupting social organization, increase the possibility of crime [86, 87]	1	1
	V12: Youth rate	Youth 15-34 years old/total population × 100	Some studies have shown that crime rates are higher than normal when the youth proportion in the population is high [23]; youth commit more crimes in easily accessible places and where there is less social control [7, 47, 48]	3	1
	V13; Rate of rented homes	Total number of renter households/total number of private households × 100	The highest crime rates are in neighbour-hoods where a significant portion of all homes are rented [32]	3	1
	V14: Rate of homes needing major repairs	The number of private households whose dwellings are in need of major repairs/total number of private households × 100	Urban decay and deterioration of buildings can turn neighbourhoods into areas where crime commonly occurs [62, 88]	3	1

Table 1 (continued)

Dimension	Indicator	Description	Rationale	Status	Data source(s)
	V15: Unsuitable house rate	Total number of private households who are living in unsuitable accommodations /Total number of private households × 100	Poor housing condition is a potential risk factor for crimes and may be associated with areas with higher crime rates [89]	3	2
Built-environment (N = 10)	V16: Property units	The total number of property units/total land area (km2)	As confirmed by some studies, the classic argument is that urban high density areas offers opportunities for violent crimes [90, 91]	3	3
	V17: Commercial establishments	The total number of commercial places/total land area (km^2)	The rate of violent crimes, especially property theft, is higher in commercial spaces than in other spaces and may associate with homicide [41]	5	3
	V18: Sport places	The total number of sport places/total land area (km^2)	Some studies [42, 47, 48] have shown that rates of violent crimes, especially those committed by young people, are high in public areas and sports places	1	2
	V19: Places of interest	The total number of places of interest/total land area (km^2)	Recreational and interesting spaces may be a target for thieves due to overcrowding and disputes may lead to violence [61, 92].	3	3
	V20: Intersections	Dividing the total number of road intersections by total land area (km^2)	Intersections provide opportunities for death by shooting, intentional car crashes or during escapes from crime scenes [44]	3	3
	V21: Public secondary schools	The total number of public secondary school locations/total land area (km^2)	Schools are often examined in relation to delinquent behaviour [46, 93, 94] and this environment may protect youths at risk of delinquency [47]	3	3
	V22: Large buildings	The total number of buildings that includes >5 independent homes/total land area (km^2)	Large, crowded buildings are more prone to all kinds of crime and violence [43, 95]	5	3
	V23: Parking lots	The total number of parking lots/total land area (km2)	Some studies have shown that the incidence of violent crimes, such as homicide, is higher in certain places such as parking lots [96]	2	3
	V24: Subway stations	The total number of subway stations/total land area (km2)	According to surveys, crime rates are high near subway stations [97]. High crowds at subway stations have the potential to lead to violent crimes such as robbery that lead to homicide [98]	1	3
	V25: Public parks	The total number of municipality public parks/total land area (km2)	Some studies have reported high rates of violence and violent crime in public parks [99, 100]	1	3

WT Wellbeing Toronto, *V* Variable

Status in this study: 1= Excluded by Pearson correlation; 2=Excluded by the first exploratory regression analysis, 3=Excluded by the second exploratory regression analysis, 4= Excluded by the OLS model, 5= Used in final model (GWR and MGWR)

Data source(s): 1=Wellbeing Toronto (http://toronto.ca/wellbeing); 2=Ontario Marginalization Index (ON-Marg), http://www.ontariohealthprofiles.ca/onmargON.php; 3=The City of Toronto's Open Data Portal (https://www.open.toronto.ca) identify associated variables with homicide rates at the neighbourhood scale; five (dependency ratio, subway stations, sport places, public parks and mobility status) of the 25 variables did not significantly associate with the homicide rate and were removed from the rest of analyses (Supplementary File 1). Then, the exploratory regression analysis was conducted to remove the variables that had collinearity with each other, resulting in removing four variables (ethnic concentration, parking lots, rate of adults lacking tertiary education and residential instability) of the 20 remained variables with VIF bigger than 7.5 (Supplementary File 2). The exploratory regression model was run again with the remaining 16 variables as input, with the best model based on six variables (unemployment rate, population density, material deprivation, sex ratio, commercial establishments and large buildings) selected for the OLS regression (Supplementary File 3). Four variables (population density, material deprivation, commercial establishments and large buildings) remained for the geographical regression analysis (Supplementary File 4). Figure 2 shows the complete, methodological framework used in this study. Model implementation was thus carried out with only four independent variables, leaving three datasets to spatially analyse and explore the association between homicide rates and neighbourhood characteristics as follows:

1. The homicide dataset, containing 701 homicides recorded by Toronto Police Services (TPS) between 2012 and 2021, was extracted as geocoded points in a GIS shapefile [8]. It included the total number of homicides, killing locations, occurrence dates and type of homicide (shooting, stabbing etc.). These point data were aggregated to the neighbourhood polygon layer and used for analysis.
2. The socio-economic characteristics (Table 1) of 140 Toronto neighbourhoods were derived from the Toronto City government open data portal [79] and Ontario Marginalization Index (ON-Marg) (http://www.ontariohealthprofiles.ca). The population for the last Census of the study period (2016) was used to calculate the homicide rate. Since the socio-economic and built environment factors of neighbourhoods were presumed to become associated with crimes in the long term, the 2016 Toronto Census data and neighbourhood profiles were used as basis for selecting the independent variables [79, 80].
3. The built-environment indicators (Table 1) were extracted from the Toronto City government portal. Due to the importance of determining an accurate location of different places and built-environment features for spatial analysis, we calculated the spatial density per/km^2 (based on the number of dwellings in each building) in each of these places (Table 1). This indicator allowed us to more accurately identify the areas of the city where large buildings are located. Figure 3 presents the spatial distribution and values (low to high) of each of the variables

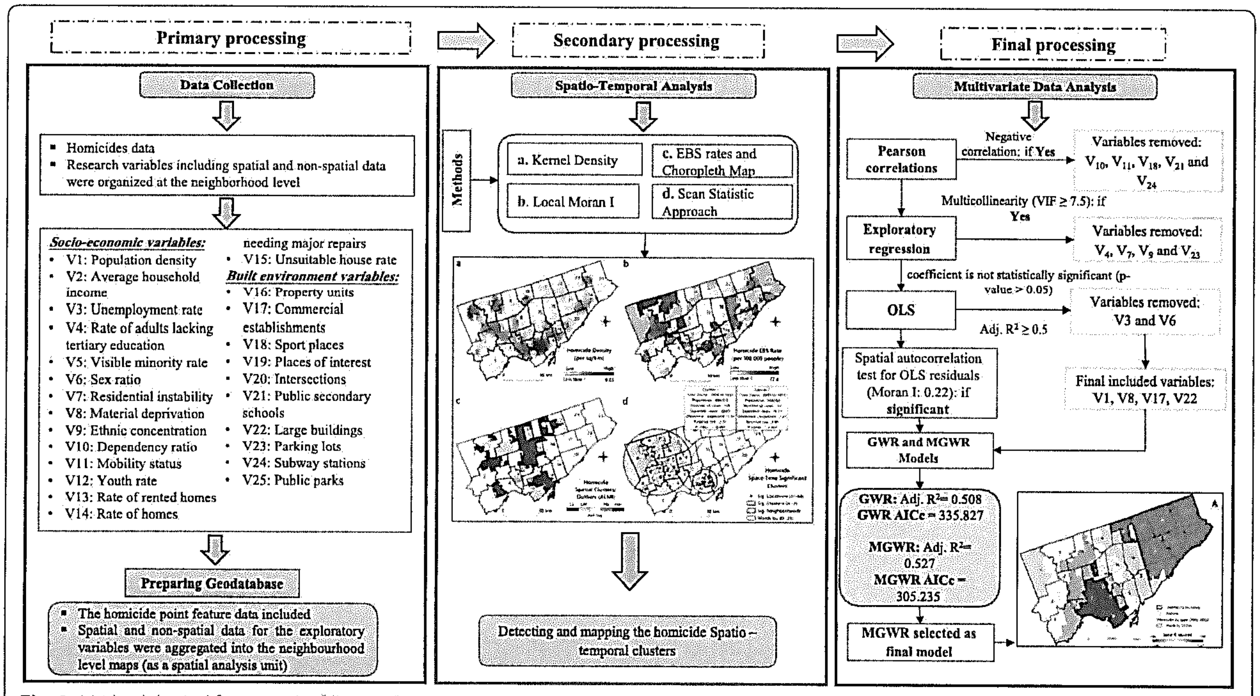

Fig. 2 Methodological framework of this study

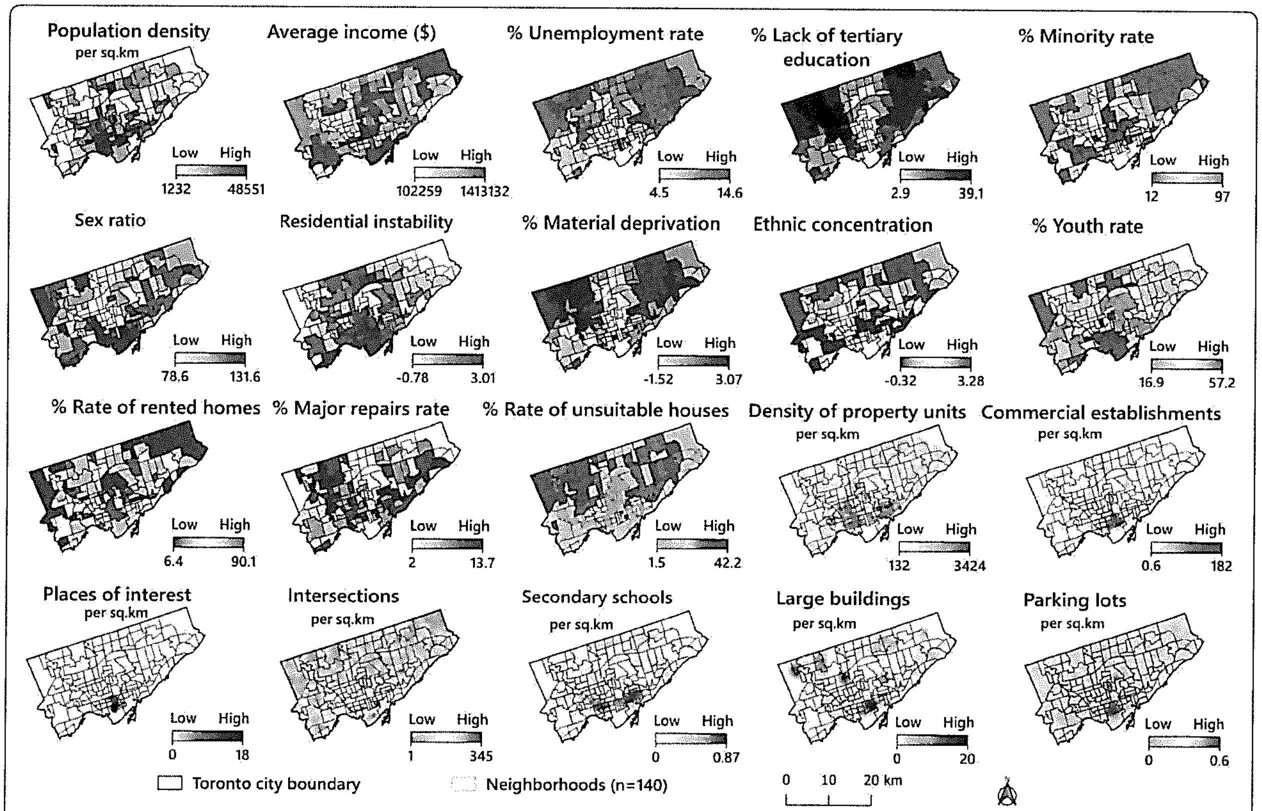

Fig. 3 Spatial distribution of explanatory variables used for homicide modelling in the city of Toronto at the neighbourhood level

analysed in this study. It should be noted that the excluded variables by Pearson's correlation have not been included in this figure.

Data analysis

Kulldorff's spatio-temporal analysis [101, 102] and spatial statistics [103] were used to map out the homicide patterns followed by application of OLS, GWR and MGWR to determine the associations between neighbourhoods characteristics and homicide rates. OLS regression was used to explore the associations globally [7, 104], with GWR and MGWR used for investigating the local changes of associations for each neighbourhood separately [30]. We also applied empirical Bayes smoothing (EBS) when mapping the homicide rate (Fig. 5-b) using the neighbourhood as spatial unit. The relevant population at risk typically varies across areas under investigation, which means that the precision of the raw homicide rate varies as well. This variance instability requires smoothing and we used the EBS technique to reduce the random fluctuations due to population size by computing the risk as a weighted sum of the raw rate for each unit and a prior mean. Thus, in this model, the underlying real rates were estimated by an assumed prior incident distribution based on the observed data [105–107]. The Jenks natural breaks classification [108] was used for generating a homicide rate map (Fig. 5b).

Purely temporal cluster analysis by SaTScan v.10 exclusively identifies time clusters in a particular time period and does not consider their geospatial patterns [109]. We first applied this approach using Poisson discrete scan statistic [110] to detect high-rates and low rate clusters with the length of time aggregation set at 1 year and the window size at 50%.

To visualize the degree of risk in the geographical areas under study, we used kernel density estimation (KDE), one of the non-parametric and distance-based techniques for calculation of the spatial intensity of point incidents [111–113]. Here, the value of each cell at the raster surface (image file format) refers to the number of values (incident density) [114, 115]. We used a 30-m cell size within a 3,500-m bandwidth displaying a smoothed spatial density map. The homicide density for each of the cells across the grid was estimated using equation 1 [116], while the spatial analyst mode in ArcGIS 10.8 (ESRI. Redlands, CA, USA) was used to conduct the KDE of spatial density of the homicides (Fig. 5-a). The KDE calculations are expressed by equation 1.

$$f(x,y) = \frac{1}{nh^2}\sum_{i=1}^{n} K\left(\frac{d_i}{h}\right) \quad (1)$$

where; $f(x,y)$ is is the density estimate at the location (x,y); n the number of observations (homicides in this case); h the bandwidth or the kernel size; K, is the kernel function; and d_i the distance between the location (x,y) and the location of the i^{th} observation.

Waldo Tobler's First Law of Geography states that "Everything is related to everything else, but near things are more related than distant things " [117], which encapsulates the concept of spatial dependence that can be estimated by autocorrelation techniques. The global autocorrelation techniques can identify any non-random distribution of clusters but do not tell where they are situated, which is revealed by local autocorrelation [110]. We used Global Moran's Index (GMI) [40] and Anselin's Local Moran's Index (ALMI) [41] since they are generally more accurate concerning measuring autocorrelation than other statistics [34, 37, 40, 41]. We used GMI to explore the general, spatial pattern of homicide rates in Toronto and also to test the residual values of the OLS results. To discover spatial autocorrelation, the spatial weights matrix [115] was used to conceptualize the spatial relationships, which is an essential element in the construction of spatial autocorrelation statistics in GIS [115]. The calculation steps of the ALMI and GMI models were done by equations 2 and 3.

GMI, an index of spatial autocorrelation is mathematically expressed as follows:

$$I = \frac{N\Sigma_{ij}W_{ij}(X_i - \overline{X})(X_j - \overline{X})}{\Sigma_{ij}W_{ij}\Sigma_i(X_i - \overline{X})^2} \quad (2)$$

where N is the number of neighbourhoods, Xi thehomicide rate at area I; $\overline{X}$ the mean value of the homicide in the study neighbourhood; and W_{ij} elements of a spatial lag operator W (spatial weights of matrix W).

ALMI an index of local spatial autocorrelation, is mathematically expressed as follows:

$$I_i = \frac{\sum_{j=1}^{n} w_{ij}(x_i - \overline{x})(x_j - \overline{x})}{\frac{1}{n}\sum_{i=1}^{n}(x_i - \overline{x})^2}, i \neq j \quad (3)$$

where n is the number of neighbourhoods; x_i and x_j the homicide rate in neighbourhood i and j, respectively; $\overline{x}$ the average of the reported homicide rate in all neighbourhoods; and w_{ij} the spatial weight matrix corresponding to neighbourhoods i and j; and I the local Moran's I [103, 118, 119].

Spatio-temporal scan statistics were used to identify potential clustering of homicides in both space and time. This type of statistics, introduced by Naus in 1965 [120] and further developed by Kulldorff by 1997 [121], has since been applied in various types of crime analysis studies [122]. This approach can detect spatial clusters irrespective of any predefined geographical boundaries by combining any number of close locations into the same cluster in predefined periods [109]. It was designed to test whether or not an event is randomly distributed over space and time with the ability to repeat similar analyses [123]. Relative risk (RR), Log-likelihood ratio (LLR) and the Monte Carlo test, described in detail in previous studies [110], support the interpretation of space-time analysis in scan statistics. The Poisson probability model [102], which is a discrete scan statistic, was used to analyse temporal and spatio-temporal clustering in areas with high rates of total homicide incidents. The maximum window size of spatial and temporal analysis was adjusted to 50% of the population at risk in the study area during the period of study. The null hypothesis of no clusters was rejected at the simulated value of $p \leq 0.05$ for the primary clusters [124]. QGIS v.3.24.1 was used to visualize the outputs of scan statistics.

Linear and geographically weighted regression

An OLS multivariate regression model was employed to explore the global relationship between the homicide EBS rates (dependent variable) and the independent variables (Table 1). Before implementing the OLS model, Pearson's correlation [125] and exploratory regression [115] were used to identify the global variables and to determine any multi-collinearity among independent variables. The MGWR model was used to improve our understanding of the spatially varying relationships between the homicide EBS rate and the explanatory variables included in the OLS model. Unlike traditional, global regression modelling techniques, which assume that the relationships examined through the model's parameters are constant, MGWR allows variation across space [126]. Additionally, in contrast to GWR, which assumes that the local relationships within each model vary at the same spatial scale, MGWR allows the conditional relationships between the response variable and the different predictor variables to vary at different spatial scales, i.e. the bandwidths that indicate the range over which data are borrowed can vary by parameter surface [126]. The calculation steps of the GWR and MGWR models were done by equations 4 and 5. For a GWR model, the linear regression model is as follows:

Assuming that there are n observations, for observation

$$i \in \{1, 2, ..., n\} \text{ at location } (u_i, v_i), y_i = \beta_0(u_i, v_i) + \sum_{j=1}^{m} \beta_j(u_i, v_i)x_{ij} + \varepsilon_i \quad (4)$$

where $\beta_0(u_i, v_i)$ is the intercept; X_{ij} the j^{th} predictor (independent) variable: $\beta_j(u_i, v_i)$ the j^{th} coefficient; ε_i the error term; and y^i the response variable (Crime EBS rate).

For a MGWR model, the linear regression model is as follows:

Assuming that there are n observations, for observation

$$i \in \{1, 2, ..., n\} \text{ at location } (u_i, v_i), y_i = \beta_0(u_i, v_i) + \sum_{j=1}^{m} \beta_{bwj}(u_i, v_i)x_{ij} + \varepsilon_i \quad (5)$$

where bwj in β_{bwj} indicates the bandwidth used for calibration of the j^{th} conditional relationship.

Gaussian model was used to run the GWR and MGWR models [126] with the introduction of locations (identified by ID-labels), coordinates variables (x and y), four independent variables (Supplementary file 4) and the EBS homicide rate as the dependent variable. To select an optimal bandwidths in both models for comparison purposes, the adaptive Bisquare spatial kernel method [126] was used and the Golden Section mode [126] applied as a weighting scheme for calibrating both models. The corrected Akaike Information Criterion (AICc) was used as an optimization criterion in the calibration of the GWR and MGWR models, and local variation inflation factors (VIF) [127] were applied to evaluate multi-collinearity amongst explanatory variables. It was also possible to test the statistical significance of each surface of parameter estimates produced by GWR and MGWR via random sampling methods. In this study, a Monte Carlo test with 1,000 iterations [126]was applied to evaluate the spatial variability of each surface of parameter estimates produced by the MGWR model. A pseudo p-value <0.05 indicated that the observed spatial variability of a coefficient surface was significant at the 95% CL (i.e. non-random).

Results

Temporal clusters

There were 701 homicides in Toronto in the 2012-2021 period. The lowest number (57 cases) occurred in 2012 and the highest (98 cases) in 2018. Although the number of homicides decreased from 2018 to 2021, it had increased 32.14% by 2021 compared to 2012. An average of 70 homicides per year occurred during the study period. The results of the purely temporal analysis indicated that high-rate clusters of total homicides were predominantly distributed in the period 2018-2021 (Fig. 4). In the study period, the average age of the victims was 33 years and 75.7% of them were men. Death by shooting (52.35%) was the most common type of homicide in the study period.

Spatial and spatio-temporal clusters

Figure 5-A shows the density and location of the homicides for the 2012-2021 period expressing the former as number per km^2. According to this map, downtown Toronto had the highest number of homicides per km^2 (9.03). Areas in the North (Humber River and Black Creek, ID=7) and Northwest (Etobicoke North, ID=1) also showed high homicide rates (Fig. 5-B). However, this particular map only deals with population density and does not take into account the issue of neighbourhoods and the proximities of different geographical units. However, based on the following results (Moran's $I = 0.22$, Z-score $= 5.8$, $p = 0.00$), GMI revealed that the global spatial pattern of homicides rate in Toronto during the study period was autocorrelated and clustered. Figure 5-C maps the homicide clusters and outliers using EBS rates and the ALMI method. According to this map, downtown Toronto and the area Etobicoke North (ID=1)

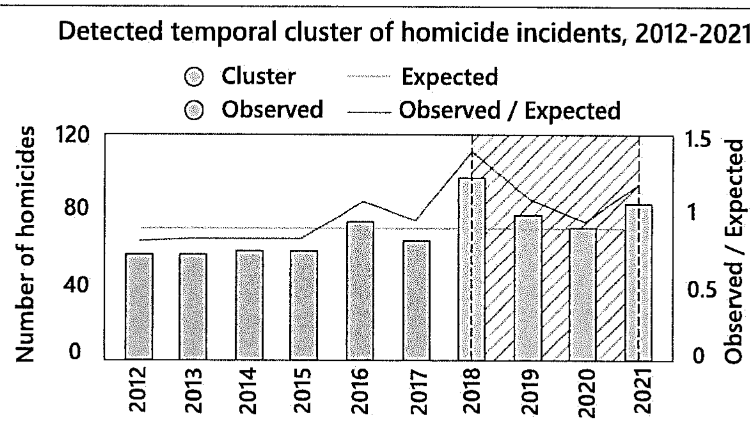

Fig. 4 Temporal clusters of homicide incidents in the city of Toronto, 2012-2021

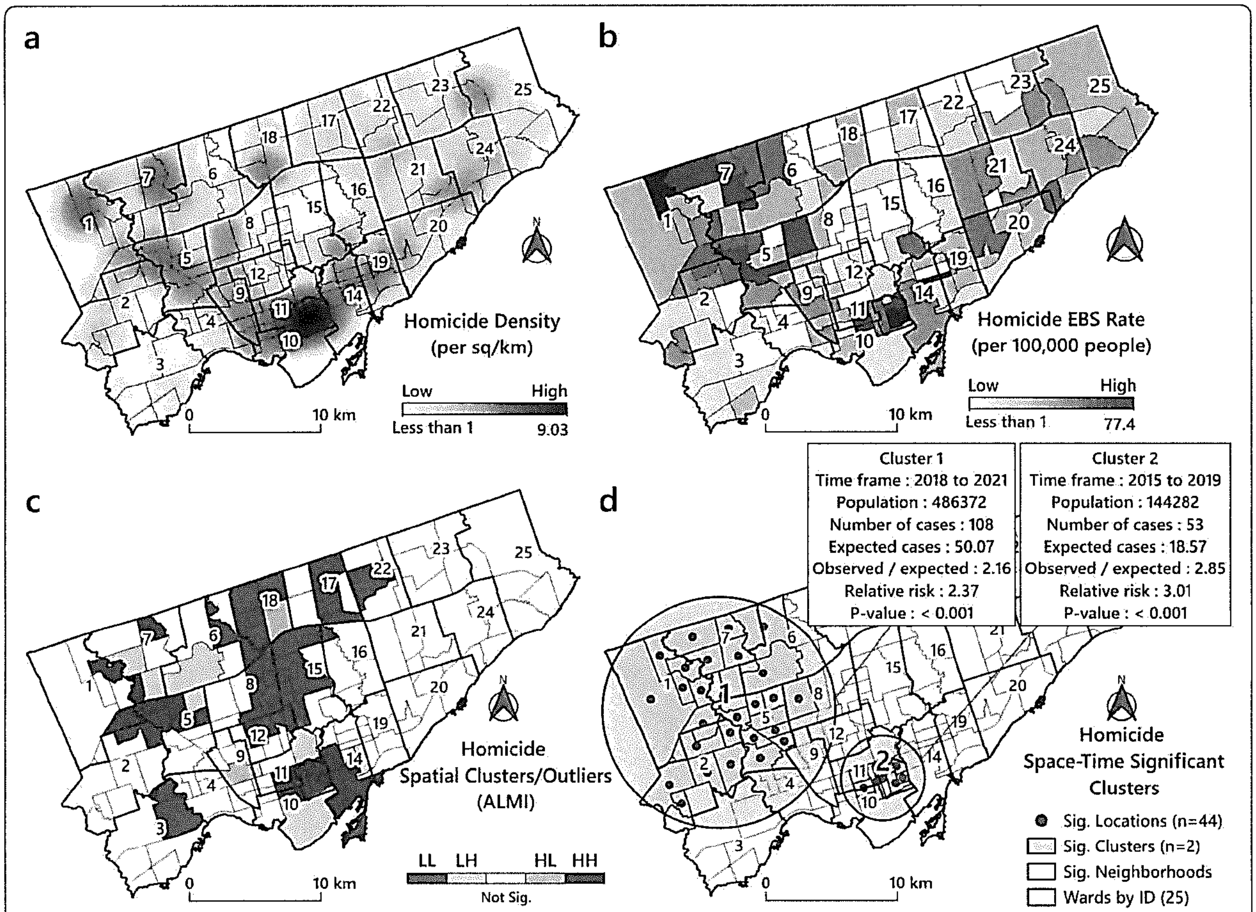

Fig. 5 Distribution of homicide by neighbourhood in Toronto2012-2021. **A** Homicide density per km2; **B** Homicide EBS rates; **C** Homicide spatial patterns (Low-Low (LL), Low-High (LH), High-Low (HL) and HH; **D** Two homicide spatio-temporal clusters were identified in this study

had two High-High (HH) clusters that were spatially autocorrelated. We identified two spatio-temporal clusters: the first cluster (RR = 2.37, OE = 2.16 and $p<0.05$) formed in Etobicoke North (ID=1) during the years 2018-2021. The second (RR = 3.01, Observed/Expected (OE) = 2.85 and $p<0.05$) covered the city centre during the years 2015-2019. The spatio-temporal homicide patterns are shown in Figure 5-D.

Pearson's correlation, ER and OLS model

As reported in Supplementary File 3, the VIF values of all dependent variables derived from the second exploratory regression analysis were <7.5, indicating that there was no multicollinearity. Neighbourhoods (e.g., Sunnylea) where no homicides occurred during the study period were identified as outliers and excluded from the analysis by OLS, GWR, and MGWR. The results of Pearson's correlation test showed that there was a global, significant relationship between the homicide rate and the selected variables, e.g., between homicide rate and the spatial density of large buildings (correlation = 0.56, $p<0.01$). However, Pearson's test does not show correlation between variables in their geographical context, which can vary in terms of strength and direction in different neighbourhoods. The OLS method, on the other hand, shows the associations between homicide rate, intercept and independent variables in their geographical context (Supplementary file 4). Our findings based on OLS calculations show that the population density, the material deprivation index, the commercial establishments and the density of large buildings were significantly associated with high homicide rates (Supplementary File 4).

Naturally, the strength of this association varied in different areas and some variables were more strongly associated with high homicide rate. R^2 and the adjusted R^2 (Adj.R^2) obtained from the OLS model explained 53% and 50%, respectively, of the total variance of homicide rates within the neighbourhoods. Moran's I statistic showed a positive, significant autocorrelation for the residuals values of the OLS model results ($I = 0.14$, z-score = 2.18, $p<0.05$) which rejects the random distribution of residual values. However, the non-random pattern of the residuals impairs their independence in the OLS model. To address this limitation, GWR and MGWR methods were applied.

GWR model results

The descriptive results of the GWR for homicides are provided in Tables 2 and 3. Adj R^2 of the GWR was 0.51, signifying a 0.6% higher value than that obtained by the OLS model and the GWR also produced a decreased AICc (309.53). Thus, compared to the OLS model, the GWR increased the explanatory level to 54% and 51%, respectively, of the variations in the observed homicide rates across different neighbourhoods.

MGWR model results

The descriptive results of the MGWR for homicides are provided in Tables 4 and 5. Table 6 compares the diagnostics indicators of all three methods used. AdjR^2 of the MGWR was 0.53, representing a 4.35 and 3.74% increase, respectively, from that in the OLS and GWR models, (Table 6). The MGWR also produced a better AICc (305.24) indicating that the MGWR is even more suitable as it explains 56 and 53%, respectively, of the variations in observed homicide rate. Moran's I statistic was negative and had no significant autocorrelation for the MGWR residuals ($I = -0.021$, z-score = -0.36, $p>0.05$), which is a random pattern that confirms their independence.

The spatial results of GWR and OLS models are not visualized in this article; however, they are presented in Tables 2 and 3 and Supplementary file 4. Geographical mapping of the estimated locally weighted R^2contributes to the understanding of how well the MGWR model fits observed homicide rate in the different neighbourhoods. Figure 6 depicts the distribution of local R^2, which is heterogeneously distributed. In general, MGWR operates well in the downtown area, with R^2 values over 0.64. Indeed, Eglinton-Lawrence (ID=8), Davenport (ID=9), Spadina-Fort York (ID=10), University Rosedale (ID=11), Toronto St. Paul's (ID=12) and small part of the Toronto Centre (ID=13) wards included neighbourhoods

Table 2 Summary statistics of GWR model estimated coefficients of local terms for homicides

Variable	Bandwidth	Mean	STD	Minimum	Median	Maximum
Intercept	123	-0.027	0.060	-0.146	-0.046	0.075
Population density	123	-0.267	0.011	-0.300	-0.265	-0.245
Material deprivation	123	0.424	0.083	0.311	0.437	0.555
Commercial establishments	123	0.350	0.062	0.251	0.333	0.526
Large buildings	123	0.401	0.042	0.288	0.404	0.480

Table 3 Model specifications and diagnostics indicators for the fitted GWR model

Diagnostic name	Value		Value
Residual sum of squares	64.627	AICc	309.528
Effective number of parameters (trace (S))	8.459	BIC	335.827
Degree of freedom (n – trace (S))	131.541	**R^2**	**0.538**
Sigma estimate	0.701	**Adj. R^2**	**0.508**
Log-likelihood	-144.541	Adj. alpha (95%)	0.030
Degree of Dependency (DoD)	0.894	Adj. critical t value (95%)	2.199
AIC	308.000		-

Table 4 Summary statistics of MGWR model estimated coefficients of local terms for homicides

Variable	Bandwidth	Mean	STD	Min	Median	Max	Monte Carlo test
Intercept	139	0.006	0.012	-0.030	0.007	0.030	0.840
Population density	139	-0.254	0.005	-0.272	-0.252	-0.249	0.905
Material deprivation	123	0.415	0.079	0.301	0.427	0.522	0.143
Commercial establishments	70	0.375	0.247	0.068	0.301	0.036	0.002
Large buildings	139	0.430	0.009	0.409	0.432	0.447	0.905

Table 5 Model specifications and diagnostics indicators for the fitted MGWR model

Diagnostic name	Value		Value
Residual sum of squares	61.667	AICc	305.235
Effective number of parameters (trace (S))	9.432	BIC	334.066
Degree of freedom (n – trace (S))	130.568	**R^2**	**0.560**
Sigma estimate	0.687	**Adj. R^2**	**0.527**
Log-likelihood	-141.259	-	-
Degree of Dependency (DoD)	0.872	-	-
AIC	303.380	-	-

Table 6 Model comparison

Model	AIC	AICc	R^2	Adj. R^2	Increased Adj. R^2(%)
OLS	1027.85	1028.95	0.526	***0.505***	-
GWR	309.528	335.827	0.538	***0.508***	0.003= 0.6%
MGWR	303.380	305.235	0.560	***0.527***	0.022=4.35%, 0.019=3.74%

associated with R^2 values over 0.64. Neighbourhoods in the western and eastern ends of the city were found to be associated with lower local R^2 values. Some of the neighbourhoods in Scarborough (IDs= 17 and 20-25) and Etobicoke North (ID=1) showed particularly low R^2 (0.46), which suggests that additional explanatory factors might be associated with the homicide rate in these neighbourhoods.

In the MGWR model, the significance of locally varying coefficients for the independent variables can be visualised through pseudo *t*-statistics [30]. Figure 7 shows the spatial distribution map of pseudo *t*-values for the intercept and each independent variable in the Toronto City. In figure 7, the non-significant relationships are shown in light yellow; significant positive relationships in orange/red; and significant negative relationships in light green/green. Figure 8 visualises local coefficients for the variables identified significant in Figure 7. It essentially reveals how the direction and strength of the association between the dependent and each independent variable varied over the total surface. Examining both pseudo *t*-values for the surface in Figure 7 and coefficient maps in Figure 8 yielded useful insights into the spatial variation of associations. In fact, the map shows that material deprivation and large buildings are positively associated with the homicide rate; however, population density is negatively associated. Finally, commercial establishments followed different directions regarding the association with the homicide rate in different neighbourhoods.

Discussion

The study aimed to explore the spatial patterns of homicide rate at the neighbourhood level in Toronto, the largest urban area of Canada. Our findings show that the homicide rate increased during the study period (2012-2021) and reached a high in 2018. Importantly, uncommon events may have distorted the study results, particularly due to the 2018 attack in the North York neighbourhood and City

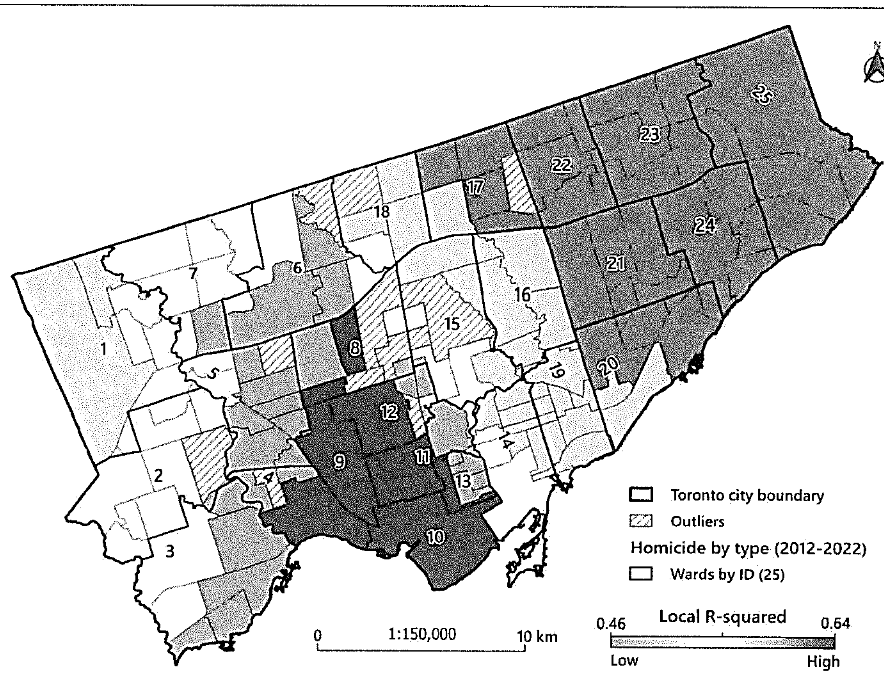

Fig. 6 Spatial distribution map of adjusted local R^2 of the MGWR model

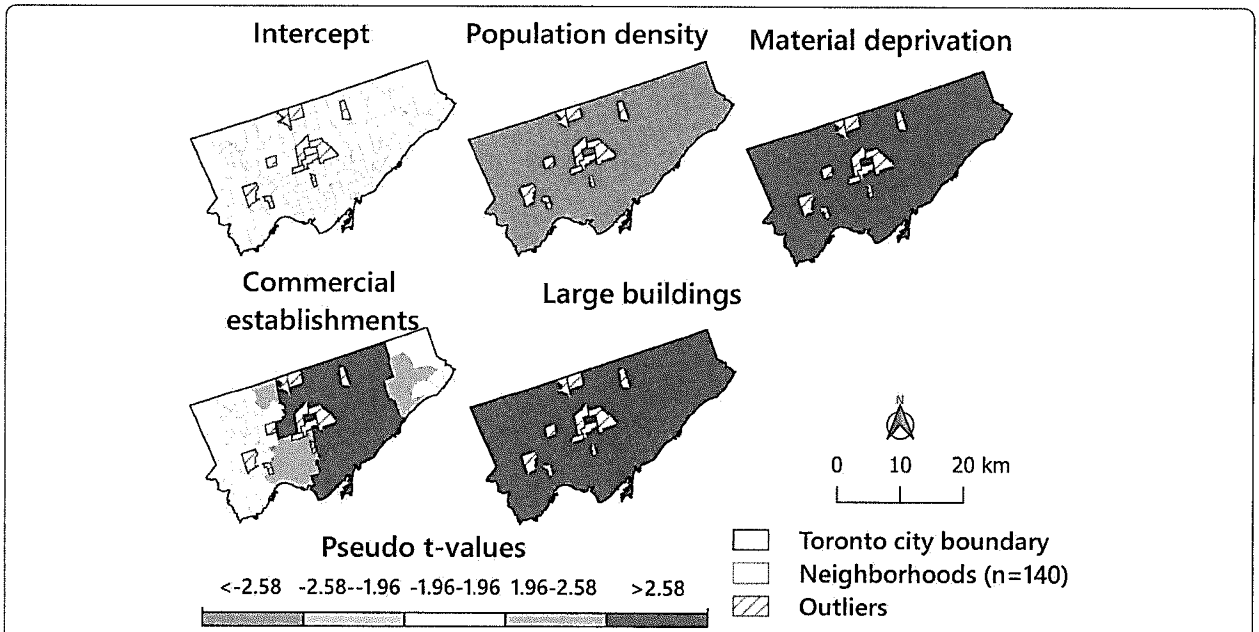

Fig. 7 Pseudo t-values for intercept and independent variables

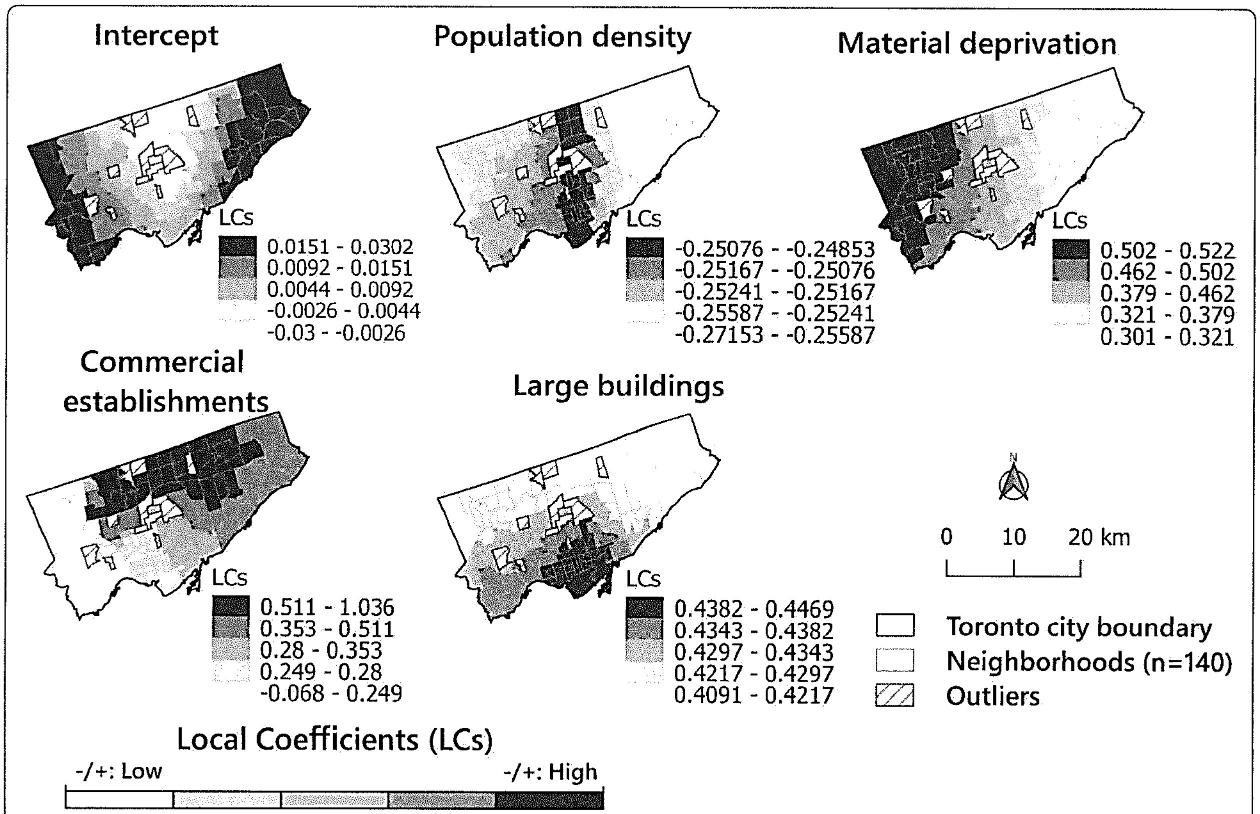

Fig. 8 MGWR local coefficients for intercept and independent variables

Centre of Toronto, where pedestrians were deliberately struck by a van resulting in 10 deaths [128], but also the fact that eight homicides discovered during the seven-year period from 2010 to 2017 were finally found to have been committed by a serial killer [129]. However, even after subtraction of these particular cases, the average homicide rate in Toronto climbed over the last decade.

Felson and Clark [130] and Brantingham [26] point out that consistent high crime rates tend to attract more crime leading to the *"law of crime concentrations at places"*, something that has been verified in Toronto [131]. Hirschfield and Bowers [68] confirm that homicides are non-random occurrences in urban areas and indeed repeated in areas with special characteristics, something which is supported by our study as well as the majority of investigations [27, 30, 48, 132]. Although violence rates in different periods and different parts of a city can be quite different [133], many scientists [29] confirm that city centres offer opportunities for crime due to their diverse social and economic attractions, while Charron [47] also notes that commercial areas bring together large numbers of people whose interactions can be associated with violent crimes. Our ALMI maps support these findings, as they reveal statistically significant spatial homicide clusters in many various parts of Toronto where spatial HH clusters of homicide rates formed during the study period, results which also are in line with previous research in Toronto by Wang et al. [30] and Charron [48].

The GWR results (R^2= 0.54) confirm the association between some socio-economic variables and the built environment and, as MGWR allows variability at different spatial scales, conditional relationships between the response variable and the different predictor variables could be traced (e.g., the local R^2 surface revealed the extent at which the regression model fits observed homicide rate in different neighbourhoods). However, in this respect, our findings differed from those by Wang et al. [30]. In their study, the R^2 values were particularly high in north-eastern Toronto, while we reached the highest values in the central parts and downtown area in our study (Fig. 6). However, this does not mean that the results are inconsistent as spatial heterogeneity with regard to homicides is not uncommon as shown by Graif and Sampson [56]. Pseudo *t* values and local coefficients also show that some variables, such as population density, material deprivation, commercial establishments and large buildings (including >5 households) density were all associated with high homicide rates in some neighbourhoods. Also, the strength and direction of local coefficients varied in different neighbourhoods, e.g., while the presence of large buildings, as commonly in city centres, were positively associated with high homicide rates. In addition, material deprivation can be associated with the high rates as they were in the city's north-western neighbourhoods. Our findings based on the MGWR model revealed that there was a strong local correlation between a high homicide EBS rate, population density and density of large buildings in most parts of the city such as central neighbourhoods. According to Colquhoun [95], areas with high population density and a concentration of large buildings can be associated with increased violent crime and homicides. Newman [134] emphatically states that when building density increases with more households in the same building, the sense of belonging decreases and crime opportunity increases. In his opinion, this occurs when buildings are poorly designed and characterised by low-income households, and environmental improvements can be an effective way to prevent crime in densely populated areas [134]. However, in our study, only some associations were identified.

Our findings based on the MGWR model also revealed that there were an association between the homicide rate and material deprivation in most parts of the city, particularly in areas with high unemployment rates, low levels of tertiary education and high rates of dilapidated, unsuitable housings (Fig. 3). This conclusion is echoed by a large number of authors [31, 58, 62, 63, 95, 135, 136], who also note that the number of various crimes grows with increased deterioration, i.e. poor areas with dwellings in need of major repair (burnout and destruction of the physical environment) populated by people with low income and a low rate of tertiary education areas. The results by Lockwood [92] and those reported by Ingram et al. [58], also confirm a significant association between homicide and both poverty in urban areas. According to Lockwood, poverty and poor areas are associated with more violent crimes. Kitchen and Schneider [133] agree regarding the role of socioeconomic disadvantage for violent crime rates in specific neighbourhoods, as do Tita et al. [137] and others [138].

Finally, the results of pseudo t-values we obtained from the MGWR model showed that the associations between homicide and areas with a high density of commercial establishments in most parts of Toronto (Figs. 7 and 8). As previous studies have confirmed [30, 41–45, 47, 48], the parts of a city characterized by a high density of commercial establishments, are attractive centres for all types of crimes that can be associated with violent crimes.

Limitations and future research areas

While the study has contributed to a better understanding of the socio-economic and built environment factors associated with homicides in Toronto, there are some limitations that need to be acknowledged. First, only data reported by Toronto Police Service were analysed and some homicides may not have been reported to the police for various reasons (such as fear, dissatisfaction with the police, etc.) [139]. Neither did we have access to data for areas outside of the City of Toronto [30] nor were detailed data for any offenders and victims available. Knowledge of the place of residence of killers and victims could deepen spatial analysis and provide a better understanding of homicide spatial variations. It is also possible that factors outside the artificial boundaries of neighbourhoods could be associated with high homicide rates. Cross-border variables could play a role and need to be investigated. Second, in this study, we only used aspects of the spatial distribution of the homicides, while data on uncertain geographic contexts and spatial behaviour of offenders were not considered (e.g., the killers' move from home to the crime scene). Future studies might be able to use interviews to get more detailed data about the spatial behaviour of offenders, thereby assisting spatio-temporal analyses. Third, we used the population data of 2016 as the middle point of the study period. However, this cannot be a serious limitation of the associations found in this study because the data of 2016 for calculating the independent variables were also used. On the other hand, it can underestimate the homicide rate of neighborhoods which grew at a faster pace between 2012 and 2021. Fourth, the current research has manifested some urban indicators associated with a high homicide rate, but this kind of research cannot show any causality inference and many of the associations we estimate could be a product of inverse causality. Future research with different study designs is needed to find the factors influencing the homicide rate in different urban neighbourhoods. Finally, choosing the neighbourhood level as the basic unit of analysis may cause the modified areal unit problem.

Conclusions

By applying geographical regression methods to identify socioeconomic and built environment factors associated with homicide, we expect the current study to improve the understanding of which factors are associated with the occurrence and recurrence of crime in each neighbourhood. Urban planners need to address the problems in downtown and north-western areas of Toronto, in particular with respect to dense urban areas with high proportion of large urban buildings, areas with high deprivation rates and urban areas characterized by a concentration of commercial establishments. Reducing violent crime requires long-term integrated strategies (socioeconomic and built-environment).

Abbreviations

GIS: Geographic Information Systems; TPS: Toronto Police Service; VIF: Local Variation Inflation Factors; OLS: Ordinary Least Square; GWR: Geographically Weighted Regression; MGWR: Multi-scale Geographically Weighted Regression; KDE: Kernel Density estimation; LCs: Local Coefficients; AIC: Akaike's Information Criterion; GMI: Global Moran's Index; ALMI: Anselin's Local Moran's Index; AICc: Corrected Akaike Information Criterion; EBS: Empirical Bayes Smoothing.

Supplementary Information

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Additional file 1.
Additional file 2.
Additional file 3.
Additional file 4.

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Authors' contributions

AM and BK drafted the manuscript and participated in spatial data analysis. RB and BK critically reviewed the manuscript. EP and GF evaluated the data and did a literature review. SND and AS reviewed the manuscript and contributed to its improvement. AM and BK are the research leaders who responded to the reviewers' comments. All authors read and approved the final version.

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Availability of data and materials

The datasets analysed during the current study come from the public databases of Wellbeing Toronto [http://toronto.ca/wellbeing], Open Toronto [https://www.open.toronto.ca] and the open data dashboard of Toronto Police [https://data.torontopolice.on.ca/pages/homicide].

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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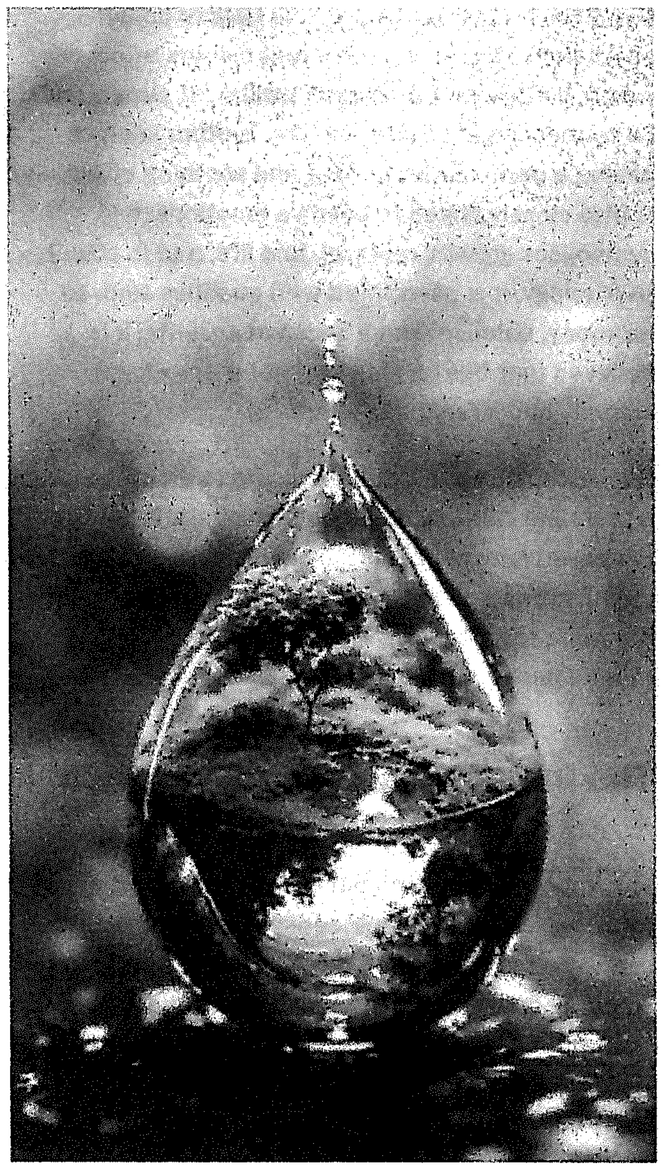
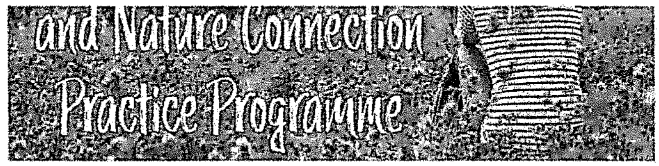
Green Therapies: Exploring the Impact of the Colour Green on Emotional and Mental Health

21st October 2023



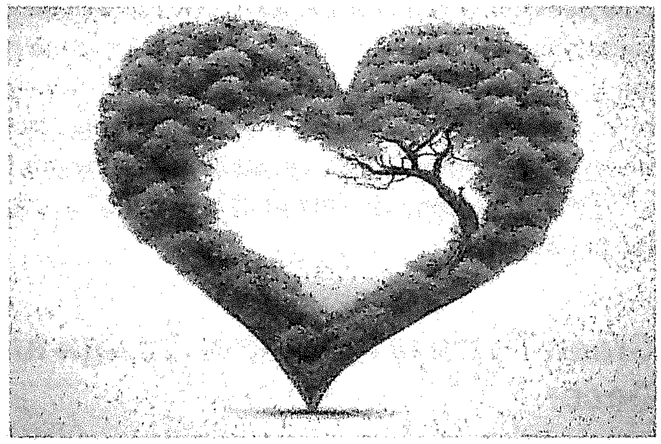
In today's often fast-paced and technology-driven world, finding peace of mind and breaking free from the associated anxiety and stress can sometimes feel like an impossible task. However, there is one solution that is readily available and has been shown to have a profound impact on emotional and mental health - the colour green. Colours can have a profound impact on our emotions, and green, the colour of nature and life, holds a special place in its ability to soothe, heal, and rejuvenate our mental and emotional wellbeing. From verdant forests to open meadows and urban parks, the colour green is abundant in nature, and its therapeutic effects should not be underestimated. Green therapy, also known as ecotherapy or nature therapy, harnesses the power of the natural environment to promote holistic wellbeing. Research has shown that exposure to the colour green can reduce stress, improve mood, increase creativity, and enhance cognitive functioning. Whether it's taking a walk in a park, tending to a garden, or simply gazing at a scenic view, incorporating more 'green' into our daily lives can have a transformative impact on our mental health.

In this article, we will explore the psychology and science behind 'green therapies' and explore how the colour green is seen as beneficial for emotional and mental health and wellbeing. We will also share some practical tips on how to incorporate more 'green' into your life, whether it's through indoor plants, nature walks, or green spaces. So, join us as we explore the positive impact of the colour green on our emotional and mental health, uncover the secrets of green therapy and learn how this colour can transform our type of depression related to changing seasons.



Physiological Benefits

In addition to its psychological effects, green has also been found to have physiological benefits. For example, exposure to green spaces has been shown to lower blood pressure and heart rate, contributing to a healthier cardiovascular system. Exposure to green environments has been shown to stimulate the parasympathetic nervous system, responsible for relaxation and recovery. Green environments also promote physical activity, which is known to have positive effects on mental health.



Green Therapy in Nature and Outdoor Spaces

The natural environment provides an ideal setting for green therapy. Whether it's the sight of green trees, the sound of flowing water, or the smell of fresh air, nature has a way of rejuvenating our minds and soothing our souls. Research has shown that spending time in green spaces can reduce symptoms of anxiety and depression and improve overall wellbeing.

Incorporating green therapy into your outdoor activities can be as simple as choosing to exercise outdoors instead of in a gym or taking your lunch break in a nearby park. Even small doses of nature can have a positive impact on our mental health.

Green Therapy Techniques and Practices

Green therapy, also known as ecotherapy or nature therapy, encompasses a range of techniques and practices aimed at harnessing the healing power of nature and the colour green. These techniques can be used to improve emotional wellbeing, reduce stress, and enhance overall mental health.

One of the simplest ways to incorporate green therapy into your life is by spending time in nature. Taking walks in parks, walking in forests, or simply sitting in a garden can help you reap the benefits of green therapy. Engaging in activities such as gardening, or nature photography can also be therapeutic and provide a sense of few simple ways to harness the power of green for emotional and mental wellbeing:

- **Spend time in nature**
  Take regular walks in parks, plan weekend outings, or simply find a quiet spot to sit and enjoy the beauty of nature.
- **Bring nature indoors**
  Fill your home or workspace with potted plants as they not only improve air quality but also promote a sense of calm and relaxation. You can also hang nature-inspired artwork, or create a green accent wall to create a more relaxing and nurturing environment.
- **Practice mindfulness in green spaces**
  Take a few moments to be fully present and engage your senses when you're surrounded by nature. Notice the colours, smells, and sounds around you. Have a look at our range of self-guided nature connection resources.
- **Engage in green activities**
  Try gardening, nature photography, or birdwatching as a way to connect with the natural world and reap the benefits of green therapy.

Final Thoughts

In a world that often feels overwhelming and stressful, 'green therapies' can offer a simple and effective way to improve our emotional and mental wellbeing. Whether it's spending time in nature, incorporating green elements into our indoor spaces, or engaging in green activities, there are countless ways to harness the power of green in our daily lives.

Research has shown that exposure to green spaces, whether in the form of lush forests or urban parks, can have a profound calming effect on our minds. It has been associated with reduced stress levels, improved mood, and increased relaxation. Furthermore, studies have also linked the colour green to enhanced cognitive function, creativity, and overall psychological wellbeing.

By embracing the colour green and immersing ourselves in the healing power of nature, we can find solace, rejuvenation, and a greater sense of peace. So, next time you're feeling overwhelmed or in need of a mental boost, remember the transformative impact of green therapy and let the colour guide you to a place of emotional and mental wellbeing.

However, it's important to note that the effects of colour on wellbeing can vary from person to person. Individual preferences, cultural influences, and personal experiences play a significant role in how people perceive and respond to colours. While green is generally associated with positive wellbeing effects, it may not have the same impact on everyone. Nonetheless, incorporating green elements into your surroundings, spending time in nature, or even using green in interior decor can be ways to potentially enhance your wellbeing, even if the effects are