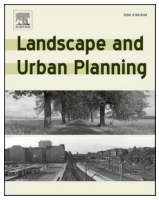
Landscape and Urban Planning 250 (2024) 105143

Contents lists available at ScienceDirect

Landscape and Urban Planning

journal homepage: www.elsevier.com/locate/landurbplan



Research Paper

A dose of nature to reduce sexual crimes in public outdoor spaces: Proposing the Landscape-Sexual Crime Model

Huan Lu [a,b,c], Lin Liu [d], Hua Zhong [e], Bin Jiang [a,b,c,*]

[a] Urban Environments and Human Health Lab, HKUrbanLabs, Faculty of Architecture, The University of Hong Kong, Hong Kong
[b] Division of Landscape Architecture, Department of Architecture, The University of Hong Kong, Hong Kong
[c] Urban Systems Institute, The University of Hong Kong, Hong Kong
[d] Department of Geography and GIScience, University of Cincinnati, Cincinnati, OH 45221, USA
[e] Department of Sociology, The Chinese University of Hong Kong, Hong Kong

HIGHLIGHTS

- Proportion of trees predicted a lower sexual crime probability.
- Proportion of trees mixed with grass predicted a higher sexual crime probability.
- Landscape complexity and aggregation predicted a lower sexual crime probability.
- Green spaces had stronger impacts on sexual crime rate in disadvantaged areas.
- A Landscape-Sexual Crime Model was proposed to facilitate future research.

ARTICLE INFO

Keywords:
Urban safety
Landscape metrics
Dose-response curve
Nonlinear association
Landscape-Sexual Crime Model
Interaction effect

ABSTRACT

Sexual crime is a critical global social problem. There remains a critical knowledge gap concerning whether and to what extent sexual crimes in public outdoor spaces can be influenced by landscape morphology of green spaces. This missing knowledge hinders the effective use of green spaces to reduce sexual crimes in these public settings. To address this issue, we collected a dataset comprising 5,155 cases of sexual crimes that occurred in public outdoor spaces in the United States from August 2021 to July 2022. A random forest model was employed to examine the statistical relationships between landscape morphology and sexual crimes. Additionally, we utilized the Shapley Additive Explanations (SHAP) model to quantify the interaction effects of landscape morphology with socioeconomic and demographic characteristics. This study yields three key findings: (1) Both the proportion and configuration factors of landscape morphology may significantly influence the sexual crime probability. (2) The relationships between landscape morphology and sexual crimes are nonlinear, and threshold values for the satisfactory dose and the preferred dose of green spaces can be identified. (3) There are significant interaction effects between landscape morphology with socioeconomic and demographic characteristics, emphasizing the importance of prioritizing green space interventions in socioeconomically disadvantaged areas. Lastly, through summarizing the findings of this study and previous research, we propose the Landscape-Sexual Crime Model (LSCM), which advocates for further research to explore effective strategies for using green spaces to reduce sexual crimes.

1. Introduction

1.1. Background

Sexual crimes, including forcible rape and sex offenses as defined by the Federal Bureau of Investigation (FBI)'s Uniform Crime Reporting Program (UCR) (Greenfeld, 1997), pose significant societal challenges. The United States Department of Justice reported a substantial increase in rape and sexual assault cases, from 319,950 in 2020, 324,500 in 2021, to 531,810 in 2022 (Thompson & Tapp, 2023). Compared to general

* Corresponding author at: 614 Knowles Building, The University of Hong Kong, Pokfulam, Hong Kong.
E-mail address: jiangbin@hku.hk (B. Jiang).

https://doi.org/10.1016/j.landurbplan.2024.105143
Received 1 December 2023; Received in revised form 8 June 2024; Accepted 10 June 2024

crimes, sexual crimes disproportionately affect vulnerable populations, such as women and children (Abrahams et al., 2014). These crimes have far-reaching consequences, inflicting long-term physical and mental harm on victims, violating basic human rights, disrupting communities, and perpetuating social inequality. Sexual crimes affect individuals from diverse backgrounds and span all age groups, constituting a significant public safety crisis (World Health Organization, 2014). In May 2023, the White House released the first-ever United States National Plan to *End Gender-Based Violence: Strategies for Action*, which emphasizes the prevention and addressing of sexual violence, intimate partner violence, stalking, and other forms of gender-based violence.

Previous research on sexual crimes has primarily focused on the behavioral and psychological characteristics of offenders and victims. However, some scholars, such as Beauregard et al. (2005), have initiated the investigation of the spatial distribution patterns of sexual crimes. Myhill & Allen, (2002) found that rape cases often exhibit a spatially concentrated distribution, with occurrence locations linked to neighborhood-level socioeconomic factors, land use, and social disorganization. Ceccato (2014) further delved into the environmental characteristics of rape crime scenes to identify risk factors associated with sexual crimes.

Sexual crimes that occurred in public outdoor spaces, in contrast to those committed indoors and in private areas (often by acquaintances), are more likely to be influenced by the surrounding environment. For example, secluded parks or alleys can provide hidding venues for sexual offenders, allowing them to carry out actions without being seen or heard by others (Myhill & Allen, 2002). Unlike property crimes such as robbery, which demand swift execution, sexual crimes typically require more time for the offender to control the victim and perpetrate the crime. This makes environmental characteristics of the crime locations more critical to offenders (Ceccato et al., 2019). Given these distinctions, landscape and urban planning are more likely to impact the incidence of public outdoor sexual crimes.

While many empirical studies in the field of environmental health have reported findings to suggest a good possibility to link physical environment characteristics to sexual crime probability, their research design, data analysis, and interpretations of findings were not guided by a comprehensive theoretical framework. This deficiency may lead to potential confusion in research findings and implications. Adding a new layer of environmental theory upon a widely recognized theory in sexual criminology could be a viable approach to addressing this issue (Jiang, Shen, et al., 2021).

1.2. Sexual Assault Analysis Triangle: A widely recognized theoretical model and its constraints

The Sexual Assault Analysis Triangle (SAAT) has been adopted as a theoretical model that explains the occurrence of sexual crimes, identifying three fundamental elements: offenders, victims, and crime locations (Dedel, 2011). This model is grounded in both the Rational Choice Model and the Routine Activity Theory. The Rational Choice Model elucidates the decision-making process of offenders, who seek suitable locations that maximize the likelihood of successful crime commission while minimizing the risk of apprehension (Cornish & Clarke, 2017). The Routine Activity Theory posits that the characteristics of offenders, victims, and crime locations collectively determine the probability of crime occurrence (Felson, 2017). SAAT suggests that the occurrence of sexual crimes requires the convergence of motivated offenders, potential victims, and locations lacking supervision. Altering the risks associated with these three elements may potentially contribute to the prevention of sexual crimes.

The SAAT has proven to be an effective tool in identifying and differentiating the characteristics of offenders, victims, and crime locations associated with sexual crimes (Densley et al., 2013; Sule et al., 2019; Waltermaurer & Akers, 2014). However, it is crucial to recognize that the sexual crime probability is not solely determined by these factors alone. Indeed, numerous studies have reported that socioeconomic and demographic characteristics can play significant roles in shaping the sexual crime probability. These factors can influence the motivations and opportunities for potential offenders, as well as the vulnerability and resilience of potential victims. However, findings of many empirical studies suggest that the characteristics of physical environments in which sexual crimes take place cannot be overlooked. The physical environments, including green spaces, may have profound impacts on the behaviors and psychologies of both potential offenders and victims. Integrating physical environments, socioeconomic and demographic characteristics into the SAAT model is essential for understanding sexual crimes. The following section will elaborate more on this critical perspective.

1.3. An overview of physical environment research on sexual crimes

Findings of some studies give strong hints that there are logical links between three aspects of the Sexual Assault Analysis Triangle (SAAT) with the physical environments, although those studies did not use the SAAT as the theoretical foundation.

From the perspective of offenders, concealed areas allow them to control and perpetrate crimes (Beauregard et al., 2007; Hewitt et al., 2018), while isolated locations that prevent sounds from attracting nearby pedestrians influence their motivation and methods of attack (Crowe & Fennelly, 2013). Locations near roads and far from crowds may provide escape routes for offenders (Ceccato, 2014). From the perspective of victims, vulnerable women who appear on the street or within residential areas, may become potential targets (Hewitt & Beauregard, 2014). Alcohol consumption in retail stores and bars may reduce their resistance (Clougherty et al., 2015). From the perspective of locations, enclosed and concealed places that limit bystander intervention align with SAAT's description of areas that are more likely to lack supervision (McDonald et al., 2016). Outdoor sexual crimes often occur in hidden locations that are isolated, lack lighting, or have poor natural surveillance (Ceccato et al., 2019). Physical environment characteristics of sexual crime locations encompass areas situated in or near vegetated spaces, such as unsupervised parks and forests (Ceccato, 2014).

There are four main constraints in existing environmental research sexual crimes. First, compared to research on other types of crimes, studies on the relationships between environmental characteristics and sexual crimes are much fewer (Hewitt et al., 2018). More evidence is needed to support the relationships between physical environments and sexual crimes. Second, in the past, some studies have attempted to analyze the environmental characteristics of outdoor sexual crime scenes, but the sample sizes were relatively small (Ceccato, 2014). In recent years, with the rapid development of large databases and corresponding data analysis tools, large-sample studies on sexual crimes have become possible and critical. They can provide more comprehensive and statistically robust findings than small-size studies (Seto & Lalumiere, 2010). Third, the results of past environmental studies on sexual crimes are often scattered across different research projects with varying scales and contexts, lacking a comprehensive investigation of the relationships between physical environments and sexual crimes within a single study (Ceccato, Li, & Haining, 2019; Clougherty et al., 2015). With larger sample data, it may be possible to establish a more comprehensive investigation of the physical environments and sexual crimes, taking into account socioeconomic and demographic backgrounds. Lastly, curvilinear associations between environmental characteristics and psychological or behavioral outcomes have been frequently reported (Cox et al., 2017; Jiang et al., 2014; Jiang et al., 2016; Mears et al., 2020), suggesting that curvilinear models might be more effective than linear models for exploring potential relationships.

1.4. Potential relationships between green spaces and sexual crimes

Only a few studies have investigated the relationships between green

spaces and sexual crimes. However, many other studies in the fields of environmental psychology and criminology reported circumstantial findings. Those findings suggest that green spaces may influence sexual crime activities through two major mechanisms: sexual crime-facilitating effect and sexual crime-deterring effect. These two mechanisms, like two sides of a coin, may result in different relationships between green spaces and sexual crimes when the characteristics of green spaces and contextual factors vary.

On the one hand, the sexual crime-facilitating effect encompasses several important aspects: First, places with tall and dense low-lying vegetation will lead to a poor visual connection between the inside and outside spaces, which may provide an ideal location for discreet observation and ambushing potential victims, thereby encouraging criminal activity. (Gaertner et al., 2016). Second, mixed and unkempt vegetation indicates a lack of maintenance and care for the physical environments, which reflects social barriers. Studies suggest that this barrier hinders community control mechanisms, thereby creating an environment conducive to criminal opportunities (Wilson & Kelling, 1982). Third, the use and functions of green spaces, including the insufficient consideration of residents' usage and recreational purposes, may be overlooked (Shams & Barker, 2019). This results in green spaces, such as ecological reserves, lacking potential visitors and becoming potential crime sites. Fourth, the size and location of green spaces matter. Isolated green spaces can inadvertently attract criminal activity, as the natural surveillance effect of unmonitored green spaces may be weaker compared to their capacity to provide hiding places (Kimpton et al., 2017). Excessively large green spaces with a lack of visitors can contribute to increased crime rates by providing ample space for criminals to hide and carry out illicit activities (Kim & Hipp, 2018; Sukartini, Auwalin, & Rumayya, 2021). It is important to note that these four aspects may independently or interactively facilitate crimes. The crime-facilitating effect may become stronger when a site possesses multiple characteristics mentioned above.

On the other hand, the sexual crime-deterring effect encompasses the following aspects: First, green spaces with spacious open space, tree canopy shade, and diverse facilities can foster street-level social interactions and outdoor activities. This can promote social cohesion and informal surveillance among citizens, thereby enhancing the crime-deterring effect (Jacobs, 1961; Kuo & Sullivan, 2001). Second, Jiang et al. (2018) proposed the Perceived Routine Activities Theory, suggesting that well-designed and well-maintained green spaces can create a stronger perception among potential offenders of active routine activities in an area, thereby inhibiting their intention to commit crimes. Third, notable gender differences in perception exist, with females demonstrating a stronger preference for green spaces that exhibit clear signs of good management, strong visual and physical accessibility, and active recreational or social functions. This suggests that these types of green spaces may have a decent crime-deterring effect (Jiang et al., 2017). Fourth, green spaces can bring multiple mental health benefits to visitors and users, including the reduction of negative emotions, anxiety, mental stress, mental fatigue, aggressive behaviors, and impulsivity. These benefits may indirectly mitigate the probability of crime (Branas et al., 2018; Bratman et al., 2019; Jiang et al., 2014; Jiang et al., 2015; Jiang, Xu, et al., 2021; Kuo & Sullivan, 2001; Wang & Tassinary, 2024).

Moreover, another noteworthy issue is that "green space" is a general concept, and our analysis on its negative or positive impacts on sexual crimes should be built upon the specific characteristics of green spaces (Ceccato, 2014; Ceccato et al., 2020). Some specific characteristics of green spaces warrant attention:

The proportion of green spaces may matter: Some studies provide relevant evidence suggesting that areas with a higher proportion of green spaces may potentially reduce instances of sexual crimes (Jonescu et al., 2023; Khatri & Abdellatif, 2020; Mancus et al., 2022; Venter et al., 2022), and this relationship might not necessarily be linear (Jiang et al., 2014).

The categories of green spaces may matter: Low-lying, dense vegetation, such as shrubs, may provide offenders with spaces to hide and wait (Michael et al., 2001), which can diminish women's sense of safety (Jiang et al., 2018). In contrast, trees are more likely to serve as natural surveillance elements and reduce the risk of crimes (Kuo & Sullivan, 2001).

The spatial patterns of green spaces may matter: Although limited studies have directly investigated the relationships between spatial patterns of green spaces and sexual crimes, indirect evidence indicates that the shape, connectedness, and aggregation of green spaces could potentially influence the occurrence of sexual crimes. For example, green spaces with complex shapes may increase the likelihood of residents entering and participating in activities, thereby enhancing natural surveillance in surrounding areas and reducing the likelihood of crimes (De Clercq et al., 2007; Zhang et al., 2020). Furthermore, visiting more concentrated and continuous green spaces enables a greater variety and duration of outdoor activities (Wang & Tassinary, 2024), which not only increases natural surveillance but also improves mental health. These factors, in turn, are associated with a lower sexual crime probability. Despite the paucity of direct evidence, these indirect findings underscore the potential significance of spatial patterns of green spaces in mitigating the occurrence of sexual crimes.

As a summary, the literature review indicates that the relationships between green space characteristics and sexual crimes has been insufficiently explored. To address this issue, it is crucial to move beyond the general concept of green spaces and differentiate between the specific characteristics of green spaces. The characteristics of green spaces can be summarized as landscape morphology, which comprises multiple key factors such as proportion, category, shape, connectedness, and aggregation (Jia et al., 2019; Wang & Tassinary, 2019). Additionally, socioeconomic, demographic, and other contextual factors should be taken into account and controlled in our study.

1.5. Knowledge gaps and research questions

Drawing upon the literature review presented above, we have summarized four critical knowledge gaps that we aim to address in this study: (1) While a handful of studies have provided empirical evidence for the relationships between environments and sexual crimes, few of them have presented a theoretical framework to guide the research design and the interpretation of research findings. (2) Most studies used linear regression models and neglected the potential non-linear relationships and thresholds between environmental characteristics and sexual crimes. However, an increasing number of studies have indicated that green spaces may have dose–response effects on psychologies and behaviors (e.g., Cox et al., 2017; Jiang et al., 2014; Jiang et al., 2016; Mears et al., 2020). (3) Previous studies only focused on the presence or the proportion of green spaces, lacking more specific, accurate, and objective measurements of landscape morphology. (4) Previous studies overlooked the interaction between landscape morphology with other socioeconomic and demographic characteristics, thus limiting our understanding of the effects of landscape morphology in diverse contexts.

To address the four critical knowledge gaps, this study aims to ask and answer four specific research questions:

(1) Whether and to what extent can landscape morphology (including proportion, category, shape, connectedness, and aggregation of green spaces) affect sexual crime probability?
(2) Whether and to what extent the relationships between landscape morphology and sexual crime probability can be explained by curvilinear relationships?
(3) Whether and to what extent does landscape morphology interact with socioeconomic factors to affect sexual crime probability?
(4) How can we propose an updated theoretical framework to interpret the relationships between landscape morphology and sexual crimes? This framework could potentially be an evolution of the Sexual Assault Analysis Triangle (SAAT).

2. Methods

2.1. Crime data

The sexual crime records in the United States used in this study were collected from CrimeMapping.com (Felka et al., 2020; Marteache et al., 2021; Wagner, 2023). CrimeMapping.com relies on crime data received from various law enforcement agencies, and the data is only retained for 180 days. Although the data on CrimeMapping.com does not encompass all crimes, it is reliable for research purposes as it originates from police departments or relevant agencies. Felka et al. (2020) compared CrimeMapping.com with official datasets and found that the two datasets were highly consistent, validating the effectiveness of our data source.

We developed a protocol to extract sexual crime records from 1 August 2021 to 31 July 2022. Sexual crime records in the dataset include rape, prostitution, and sexual offenses. Our study excluded records that contain descriptions of prostitution, as the nature of prostitution differs from that of rape and sexual offenses. In addition, the records also contain reported incident times and descriptions of the process of the sexual crimes. We did not consider the reported incident times, as they may not align with the actual occurrence times of the crimes. We also did not take into account the process of sexual crimes due to the incomplete descriptions.

Since outdoor sexual crimes are more likely (Fig. 1) to be influenced by the physical environments (Ceccato, 2014), we filtered the original dataset of 6,983 records using building outlines provided by OpenStreetMap, extracting 5,656 records that occurred outdoors. We also used data provided by OpenStreetMap to distinguish whether the locations of sexual crimes were private or not, and we identified 5,155 crime records that occurred in non-private areas (n = 5155, y = 1) (see Fig. 2 c). The distribution of the dataset is shown in Fig. 2. The data samples mainly located in low and moderate latitude regions in the United States. To mitigate biases arising from location, we included control variables to control for the impact of socioeconomic and demographic characteristics on sexual crimes.

We employed ArcGIS 10.8 to randomly generate non-sexual crime control points in each census block where sexual crime cases occurred. These control points were selected from outdoor spaces. A total of 4,679 control points (y = 0) (one for each census block) were generated. The method of random point selection has been proven to be viable in crime research (Hanaoka, 2018; Clougherty et al., 2015). Clougherty et al. (2015) generated non-crime random points for sexual assault data through random point selection and conducted spatial and temporal analyses of sexual assaults.

We selected a 200 m buffer radius as the analytic scale of physical environments because this distance is often considered a relatively small area accessible within a short walking distance (Villanueva et al., 2014). Moreover, the 200 m distance is regarded as a human sight distance that can reflect neighborhood-scale environmental characteristics (Huang et al., 2022). Within 200 m, people can have a clear perception and comprehension of the social and physical environments, which is one essential reason why many relevant studies have chosen to employ this distance as a buffer zone (e.g., Borbely & Rossi, 2022; Xu et al., 2024). Therefore, we opted for a 200 m buffer radius to account for the physical environment characteristics surrounding sexual crime locations. Nevertheless, to enhance the robustness of our results, we also included 400 m, 800 m, and 1200 m as supplementary buffer distances (see Appendix F to L).

2.2. Physical environment characteristics

To describe physical environment conditions, we incorporated variables encompassing urban design factors and landscape morphology factors.

For the urban design factors, we assessed the percentage of residential, commercial, and retail areas within buffer areas to reflect land use patterns. Recognizing the potential relations between sexual crimes and locations such as bars and hotels (Clougherty et al., 2015), we calculated the number of points of interest (POIs) for bars, restaurant retailers, and hotels. Nightlight data was used to measure lighting conditions, which are potentially associated with crimes (Ceccato et al., 2019), while road density was included as a metric to evaluate potential escape routes for offenders.

For landscape morphology factors, we considered the category, proportion, shape, connectedness, and aggregation of green spaces. We used the 2020 United States Land Cover Monitoring System (LCMS) with a 30-meter resolution for analysis (USDA Forest Service, 2021). With LCMS identifying 15 land cover categories (Appendix A), we specifically examined three of them: trees, grass, and trees mixed with grass, as they constituted the most significant proportions in our study areas. Other categories accounted for smaller proportions.

We computed four landscape metrics to assess green space proportion, shape, connectedness, and aggregation: Percentage of Landscape (PLAND), Landscape Shape Index (LSI), Mean Euclidean Nearest

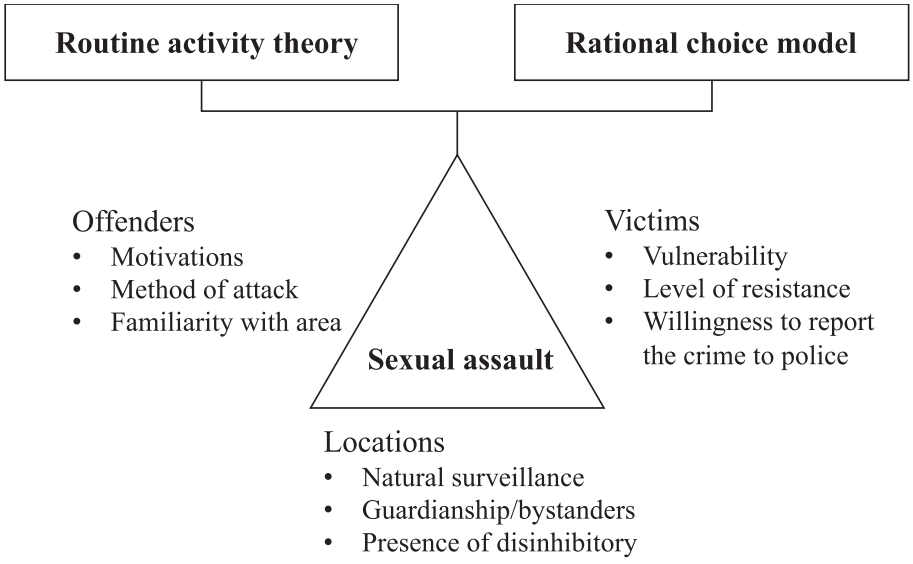


Fig. 1. The Sexual Assault Analysis Triangle (SAAT) model is grounded in both the Routine Activity Theory and the Rational Choice Model and includes different characteristics of motivated offenders, potential victims, and suitable locations (Dedel, 2011).

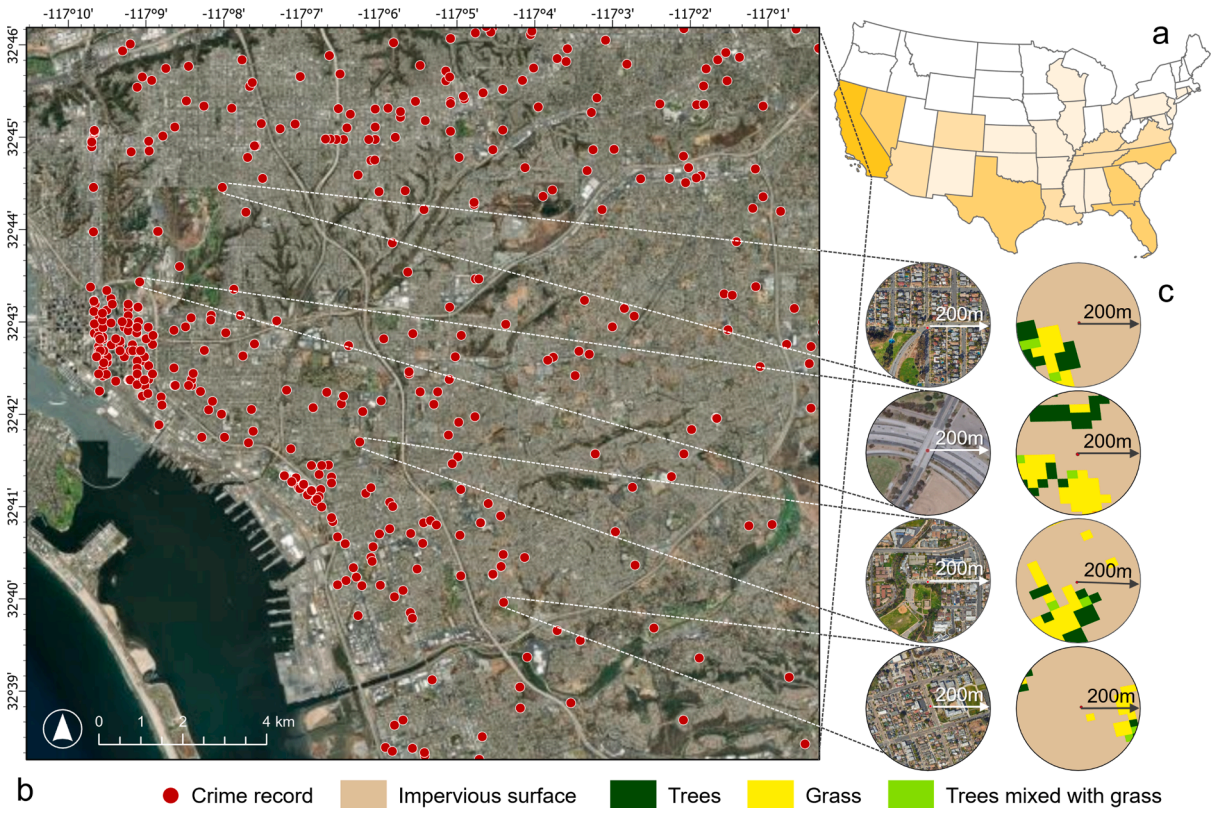


Fig. 2. A sample area of this study. (a) presents the spatial distribution of crime records we used. (b) exhibits the crime records in San Diego County, the red dots are crime incidences. (c) presents circular zones with radii 200 m centered at four sexual crime locations. The left circles are created using remote sensing data, while the right circles are based on land cover data (LCMS). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Neighbor Distance (ENN_MN), and Aggregation Index (AI) (Appendix B) (McGarigal, 2015). These metrics are associated with human activities and health outcomes (Wang & Tassinary, 2019; Wang et al., 2024), and our objective was to delve deeper into their correlations with sexual crimes.

2.3. Socioeconomic and demographic characteristics

Existing literature posits that the likelihood of crime occurrence is often associated with the demographic and economic dynamics of the community, ethnic composition, and housing vacancies (Sohn, 2016; Kim & Hipp, 2018). Similarly, sexual crimes are linked to these general criminogenic attributes. Socioeconomic and demographic characteristics of a location often reflect regional influences, which justifies the use of census tract-level data as representative variables. This methodology has been widely employed in previous studies (Lee, Lee, et al., 2023; Zhou et al., 2021).

Our study encompasses the following socioeconomic and demographic characteristics: First, we incorporated variables such as population density, median age, poverty rate, unemployment rate, and education level (specifically, the percentage of the population over 25 without a high school diploma) to depict the demographic and economic status of the communities. These factors serve as indicators of socioeconomic disadvantage, a circumstance that is closely associated with criminal activities (Beavon et al., 1994; Boessen & Hipp, 2015). Subsequently, we integrated demographic proportions of African American, Hispanic, and Asian populations as measures of ethnic distribution within the areas. Third, we employed rental and vacancy rates as metrics to gauge housing occupancy status. Historical research suggests that higher vacancies and rental rates are associated with less stable social conditions and may influence crime rates (Hipp, 2010). Furthermore, we took into account the gender distribution, particularly the proportion of young males and females aged 15–34, which is potentially pertinent to sexual crimes (Hewitt, Beauregard, Andresen, & Brantingham, 2018; Rocque, Posick, & Hoyle, 2015).

2.4. Random forest model

This study deployed a random forest model in Python 3.9 (Fig. 3). While logistic regression models might be sufficient for binary dependent variables, we opted for the random forest model for three pivotal reasons: First, the random forest model can capture nonlinear relationships and interaction effects among variables. Traditional regression models are often limited by linear assumptions and may overlook important nonlinear associations. Second, the random forest model is capable of handling missing values, outliers, and imbalanced data. Third, the random forest model can assess the contribution of each variable to the response variable through measures such as feature importance, providing insights for identifying key influencing factors (Breiman, 2001). Due to the numerous advantages it offers, several studies have opted to utilize the random forest model for regression analysis (Kim & Lee, 2023; Yang et al., 2024).

For our model construction, we partitioned the whole dataset into a 70 % training dataset and a 30 % testing dataset. Random forests provide a relative measure of variable importance based on the decrease in model accuracy when a variable is excluded, but they do not offer p-values to assess the significance of each predictor. To address this issue and determine the statistical significance of variable importance, we applied the Boruta algorithm, which creates shadow features (random permutations of real features) and iteratively compares their importance with that of the real features. This method tests the significance of each feature, confirming whether it genuinely contributes to the predictive

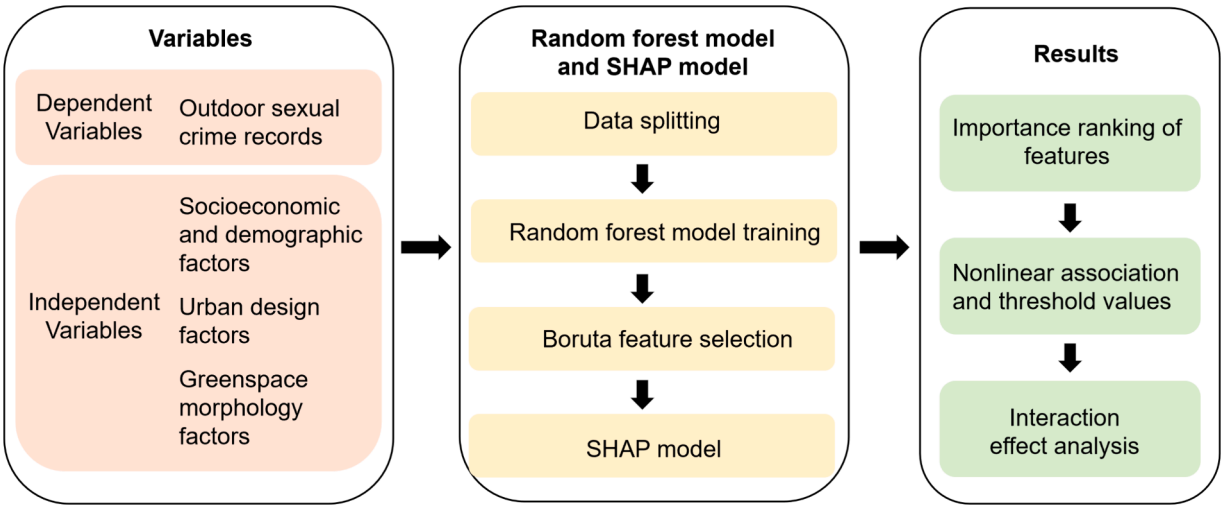


Fig. 3. A framework to describe methods and procedure of data analysis in this study.

model beyond random chance (Kursa et al., 2010). To elucidate the random forest model outcomes, we applied the Shapley Additive Explanations (SHAP) approach, a method grounded in statistically validated cooperative game theory, as proposed by Lundberg and Lee (2017). SHAP values facilitate a comprehensive understanding of global, local, and interaction effects, offering a more nuanced interpretation than the potentially biased estimates of Partial Dependence Plots (PDPs) proposed by Friedman (2001).

3. Results

The results of statistical analysis are presented as follows: First, we present the overall results of the model, including descriptive statistics, model accuracy, feature importance ranking, and brief results of control variables (including socioeconomic and demographic characteristics, land use, road density, and nightlight). Next, we show the nonlinear outcomes of the landscape morphology factors. Last, the results of the interaction effects of landscape morphology factors with socioeconomic and demographic characteristics are reported.

3.1. Random forest model results

To mitigate the multicollinearity problem, we checked and ensured that the variance inflation factor (VIF) of the variables in the model was less than 10 (Chen & Ye, 2021; Yang et al., 2024). Descriptive statistics for the landscape morphology factors are listed in Table 1, and descriptive statistics for other variables can be found in Appendix C. The random forest model yielded a mean squared error (MSE) of 0.003 for the training set and 0.056 for the test set, with corresponding R^2 values of 0.988 and 0.777, respectively.

Subsequent analyses using the random forest model included an assessment of SHAP contributions to determine the effect of different environmental elements on crime rates. The higher the SHAP value, the greater the role of the variable in the model. Fig. 4 illustrates the relative importance of independent variables. To obtain more accurate results and reduce bias, we included socioeconomic and demographic characteristics, land use, road density, and nightlight as control variables.

Following the Boruta algorithm, we identified twelve variables marked as confirmed features, which also exhibited high importance in the traditional random forest model. Moreover, Boruta provided additional evidence demonstrating that the importance of these variables is statistically significant. However, it is crucial to understand that conclusions drawn by machine learning models do not imply causality (Kursa et al., 2010). Nonetheless, our results remained valid in demonstrating a correlation between landscape morphology factors and sexual crimes (Kim & Lee, 2023; Wang et al., 2021). Boruta filtered out confirmed, tentative and rejected variables (Appendix D). The confirmed features included the proportion of total green spaces, trees and trees mixed with grass, shape index of total green spaces, trees, trees mixed with grass, and grass, aggregation index, road density, night light, population density, and median age. Although other variables also contributed to the model's performance, their relative importance was less significant and is depicted as grey images in the figures (Appendix E & F).

Table 1
Descriptive statistics of landscape morphology factors.

Landscape morphology variables	y = 0 & 1 (N = 9834)				y = 0 (N = 4679)				y = 1 (N = 5155)			
	Min	Max	Mean	S.D.	Min	Max	Mean	S.D.	Min	Max	Mean	S.D.
Aggregation index	0	100	86.64	13.75	0	99.6	86.27	16.75	44.90	100	86.97	10.28
Proportion of total green spaces	0	100	43.49	36.75	0	100	50.66	37.95	0	100	36.99	34.35
Shape index of total green spaces	0	4.37	1.70	0.83	0	4.37	1.75	0.83	0	3.90	1.66	0.82
Distance of total green spaces	0	349.85	46.21	55.29	0	349.85	43.85	55.76	0	342.05	48.35	54.78
Proportion of trees	0	100	25.69	31.41	0	100	31.58	33.93	0	100	20.34	27.88
Shape index of trees	0	4.21	1.40	1.00	0	4.21	1.57	1.02	0	4.14	1.25	0.96
Distance of trees	0	351.14	42.99	56.31	0	351.14	45.42	57.11	0	349.85	40.79	55.52
Proportion of trees mixed with grass	0	67.91	2.86	5.77	0	67.91	3.06	5.64	0	66.66	2.68	5.87
Shape index of trees mixed with grass	0	4.67	0.89	0.99	0	4.67	1.06	1.06	0	3.78	0.74	0.90
Distance of trees mixed with grass	0	362.49	40.21	63.17	0	362.49	49.84	67.94	0	339.41	31.47	57.13
Proportion of grass	0	100	14.15	19.37	0	100	15.77	20.93	0	97.80	12.69	17.71
Shape index of grass	0	4.64	1.53	1.04	0	4.5	1.70	1.05	0	4.64	1.38	1.01
Distance of grass	0	390	58.37	61.82	0	390	64.72	63.50	0	342.05	52.60	59.69

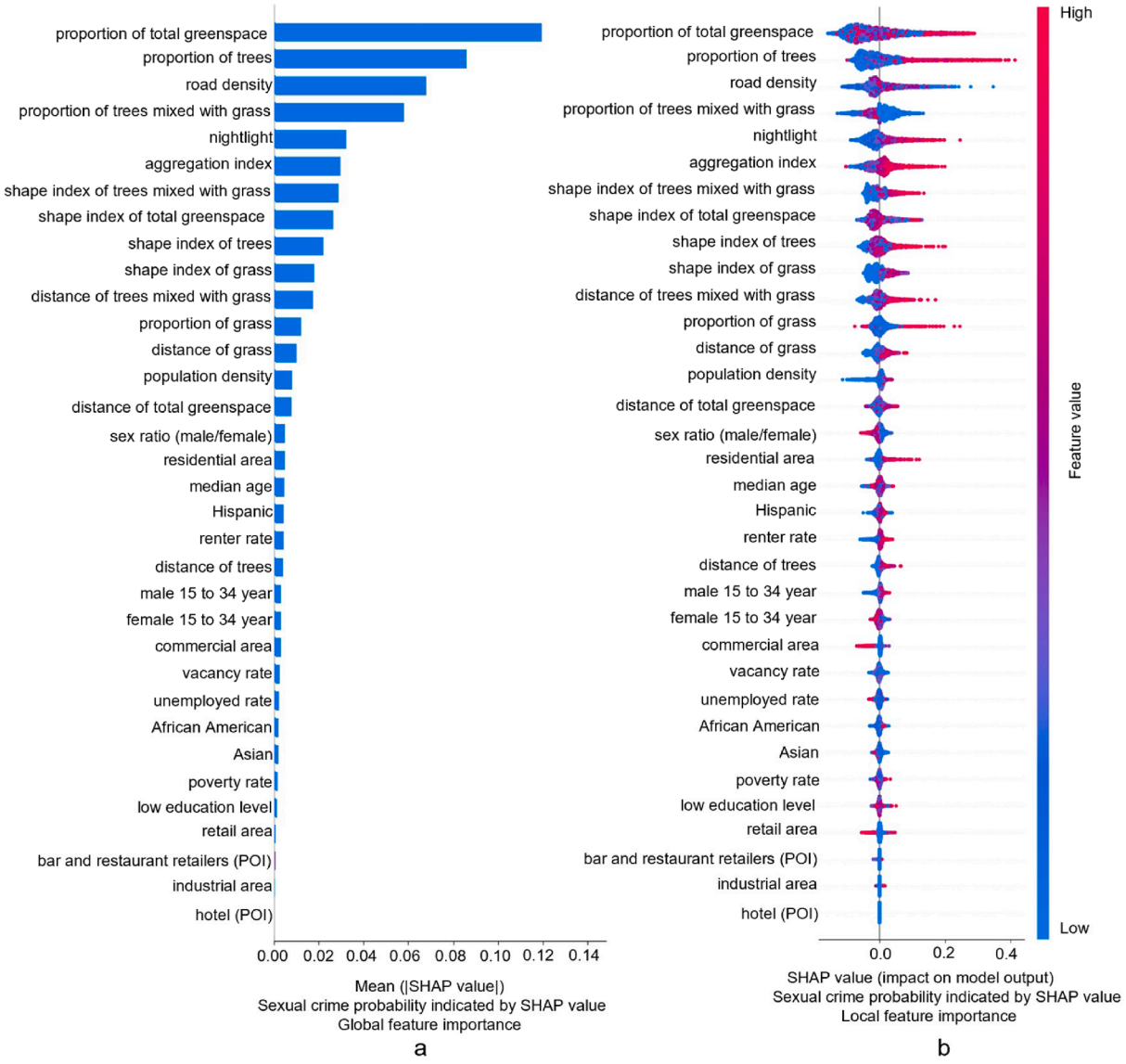


Fig. 4. The relative importance of independent variables. (a) presents the global feature importance in our model. (b) presents the local feature importance.

3.2. Curvilinear relationships between landscape morphology and sexual crime probability

This study utilized SHAP and Locally Weighted Scatterplot Smoothing (LOWESS) to substantiate the profound nonlinear associations between landscape morphology and sexual crime probability, as shown in Fig. 5.

3.2.1. Association between total green spaces and sexual crime probability

The SHAP analysis delineated a relatively flat curve within the range of 0–37 % for the proportion of total green spaces (Fig. 5 a). Beyond this threshold, a descending trend emerged, signifying a reduction in the sexual crime probability as the proportion of green spaces exceeded 37 %. This downward trajectory persisted until the proportion of total green spaces surpassed 85 %, at which point the local effect on sexual crime probability shifted from positive to negative.

3.2.2. Associations between different categories of green spaces and sexual crime probability

The SHAP value associated with the proportion of trees also showed a nonlinear curve (Fig. 5 b). The values remained stable up to 23 % tree coverage, after which a significant decrease in sexual crime probability was observed, indicating an inverse relationship between the proportion of trees and sexual crime probability. The inflection point, marking the shift from a positive to negative association with sexual crimes, was identified at 42 %. Conversely, the proportion of trees mixed with grass (more than 1 %) demonstrated an ascending curve (Fig. 5 c), suggesting a direct association with an increased sexual crime probability. The shift from a negative to a positive sexual crime probability occurred at 4 %. The proportion of grass did not rank among the top ten influential variables (Appendix E a). Grass exhibited a near-zero probability of sexual crimes within a substantial proportion range, resulting in a relatively flat curve between grass and sexual crimes.

3.2.3. Association between green space shape and sexual crime probability

Although the shape index curves for total green spaces, trees, trees mixed with grass, and grass were not identical, a general decreasing trend was discernible (Fig. 6). A higher shape index was associated with a negative sexual crime probability, implying that more intricately shaped green spaces were inversely associated with sexual crime probability.

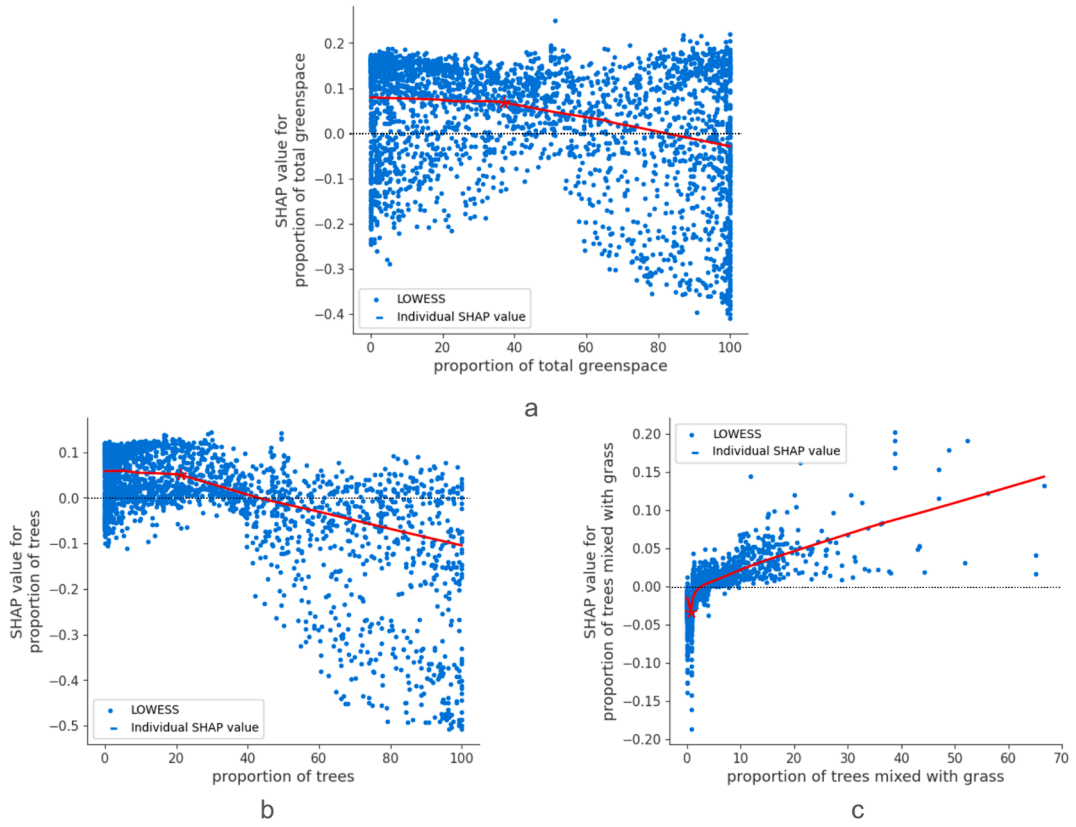


Fig. 5. Nonlinear associations between green space proportions and sexual crime probability. (a) is the SHAP value for the proportion of total green spaces. (b) is the SHAP value for the proportion of trees. (c) is the SHAP value for the proportion of trees mixed with grass. (d) is the SHAP value for the proportion of grass. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.2.4. Association between green space aggregation level and sexual crime probability

Except for a minority of data points clustering near zero, the aggregation index displayed a descending curve, particularly when the index exceeded 52 (Fig. 7), indicating that a higher aggregation level in green spaces was associated with a lower sexual crime probability. At an aggregation index of 83, the sexual crime probability shifted from positive to negative.

3.2.5. Association between green space connectedness and sexual crime probability

The connectedness of green spaces, as measured by distance metrics such as the ENN_MN (Euclidean Nearest Neighbor Mean), did not feature among the most significant variables (Appendix D). However, the SHAP visualization revealed a downward trend in the connectedness curve. Green spaces in closer proximity may inadvertently provide potential offenders with concealment opportunities, thus smaller ENN_MN values might correlate with a higher frequency of sexual crimes. Nevertheless, the affected SHAP value range was within 0.02, which could account for the low importance attributed to connectedness in this context.

3.3. Interaction effects of landscape morphology with socioeconomic and demographic characteristics

Urban socioeconomic characteristics may interact with environmental characteristics, thereby influencing crimes. However, the interaction effects between different categories of green spaces and other socioeconomic and demographic characteristics remain unclear. According to the importance ranking, two categories of green spaces, trees and trees mixed with grass, were more important, while the shape and aggregation of green spaces were more important than connectivity.

According to recognized studies, five indicators are often considered essential for illustrating regional socioeconomic and demographic characteristics: poverty rate (Stretesky et al., 2004), unemployment rate (Raphael & Winter-Ebmer, 2001), education level (Lance, 2011), vacancy rate (Cui & Walsh, 2015), and gender ratio (Edlund et al., 2013). We conducted an interaction effect analysis between these indicators and landscape morphology. A matrix plot of the top 13 feature pairs (greater than 0.005) based on their average interaction effects is presented. A Shapley value of 0 indicates no interaction effect, while a value greater than or less than 0 represents a positive or negative interaction effect, respectively, on sexual crime probability.

In areas with high poverty rates, the suppressive effect of trees on crime was stronger (see the grey part in Fig. 8 a). When the poverty rate exceeded 26 % and the proportion of tree coverage exceeded 39 %, the sexual crime probability was negative; however, when tree coverage was less than 20 %, areas with poverty rates exceeding 26 % were more prone to sexual crimes. There was also an interaction between trees mixed with grass and the poverty rate (Fig. 8 b): in areas with poverty rates exceeding 30 %, when the proportion of trees mixed with grass was less than 6 %, the sexual crime probability was negative. Furthermore, when the shape complexity of trees exceeded 1.8, it also had a suppressive effect on sexual crimes in areas with poverty rates exceeding 19 % (Fig. 8 c).

In areas with unemployment rates exceeding 2 %, when tree coverage was greater than 41 % or the tree shape index was greater than 0.7, there was a suppressive relationship with sexual crimes (Fig. 9). This indicates that in areas with high unemployment rates, increasing tree coverage or improving tree shape complexity can help reduce the sexual crime probability.

There were also interactions between a low education level and

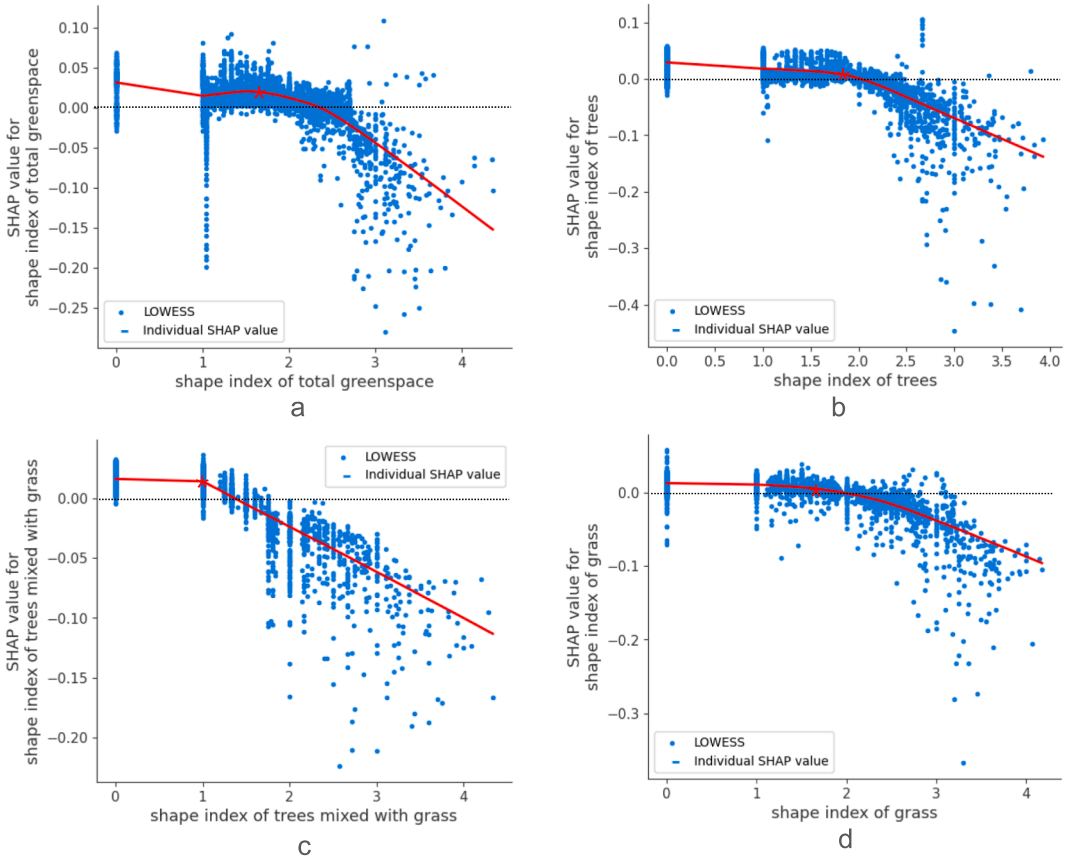


Fig. 6. Nonlinear associations between green space shapes and sexual crime probability. (a) is the SHAP value for the shape index of total green spaces. (b) is the SHAP value for the shape index of trees. (c) is the SHAP value for the shape index of trees mixed with grass. (d) is the SHAP value for the shape index of grass. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

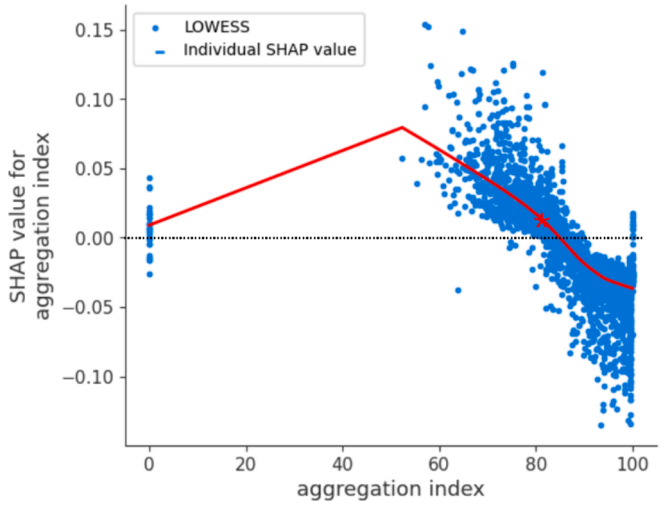


Fig. 7. Nonlinear association between green space aggregation index and sexual crime probability. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

landscape morphology. A higher value indicates a higher proportion of the population aged 25 and above with less than a high school education. When tree coverage exceeded 49 %, the sexual crime probability was negative in areas where the proportion of the population aged 25 and above with less than a high school education exceeded 19 % (Fig. 10a). Conversely, a proportion of trees mixed with grass not exceeding 6 % was associated with a lower sexual crime probability. Specifically, when the proportion was below 2 %, the sexual crime probability became negative (Fig. 10 b). Additionally, when the aggregation index exceeded 84, the sexual crime probability was also negative (Fig. 10 c). This suggests that in areas with lower education levels, increasing tree coverage, reducing the proportion of trees mixed with grass, or increasing aggregation can help curb sexual crimes.

In areas with vacancy rates greater than 0.06 and tree coverage greater than 43 %, the sexual crime probability was lower (Fig. 11 a). In areas with high vacancy rates, increasing the shape complexity of trees and trees mixed with grass also presented an opportunity to reduce the sexual crime probability (Fig. 11 b & c).

A sex ratio exceeding 100 implies an imbalance in the ratio of males to females. In areas with higher sex ratios, when tree coverage exceeded 63 % or the proportion of trees mixed with grass was less than 4 %, the sexual crime probability was lower (Fig. 12).

4. Discussion

This study investigates the relationships between landscape morphology and sexual crime probability after controlling for physical environments, socioeconomic, and demographic factors. We interpret and discuss the results from the following perspectives: First, we offer explanations for the associations between landscape morphology and sexual crime probability. We then interpret why beneficial effects of green spaces in reducing sexual crimes are stronger in socioeconomically disadvantaged areas. Second, we propose a hypothetical framework that integrates a new layer of environmental theory related to landscape morphology into the Sexual Assault Analysis Triangle (SAAT) theory. Third, we present potential implications for green space planning and design based on our findings. Lastly, we acknowledge the

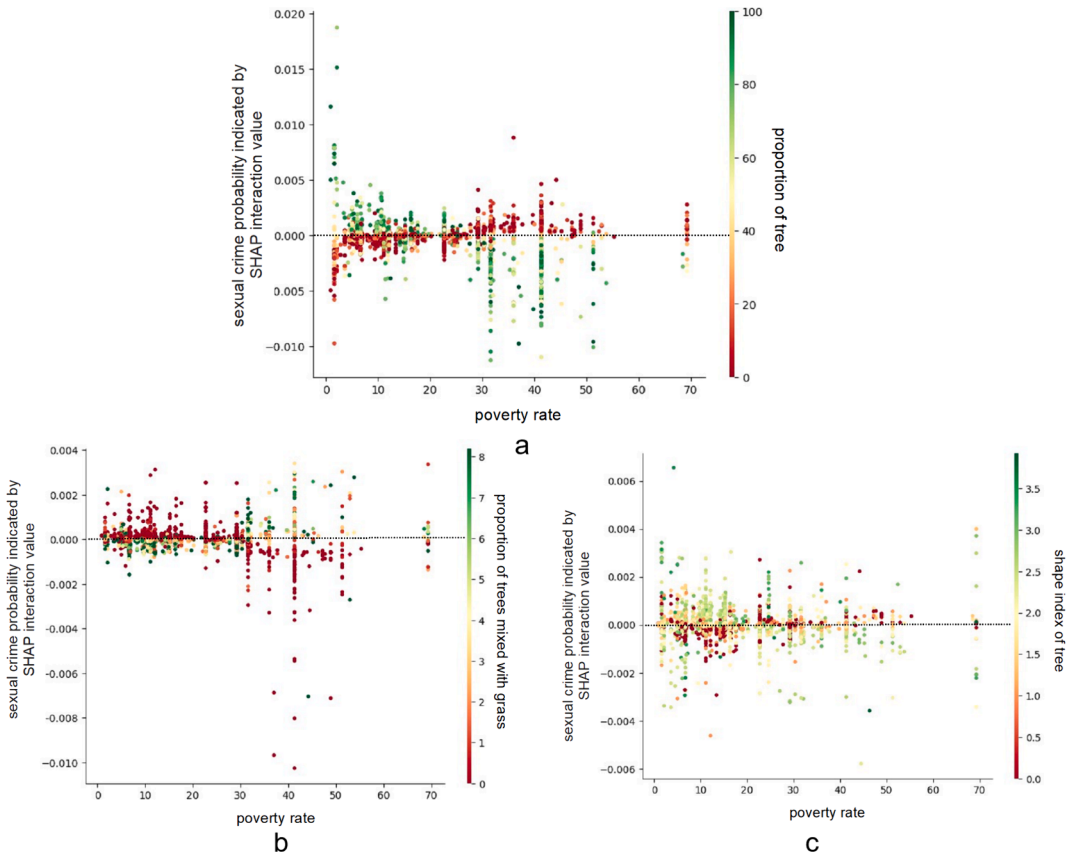


Fig. 8. Interaction effects between landscape morphology factors and poverty rates on sexual crime probability. (a) presents the proportion of trees and poverty rates; green means higher proportion of trees, and red means lower proportion of trees. (b) presents the proportion of trees mixed with grass and poverty rates; green means higher proportion of trees mixed with grass, and red means lower proportion of trees mixed with grass. (c) presents the shape index of trees and poverty rates; green means higher shape index of trees, and red means lower shape index of trees. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

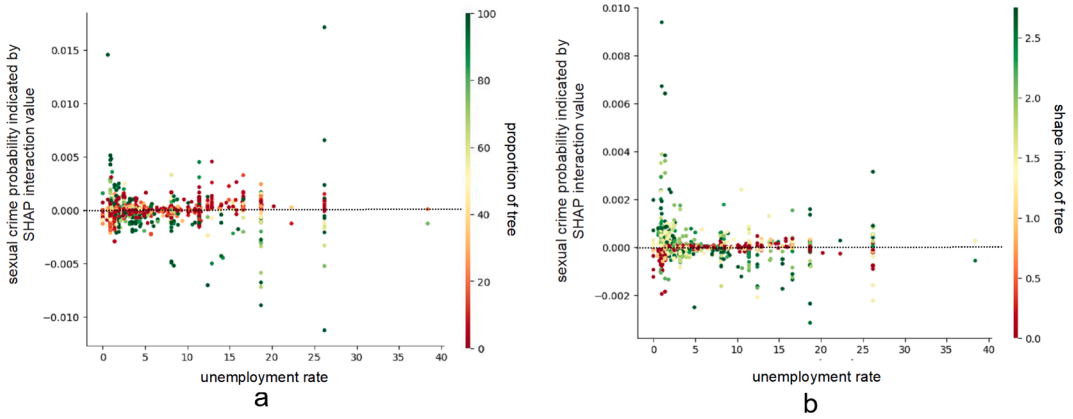


Fig. 9. Interaction effects between landscape morphology factors and unemployment rates on sexual crime probability. (a) presents the proportion of trees and unemployment rates; green means higher proportion of trees, and red means lower proportion of trees. (b) presents the shape index of trees and unemployment rates; green means higher shape index of trees, and red means lower shape index of trees. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

limitations of this study and offer suggestions for future research.

4.1. Interpretation of the key findings

4.1.1. Potential deterring effect of total green spaces on sexual crime probability

Our findings reveal that the association between total green spaces and the sexual crime probability follows a nonlinear but descending curve. This pattern suggests that a higher proportion of total green spaces can predict a lower sexual crime probability. This finding aligns with the results of several previous studies on violent crimes. Some studies have investigated the relationships between total green spaces, e.g., measured by the Normalized Difference Vegetation Index (NDVI), and various types of violent crimes, including sexual violence (e.g.,

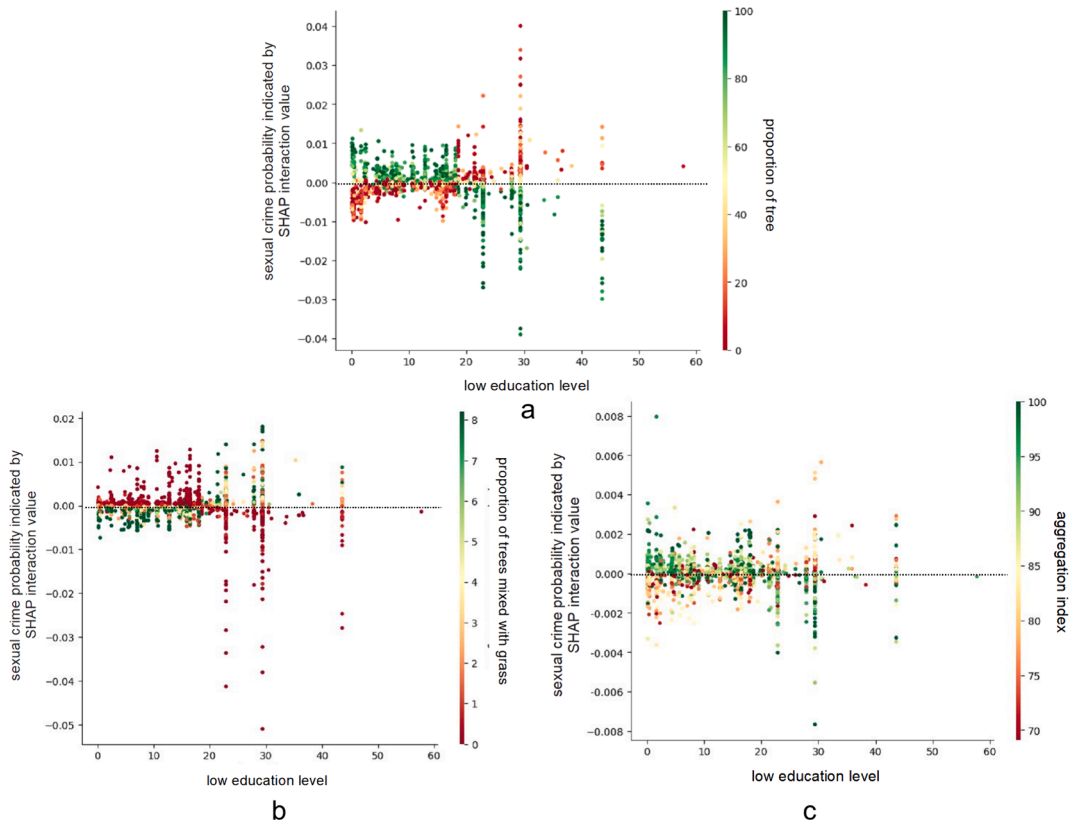


Fig. 10. Interaction effects between landscape morphology factors and low education levels on sexual crime probability. The higher value indicates the higher proportion of the population aged 25 and above with less than a high school education. (a) presents the proportion of trees and low education level; green means higher proportion of trees, and red means lower proportion of trees. (b) presents the proportion of trees mixed with grass and low education level; green means higher proportion of trees mixed with grass, and red means lower proportion of trees mixed with grass. (c) presents the aggregation level and low education level; green means higher aggregation index, and red means lower aggregation index. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Jonescu et al., 2023; Khatri and Abdellatif, 2020; Mancus et al., 2022; Venter et al., 2022). Their findings indicated that increased greenness may reduce the incidence of violent crimes, at least within the specific context examined in those studies. As introduced in section 1.4, total green spaces are likely to have a sexual crime-deterring effect; however, it is a general concept that encompasses diverse combinations of various green space categories. Therefore, the finding about total green spaces is meaningful but insufficient to accurately evaluate the impacts of green spaces on sexual crime probability. It is also not informative enough to guide the administration and design practice of green spaces. More attention should be devoted to the associations between specific categories of green spaces and sexual crime probability, as interpreted below.

4.1.2. Potential deterring effect of trees on sexual crime probability

One of major findings is that trees, in general, yield a negative association with the sexual crime probability. Different from the findings of many previous studies, the association is curvilinear, and several critical threshold values are identified. This complex relationship calls for a more nuanced interpretation.

When the proportion of trees was at a low or moderately low level (≤23 % in this study), the association between the tree proportion and sexual crime probability was negative, and there was no clear change as the tree proportion increased. This finding is supported by a previous study that suggested a low density of trees may encourage crime by offering hiding spaces for offenders, which results in a sexual crime facilitating effect (Donovan & Prestemon, 2012). Meanwhile, the natural surveillance effect is low due to the sparse distribution of trees, which results in a low sexual crime deterring effect. Together, the facilitating effect outweighs the deterring effect when the proportion of trees is at a low or moderately low level.

As the proportion of trees exceeded a moderately low level (23 % in this study), the curve showed a clear descent pattern, indicating a significant increase in the deterring effect of trees and a significant decrease in the facilitating effect. As the proportion of trees reached a moderate level (42 % in this study), the deterring effect started to outweigh the facilitating effect. This phenomenon echoes findings of previous studies: Two studies found that a large area of trees yielded a negative association with crime rates, and they ascribed this beneficial association to the significant natural surveillance effect of those trees (Kuo & Sullivan, 2001; Welsh et al., 2010). Other studies also made similar interpretations. Donovan and Prestemon (2012) argued that a larger tree coverage often suggests a presence of more mature, expansive, and taller tree canopies. These tree canopies can provide better and more spaces for residents and visitors to stay and relax, which can promote social connections and natural surveillance and finally deter the crime activities. This argument is also supported by two other important studies (Kuo et al., 1998; Bjerke et al., 2006).

4.1.3. Potential facilitating effect of trees mixed with grass on sexual crime probability

In contrast to the findings on tree proportion, our study reveal that trees mixed with grass have a significant positive association with sexual crimes. This landscape configuration represents a combination of vegetation characterized by a dense, low-growing understory and a sparse tree canopy (according to United States Land Cover Monitoring System, the proportion of trees is less than 10 %).

The sparse tree coverage in trees mixed with grass (less than 10 %)

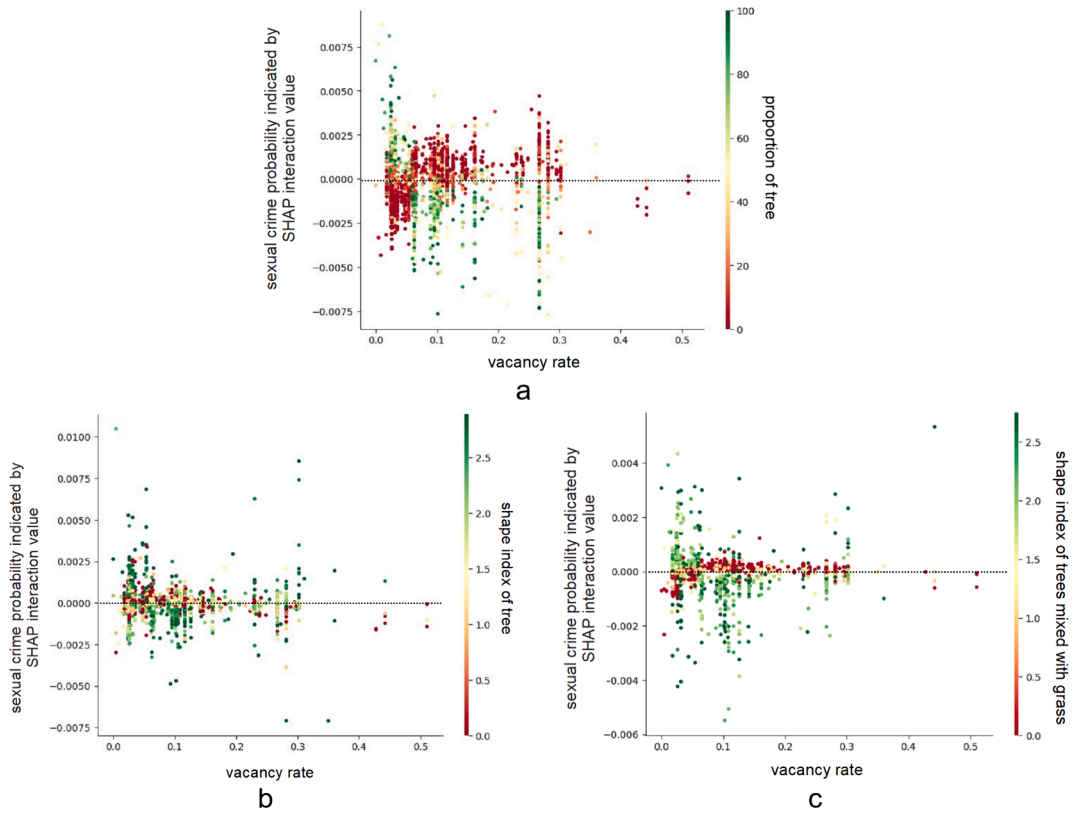


Fig. 11. Interaction effects between landscape morphology and vacancy rates on sexual crime probability. (a) presents the proportion of trees and vacancy rates. (b) presents the shape index of trees and vacancy rates. (c) presents the shape index of trees mixed with grass and vacancy rates.

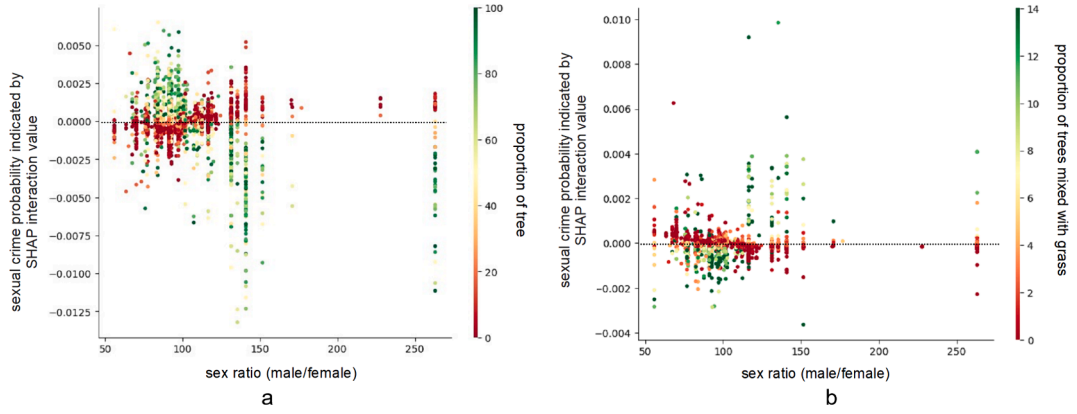


Fig. 12. Interaction effects between landscape morphology factors and sex ratios (male/female) on sexual crime probability. (a) presents the proportion of trees and sex ratio (male/female); green means higher proportion of trees, and red means lower proportion of trees. (b) presents the proportion of trees mixed with grass and sex ratio (male/female); green means higher proportion of trees mixed with grass, and red means lower proportion of trees mixed with grass. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

fell below the critical threshold mentioned earlier (23 %), suggesting that trees in this context may not provide adequate natural surveillance. Consequently, the deterring effect of trees is diminished, as the sparse canopy fails to create sufficient spaces for promoting social connections and natural surveillance (Donovan & Prestemon, 2012; Bjerke et al., 2006).

Furthermore, as dense, low-growing vegetation is generally less preferred, and this perception of heightened risk may deter residents from engaging in activities near such places (Kaplan & Kaplan, 1989; Bjerke et al., 2006). The thick understory can provide concealment for offenders, reducing the visibility of potential victims and creating a sense of vulnerability. It may also increase the perceived risk of crime and the likelihood of successful criminal activity (Potgieter et al., 2019).

4.1.4. Potential deterring effect of more complex-shaped green spaces on sexual crime probability

Besides the findings related to proportion variables, we find that the spatial configuration of green spaces matters for the sexual crime probability. The complexity of green spaces is inversely related to sexual crime probability. A higher shape index, indicative of more complex shapes and longer boundaries, can create a stronger spatial connection and interactions between green spaces and the surrounding urban spaces (Dramstad et al., 2013). This shape complexity highlights the interconnection between the inner and outer areas of green spaces,

facilitating increased interactions between these spaces and their adjacent urban environments.

This heightened integration of green spaces into the urban landscape can enhance their accessibility and frequency of use by residents, fostering a greater variety and frequency of residential activities (Wang & Tassinary, 2024; Zhu et al., 2017). These intricate green space configurations offer diverse spaces and experiences that cater to various user preferences, creating appealing landscapes and inviting spaces for staying and relaxing (De Clercq et al., 2007).

Complex-shaped green spaces are influenced by edge effects, where the increased edge provides more opportunities for people to access and interact with green spaces, reducing isolation and further enhancing perceived safety and the ability to respond to potential threats (Yang et al., 2020). The combination of improved visual and auditory connections creates crime deterrence in green spaces with complex shapes (Katyal, 2001). Additionally, well-designed and maintained green spaces with complex shapes not only provide better visibility and auditory connections but also convey a strong sense of control (Bonenberg, 2015).

Lastly, our findings also highlight the non-linear association between green space complexity and sexual crime probability. As the complexity of green spaces increased beyond certain thresholds, there was a significant decrease in the sexual crime probability. Furthermore, when the complexity reached even higher levels, sexual crime probability shifted from positive to negative (Fig. 6). This curvilinear pattern may suggest that complexity generally helps reduce sexual crime probability, but a moderately high level of complexity is necessary to trigger a substantial effect, with the impact becoming more enhanced after surpassing specific thresholds.

4.1.5. Potential deterring effect of more aggregated green spaces on sexual crime probability

We also find that green spaces with a higher level of aggregation are associated with a lower level of sexual crime probability. Green space aggregation creates larger, more continuous areas that support biodiversity, ecological health, and attract more visitors who stay longer for various social and recreational activities (Dramstad et al., 2013; Wang & Tassinary, 2019). This aggregation emphasizes the interconnection and interaction among inner areas of green spaces, promoting a more cohesive environment.

Moreover, aggregated green spaces often incorporate a variety of recreational functions and facilities, such as sports fields, playgrounds, and walking trails (Ha et al., 2024; Taylor et al., 2019). These amenities encourage more frequent and longer visits, enhancing perception of safety (Jiang et al., 2018). Therefore, aggregated green spaces improve social cohesion, and cohesion enhances residents' willingness to intervene in suspicious activities and report crimes, further deterring potential sexual offenders (Pattavina et al., 2006).

Aggregated green spaces also contribute to crime reduction through enhanced visual and auditory connections, as well as the display of good management and nature surveillance (Nguyen et al., 2021; Ha et al., 2024). It is easier for a larger space to exist inside an aggregated green spaces, where internal activities and sightlines are not easily disturbed (Nguyen et al., 2021). This enhanced visibility is achieved through the open or unobstructed areas in aggregated green spaces (Sahraoui et al., 2016). Furthermore, aggregated green spaces often have fewer physical obstacles, such as buildings or dense vegetation, that can block or absorb sounds (Bild et al., 2018). The open or unobstructed nature of these spaces allows sounds to travel more freely and with less attenuation, making it easier for visitors to perceive and respond to potential threats (Han et al., 2018).

Similar to the complexity of green spaces, we also find a nonlinear but discernible pattern linking the aggregation of green spaces and sexual crime probability (Fig. 7). This pattern suggests that, in general, aggregation helps reduce the sexual crime probability. However, a moderately large degree of aggregation may be necessary to trigger a substantial effect.

4.1.6. Potential stronger deterring effect of green spaces on sexual crime probability in socioeconomically disadvantaged areas

Compared to previous studies, one original contribution of this study is that we successfully identify the significant interactive effects between landscape morphology with socioeconomic and demographic characteristics. Our results suggest that the influence of landscape morphology on crime is more prominent in socioeconomically disadvantaged areas, which are often characterized by high poverty rates, high unemployment rates, high vacancy rates, low education levels, and gender imbalances (Wheeler & Steenbeek, 2021; Kim & Lee, 2023).

The marginal effect of green spaces, as proposed by a study, can help explain this finding (Lu et al., 2021). The study highlighted that people living in disadvantaged areas often have a lower exposure to green spaces within walking distance, and this environmental disparity contributes to significant health disparities. They further proposed that introducing an equal dose of green spaces would yield a greater marginal effect in disadvantaged urban areas compared to advantaged ones. This difference in marginal effect is further corroborated by a recent study conducted by the same research team (Xu et al., 2024).

Many studies provided supporting evidence for our interpretation. For example, some studies have found that the introduction of well-designed and maintained green spaces can lead to significant reductions in crime rates, particularly in disadvantaged neighborhoods characterized by lower socioeconomic status and higher crime rates (e.g., Fleming et al., 2016; Lee, Koo, & Kim, 2023; Perkins et al., 1990). The marginal benefits of green space interventions are higher in these areas compared to advantaged neighborhoods, which often already have low crime rates and sufficient green spaces, facilities, and services, resulting in a smaller magnitude of improvement (Chalfin et al., 2021; Macdonald et al., 2021).

4.2. A promising theoretical model to link landscape morphology to sexual crime probability

The Sexual Assault Analysis Triangle (SAAT) encompasses three key elements of sexual crimes: offenders, victims, and locations. However, the SAAT model simply attributes the risk of sexual crimes to the characteristics of these three elements, ignoring the influence of the physical environments as well as socioeconomic and demographic characteristics. Landscape morphology, as a comprehensive tool to describe the physical environments, may interact with socioeconomic and demographic characteristics, thereby influencing the sexual crime probability. Thus, it is necessary to expand the SAAT model from a single-layer model to a three-layer model, which is named as the Landscape-Sexual Crime Model (LSCM) in this study (Fig. 13).

The main advantage of LSCM lies in establishing comprehensive connections among the three layers of factors, which including three aspects of SAAT (top layer), landscape morphology (middle layer), and socioeconomic and demographic characteristics (bottom layer) (Fig. 13). The physical environments, described by landscape morphology, can directly influence the sexual crime probability by affecting the three aspects of SAAT. In addition, socioeconomic and demographic characteristics can indirectly influence the sexual crime probability through influencing the proportion, configuration, and quality of physical environments, as well as directly influence the three aspects of SAAT. Meanwhile, landscape morphology can also influence socioeconomic and demographic characteristics, thus having an indirect impact on the sexual crime probability. In general, the middle and bottom layers exhibit interactive effects, and both layers have direct and indirect impacts on the sexual crime probability.

For the layer of landscape morphology factors, LSCM not only considers the proportion characteristics but also values the spatial configuration characteristics of green spaces. Unlike many studies that only highlight the importance of proportion variables, we find that

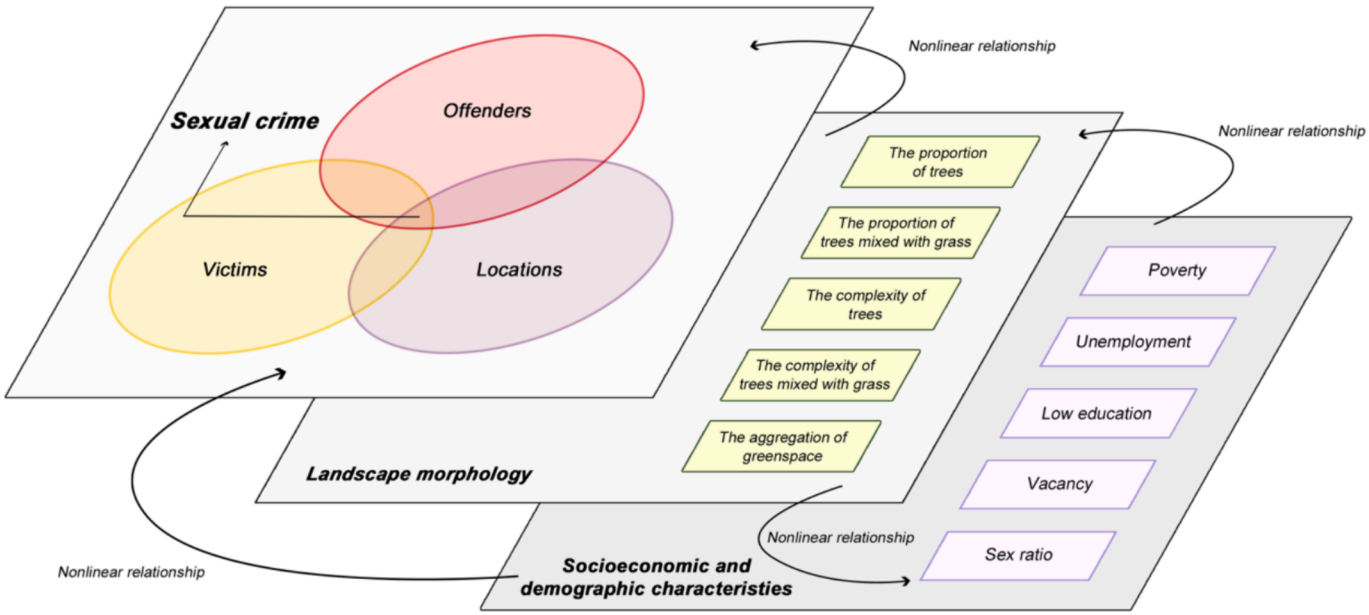


Fig. 13. The Landscape-Sexual Crime Model (LSCM) featured three layers of factors. The top layer includes three aspects of the Sexual Assault Analysis Triangle (SAAT), the middle layer includes landscape morphology factors, the bottom layers include socioeconomic and demographic characteristics. The middle and bottom layers can directly and indirectly influence the sexual crime probability (top layer), and there are interactions between the middle and bottom layers. The model needs to control other built environment covariates in the analysis, and the significant factors for the middle and bottom layers may vary when the model is applied for different regions and contexts.

optimizing the shape and aggregation of green spaces may be effective in reducing the sexual crime probability. Thus, both proportional and spatial characteristics of green spaces are incorporated in the model.

Lastly, LSCM calls for special attention to the nonlinear relationships between the landscape morphology factors and sexual crime probability. The associations between key landscape morphology factors and sexual crime probability are generally present, but the effects are relatively small when the dose of green spaces is low. However, as the dose of green spaces increases to a moderate level, it triggers a substantial reduction in the sexual crime probability, as reflected by a dramatic change in the curve's pattern.

4.3. Planning and design implications

The findings and interpretations of those findings enable us to propose some important suggestions for planning and design implications.

First, the findings reveal that the proportion of greenspaces matters for adjusting sexual crime probability. Moreover, the association is nonlinear, indicating the presence of threshold effects related to different doses of green spaces. Thus, we suggest that a fundamental step of landscape planning and design is to provide sufficient areas of green spaces within walking distance for each urban district or neighborhood. Trees, especially those without lower layers of plants that can obstruct visual and physical accessibility, should occupy at least 23 % of the land, with a preference for more than 42 %. Meanwhile, the trees mixed with grass should be controlled at a low level, with 4 % considered acceptable and less than 1 % preferred (Table 2).

Second, the spatial configuration of green spaces matters for adjusting the sexual crime probability, and the relationship is similar to what we described for the proportion of green spaces (Abd El Aziz, 2020). Attention should be given to increasing the shape complexity and aggregation of green spaces to maximize their benefits in crime prevention. The satisfactory dose and the preferred dose of configuration factors are also suggested in Table 2.

Third, the proportion and configuration factors of landscape morphology that influence sexual crime probability tend to be interactive with each other. Thus, we suggest that the planning and design of green spaces should try best to meet recommended dose values in Table 2 to ensure an optimal effect.

Table 2
Thresholds for the relationships between landscape morphology factors and sexual crime probability. The satisfactory dose is indicated by the major inflection point of a curve, and the preferred dose is indicated by the zero point (when probability value = 0).

	The satisfactory dose indicated by the major inflection point	**The preferred dose** indicated by the zero point
Proportion of trees	>23 %	>42 %
Proportion of trees mixed with grass	<4%	<1%
Shape index of total green spaces	>1.7	>2.4
Shape index of trees	>1.9	>2
Shape index of trees mixed with grass	>1	>1.4
Shape index of grass	>1.6	>2
Aggregation index	>78	>83

Fourth, our findings reveal that adding green spaces in disadvantaged areas may have a greater marginal effect on reducing sexual crime probability. Therefore, priority should be given to allocating green spaces to those areas.

Lastly, we summarize a specific set of suggestions to support evidence-based planning, design, and management of green spaces in appropriate ways to reduce the occurrence of sexual crimes. These suggestions are applicable to both socioeconomically advantaged and disadvantaged areas (Table 3).

4.4. Limitations and opportunities for future research

This study is an initial exploration of the relationships between landscape morphology and sexual crime probability. Given the various constraints, it is not possible to address all aspects of this complex issue within a single study. Collective efforts in future research are necessary to further advance our knowledge in this area. Nevertheless,

Table 3
A specific set of suggestions to support evidence-based plan, design, and management of green spaces.

Critical landscape morphology factors	Plan, design, and management strategies of public green spaces that may contribute to reducing sexual crime probability
Proportion of trees	• Utilize the existing public open space to plant more trees. • Remove the vacant buildings and utilize abandoned land to plant more trees. • Creating more areas with tree canopy coverage and clean ground with compatible recreational facilities to facilitate public use of those areas. • Choose appropriate tree species to achieve good visual, acoustic, and physical permeability: trees should have ample space beneath their canopies; trees should have a balance of shaded and illuminated areas under the tree canopies; and trees don't have substantial profile of trunks.
Proportion of trees mixed with grass	• Reduce trees mixed with grass to ensure that lower level vegetation is properly controlled to avoid significant visual obstacles. • Modify areas of trees mixed with grass to increase open space that can accommodate diverse recreational and social activities. • Remove tall grass (grass with a height above the knees) in open spaces between areas covered by tree canopies.
Shape index of green spaces	• Create an interlocking relationship between green spaces and other urban spaces to promote interconnection and interaction between the inner and outer regions of green spaces. • Create biologically and spatially comprehensive boundaries of green spaces to attract people to visit and stay in nearby areas.
Aggregation index	• Create continuous green spaces, such as large parks and greenways, to increase the frequency and duration of residents' use of green spaces. • Make sure the areas inside the large and continuous green spaces have good visual, acoustic, and physical connections. • Increase facilities and services inside the green spaces to promote routine activities for recreational, social, and exercise purposes. • Allocate high-quality and diverse recreational facilities and services inside the large and continuous green spaces to promote an equal allocation of users in different inner areas of the green spaces.

acknowledging the limitations of this study may provide valuable insights for future investigations.

First, this study employed the random forest model and Boruta algorithm, successfully identifying significant correlations between landscape morphology and sexual crime. While these methods are effective in identifying predictors for sexual crimes, they cannot provide direct evidence of causal relationships (Kursa et al., 2010). In this study, we have carefully interpreted the findings based on theoretical and empirical evidence from previous studies, which serves as a compelling argument for possible causal relationships between green space characteristics and sexual crime risk. Nonetheless, we strongly recommend that future studies seek stronger evidence of causal relationships through alternative methods, such as longitudinal, experimental, or natural experimental approaches (Branas et al., 2011; Ceccato et al., 2020; Jiang, Shen, et al., 2021).

In addition, although this study differentiated the land cover categories of green spaces, it did not differentiate the function types of green spaces. Researchers have suggested that green spaces within the same land cover category may serve different functions in urban life, which can influence the occurrence of sexual crimes (Ceccato et al., 2020). Future studies should consider using land use data or eye-level visual materials to identify the specific functions of green spaces and incorporate these factors into the data analysis.

Moreover, this study focused on violent sexual crimes, which share similar psychological and behavioral mechanisms. Additionally, we exclusively investigated crimes that occurred in public open spaces. These two choices largely enhance the validity of the findings. Nevertheless, future studies can further conduct analyses by separately investigating specific categories of sexual crimes, such as rape and sexual assault, while also considering subjects with different demographic and socioeconomic characteristics, including age and gender for both offenders and victims (Chopin & Caneppele, 2019).

Furthermore, this study analyzed 5,155 sex crime cases that occurred within one-year period, encompassing a wide variety of physical environments, which contributes to the statistical robustness of the findings. However, we recommend that future studies incorporate data from multiple years as it can further enhance the validity and reliability of the study and be beneficial in identifying potential long-term effects (Ali & Bibi, 2020).

The study area was limited to the southern and central regions of the United States, with a lack of data from the northern part. However, the investigated regions already encompassed a significant portion of the country's land and population, as well as a wide variety of landscape morphology, socioeconomic factors, and demographic characteristics. This approach to data collection ensured the robustness of our results and allowed us to provide evidence-based suggestions for the planning and management of green spaces for millions of people. Nevertheless, the climatic characteristics of the northern states may influence individuals' outdoor perceptions, behaviors, and activities differently compared to those in the southern and central regions. These characteristics include, but are not limited to, longer winters, lower temperatures, strong and cold winds, and significant seasonal changes in green spaces and plants. These factors may further affect the relationships between landscape morphology and sexual crime probability (Ranson, 2014). We recommend that future research should gather data from a broader range of regions, including the northern states, to establish the generalizability of our findings. Additionally, future studies may consider employing subdivided data to examine the relationships between green spaces and sexual crime probability in different climate zones.

Lastly, while the proposed Landscape-Sexual Crime Model is a hypothesis that requires further empirical validation, this study represents a significant step towards its development, as major pathways have been investigated and verified. Future studies may aim to test our hypothetical framework in different contexts, contributing to the establishment of a robust yet adaptable Landscape-Sexual Crime Model.

5. Conclusion

This study employed a random forest model to investigate the relationships between landscape morphology and sexual crimes. Our findings highlight the significant impact of the proportion and configuration factors of landscape morphology on sexual crime probability. Furthermore, we have identified nonlinear relationships between landscape morphology and sexual crimes, determining threshold values for the satisfactory and preferred doses of green spaces. We also observed notable interaction effects between landscape morphology with socioeconomic and demographic characteristics. Moreover, green spaces exhibited a stronger deterring effect on sexual crimes in socioeconomically disadvantaged areas, emphasizing the importance of prioritizing green space interventions in these areas. Building upon our findings and previous research, we propose the Landscape-Sexual Crime Model (LSCM), which outlines potential avenues for future research and calls for collective efforts to explore effective strategies for using green spaces to reduce sexual crimes.

CRediT authorship contribution statement

Huan Lu: Writing – review & editing, Writing – original draft,

Visualization, Software, Methodology, Formal analysis, Data curation. **Lin Liu:** Writing – review & editing, Validation. **Hua Zhong:** Writing – review & editing, Validation. **Bin Jiang:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgement

The authors would like to thank Ms. Linda Larsen for her contribution to proofreading and revising the paper. The authors appreciate Dr. Lan Luo and Ms. Chuzhen Wang for their comments on the figures. Lastly, the authors also appreciate the enormous support from Prof. William. C. Sullivan, Prof. Chris Webster, Prof. Peng Gong, Prof. Ivan Valin, Prof. Mathew Pryor, Prof. Shenjing He, and Prof. Chun-Yen Chang.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.landurbplan.2024.105143.

References

Abd El Aziz, N. A. (2020). Space syntax as a tool to measure safety in small urban parks - A case study of rod el farag park in cairo, egypt. *Landscape Architecture Frontiers, 8*(4), 42–60.
Abrahams, N., Devries, K., Watts, C., Pallitto, C., Petzold, M., Shamu, S., & García-Moreno, C. (2014). Worldwide prevalence of non-partner sexual violence: A systematic review. *The Lancet, 383*, 1648–1654.
Ali, A., & Bibi, C. (2020). Public Policies, Socio-economic environment and crimes in Pakistan: A time series analysis. *Bulletin of Business and Economics (BBE), 9*(1), 1–11.
Beauregard, E., Proulx, J., & Rossmo, D. K. (2005). Spatial patterns of sex offenders: Theoretical, empirical, and practical issues. *Aggression and Violent Behavior, 10*(5), 579–603.
Beauregard, E., Rossmo, D. K., & Proulx, J. (2007). A descriptive model of the hunting process of serial sex offenders: A rational choice perspective. *Journal of Family Violence, 22*, 449–463.
Beavon, D. J., Brantingham, P. L., & Brantingham, P. J. (1994). The influence of street networks on the patterning of property offenses. *Crime Prevention Studies, 2*(2), 115–148.
Bild, E., Pfeffer, K., Coler, M., Rubin, O., & Bertolini, L. (2018). Public space users' soundscape evaluations in relation to their activities. An Amsterdam-based study. *Frontiers in Psychology, 9*, 1593.
Bjerke, T., Østdahl, T., Thrane, C., & Strumse, E. (2006). Vegetation density of urban parks and perceived appropriateness for recreation. *Urban Forestry & Urban Greening, 5*(1), 35–44.
Boessen, A., & Hipp, J. R. (2015). Close-ups and the scale of ecology: Land uses and the geography of social context and crime. *Criminology, 53*(3), 399–426.
Bonenberg, W. (2015). Public space in the residential areas: The method of social-spatial analysis. *Procedia Manufacturing, 3*, 1720–1727.
Borbely, D., & Rossi, G. (2022). Urban regeneration projects and crime: Evidence from Glasgow. *The Sheffield Economic Research Paper Series, 2022020*(2022020).
Branas, C. C., Cheney, R. A., MacDonald, J. M., Tam, V. W., Jackson, T. D., & Ten Have, T. R. (2011). A difference-in-differences analysis of health, safety, and greening vacant urban space. *American Journal of Epidemiology, 174*(11), 1296–1306.
Branas, C. C., South, E., Kondo, M. C., Hohl, B. C., Bourgois, P., Wiebe, D. J., & MacDonald, J. M. (2018). Citywide cluster randomized trial to restore blighted vacant land and its effects on violence, crime, and fear. *Proceedings of the National Academy of Sciences, 115*(12), 2946–2951.
Bratman, G. N., Anderson, C. B., Berman, M. G., Cochran, B., De Vries, S., Flanders, J., & Daily, G. C. (2019). Nature and mental health: An ecosystem service perspective. *Science Advances, 5*(7), eaax0903.
Breiman, L. (2001). Random forests. *Machine Learning, 45*(1), 5–32.
Ceccato, V. (2014). The nature of rape places. *Journal of Environmental Psychology, 40*, 97–107.
Ceccato, V., Li, G., & Haining, R. (2019). The ecology of outdoor rape: The case of Stockholm, Sweden. *European Journal of Criminology, 16*(2), 210–236.
Ceccato, V., Canabarro, A., & Vazquez, L. (2020). Do green areas affect crime and safety?. In *Crime and Fear in Public Places* (pp. 75-107). Routledge.
Chalfin, A., Hansen, B., Lerner, J., & Parker, L. (2021). Reducing crime through environmental design: Evidence from a randomized experiment of street lighting in New York City. *Journal of Quantitative Criminology*, 1–31.
Chen, E., & Ye, Z. (2021). Identifying the nonlinear relationship between free-floating bike sharing usage and built environment. *Journal of Cleaner Production, 280*, Article 124281.
Chopin, J., & Caneppele, S. (2019). The mobility crime triangle for sexual offenders and the role of individual and environmental factors. *Sexual Abuse, 31*(7), 812–836.
Clougherty, E., Clougherty, J., Liu, X., & Brown, D. (2015, April). Spatial and temporal analysis of sexual crimes in Charlottesville, Virginia. In *2015 Systems and Information Engineering Design Symposium* (pp. 69-74). IEEE.
Crowe, T., & Fennelly, L. (2013). *Crime prevention through environmental design*. Elsevier.
Cornish, D. B., & Clarke, R. V. (2017). Understanding crime displacement: An application of rational choice theory. In *Crime Opportunity Theories* (pp. 197–211). Routledge.
Cox, D. T., Shanahan, D. F., Hudson, H. L., Fuller, R. A., Anderson, K., Hancock, S., & Gaston, K. J. (2017). Doses of nearby nature simultaneously associated with multiple health benefits. *International Journal of Environmental Research and Public Health, 14*(2), 172.
Cui, L., & Walsh, R. (2015). Foreclosure, vacancy and crime. *Journal of Urban Economics, 87*, 72–84.
De Clercq, E. M., De Wulf, R., & Van Herzele, A. (2007). Relating spatial pattern of forest cover to accessibility. *Landscape and Urban Planning, 80*(1–2), 14–22.
Dedel, K. (2011). *Sexual assault of women by strangers*. US Department of Justice, Office of Community Oriented Policing Services, Center for Problem Oriented Policing.
Densley, J. A., Davis, A., & Mason, N. (2013). Girls and gangs: Preventing multiple perpetrator rape. In *Handbook on the Study of Multiple Perpetrator Rape* (pp. 255–281). Routledge.
Donovan, G. H., & Prestemon, J. P. (2012). The effect of trees on crime in Portland, Oregon. Environ. *Environment and Behavior., 44*(1), 3–30.
Dramstad, W., Olson, J. D., & Forman, R. T. (2013). *Landscape Ecology Principles in Landscape Architecture and Land-Use Planning*. Island Press.
Edlund, L., Li, H., Yi, J., & Zhang, J. (2013). Sex ratios and crime: Evidence from China. *Review of Economics and Statistics, 95*(5), 1520–1534.
Felka, P., Mihale-Wilson, C., & Hinz, O. (2020). Mobile phones and crime: The protective effect of mobile network infrastructures. *Journal of Quantitative Criminology, 36*, 933–956.
Felson, R. B. (2017). Predatory and dispute-related violence: A social interactionist approach. In *Routine Activity and Rational Choice* (pp. 103–125). Routledge.
Fleming, C. M., Manning, M., & Ambrey, C. L. (2016). Crime, greenspace and life satisfaction: An evaluation of the New Zealand experience. *Landscape and Urban Planning, 149*, 1–10.
Friedman, J. H. (2001). Greedy function approximation: A gradient boosting machine. *Annals of Statistics*, 1189–1232.
Gaertner, M., Larson, B. M., Irlich, U. M., Holmes, P. M., Stafford, L., van Wilgen, B. W., & Richardson, D. M. (2016). Managing invasive species in cities: A framework from Cape Town, South Africa. *Landscape and Urban Planning, 151*, 1–9.
Greenfeld, L. A. (1997). Sex offenses and offenders: An analysis of data on rape and sexual assault. *US Department of Justice, Office of Justice Programs*.
Ha, J., Choi, D. H., & Darling, L. E. (2024). Is the spatial distribution of urban green space associated with crime in Chicago? *Urban Forestry & Urban Greening, 95*, Article 128282.
Han, X., Huang, X., Liang, H., Ma, S., & Gong, J. (2018). Analysis of the relationships between environmental noise and urban morphology. *Environmental Pollution, 233*, 755–763.
Hanaoka, K. (2018). New insights on relationships between street crimes and ambient population: Use of hourly population data estimated from mobile phone users' locations. *Environment and Planning B: Urban Analytics and City Science, 45*(2), 295–311.
Hewitt, A., & Beauregard, E. (2014). Sexual crime and place: The impact of the environmental context on sexual assault outcomes. *Journal of Criminal Justice, 42*(5), 375–383.
Hewitt, A. N., Beauregard, E., Andresen, M. A., & Brantingham, P. L. (2018). Identifying the nature of risky places for sexual crime: The applicability of crime pattern and social disorganization theories in a Canadian context. *Journal of Criminal Justice, 57*, 35–46.
Hipp, J. R. (2010). A dynamic view of neighborhoods: The reciprocal relationship between crime and neighborhood structural characteristics. *Social Problems, 57*, 205–230.
Huang, D., Jiang, B., & Yuan, L. (2022). Analyzing the effects of nature exposure on perceived satisfaction with running routes: An activity path-based measure approach. *Urban Forestry & Urban Greening, 68*, Article 127480.
Jacobs, J. (1961). *The Death and Life of Great American Cities*. Random House.
Jia, Y., Tang, L., Xu, M., & Yang, X. (2019). Landscape pattern indices for evaluating urban spatial morphology–A case study of Chinese cities. *Ecological Indicators, 99*, 27–37.
Jiang, B., Chang, C. Y., & Sullivan, W. C. (2014). A dose of nature: Tree cover, stress reduction, and gender differences. *Landscape and Urban Planning, 132*, 26–36.
Jiang, B., Zhang, T., & Sullivan, W. C. (2015). Healthy cities: Mechanisms and research questions regarding the impacts of urban green landscapes on public health and well-being. *Landscape Architecture Frontiers, 3*(1), 24–36.

Jiang, B., Li, D., Larsen, L., & Sullivan, W. C. (2016). A dose-response curve describing the relationship between urban tree cover density and self-reported stress recovery. *Environment and Behavior, 48*(4), 607–629.
Jiang, B., Mak, C. N. S., Larsen, L., & Zhong, H. (2017). Minimizing the gender difference in perceived safety: Comparing the effects of urban back alley interventions. *Journal of Environmental Psychology, 51*, 117–131.
Jiang, B., Mak, C. N., Zhong, H., Larsen, L., & Webster, C. J. (2018). From Broken Windows to Perceived Routine Activities: Examining Impacts of Environmental Interventions on Perceived Safety of Urban Alleys. *Frontiers in Psychology, 9*, 2450.
Jiang, B., Shen, K., Sullivan, W. C., Yang, Y., Liu, X., & Lu, Y. (2021). A natural experiment reveals impacts of built environment on suicide rate: Developing an environmental theory of suicide. *Science of the Total Environment, 776*, Article 145750.
Jiang, B., Xu, W., Ji, W., Kim, G., Pryor, M., & Sullivan, W. C. (2021). Impacts of nature and built acoustic-visual environments on human's multidimensional mood states: A cross-continent experiment. *Journal of Environmental Psychology, 77*, Article 101659.
Jonescu, E. E., Ramanayaka, C. E., Olatunji, O., Jonescu, E. E., & Olatunji, O. A. (2023). How urban heat islands effect crime: Understanding the implications of temperature, population density, and green canopy cover in shaping built environments. *Qeios.*
Kaplan, R., & Kaplan, S. (1989). *The Experience of Nature: A Psychological Perspective.* Cambridge University Press.
Katyal, N. K. (2001). Architecture as crime control. *The Yale Law Journal, 111*, 1039.
Khatri, H., & Abdellatif, I. (2020, October). A multi-modal approach for gender-based violence detection. In *2020 IEEE Cloud Summit* (pp. 144-149). IEEE.
Kim, Y. A., & Hipp, J. R. (2018). Physical boundaries and city boundaries: Consequences for crime patterns on street segments? *Crime & Delinquency, 64*(2), 227–254.
Kim, S., & Lee, S. (2023). Nonlinear relationships and interaction effects of an urban environment on crime incidence: Application of urban big data and an interpretable machine learning method. *Sustainable Cities and Society, 91*, Article 104419.
Kimpton, A., Corcoran, J., & Wickes, R. (2017). Greenspace and crime: An analysis of greenspace types, neighboring composition, and the temporal dimensions of crime. *Journal of Research in Crime and Delinquency, 54*(3), 303–337.
Kuo, F. E., Bacaicoa, M., & Sullivan, W. C. (1998). Transforming inner-city landscapes: Trees, sense of safety, and preference. *Environment and Behavior, 30*(1), 28–59.
Kuo, F. E., & Sullivan, W. C. (2001). Environment and Crime in the Inner City. *Environment and Behavior, 33*, 343–367.
Kursa, M. B., Jankowski, A., & Rudnicki, W. R. (2010). Boruta–a system for feature selection. *Fundamenta Informaticae, 101*(4), 271–285.
Lance, L. (2011). Nonproduction benefits of education: Crime, health, and good citizenship. *Handbook of the Economics of Education, 4*, 183–282.
Lee, S., Koo, B. W., & Kim, Y. (2023). Associations between tree characteristics and street crime: A case study in downtown Austin, TX. *Urban Forestry & Urban Greening, 87*, Article 128046.
Lee, S., Lee, C., Nam, J. W., Moudon, A. V., & Mendoza, J. A. (2023). Street environments and crime around low-income and minority schools: Adopting an environmental audit tool to assess crime prevention through environmental design (CPTED). *Landscape and Urban Planning, 232*, Article 104676.
Lu, Y., Chen, L., Liu, X., Yang, Y., Sullivan, W. C., Xu, W., & Jiang, B. (2021). Green spaces mitigate racial disparity of health: A higher ratio of green spaces indicates a lower racial disparity in SARS-CoV-2 infection rates in the USA. *Environment International, 152*, Article 106465.
Lundberg, S. M., & Lee, S. I. (2017). A unified approach to interpreting model predictions. *Advances in Neural Information Processing Systems, 30*.
Macdonald, J., Nguyen, V., Jensen, S. T., & Branas, C. C. (2021). Reducing crime by remediating vacant lots: The moderating effect of nearby land uses. *Journal of Experimental Criminology*, 1–26.
Mancus, G. C., Cimino, A. N., Hasan, M. Z., Campbell, J. C., Sharps, P., Winch, P. J., & Stockman, J. K. (2022). Greenness and the Potential Resilience to Sexual Violence: "Your Neighborhood Is Being Neglected Because People Don't Care. People with Power Don't Care". *Journal of Interpersonal Violence, 37*(19–20). NP17344-NP17368.
Marteache, N., Bichler, G., & Fujita, S. (2021). Using open web-based crime data for research: A word of caution–Research note. *International Journal of Social Research Methodology, 24*(6), 767–773.
McDonald, P., Charlesworth, S., & Graham, T. (2016). Action or inaction: Bystander intervention in workplace sexual harassment. *The International Journal of Human Resource Management, 27*(5), 548–566.
McGarigal, K. (2015). *FRAGSTATS help* (p. 182). Amherst, MA, USA: University of Massachusetts.
Mears, M., Brindley, P., Jorgensen, A., & Maheswaran, R. (2020). Population-level linkages between urban greenspace and health inequality: The case for using multiple indicators of neighborhood greenspace. *Health & Place, 62*, Article 102284.
Michael, S. E., Hull, R. B., & Zahm, D. L. (2001). Environmental factors influencing auto burglary: A case study. *Environment and Behavior, 33*(3), 368–388.
Myhill, A., & Allen, J. (2002). *Rape and Sexual Assault of Women: the Extent and Nature of the Problem, 237*. London: Home Office.
Nguyen, P. Y., Astell-Burt, T., Rahimi-Ardabili, H., & Feng, X. (2021). Green space quality and health: A systematic review. *International Journal of Environmental Research and Public Health, 18*(21), 11028.
Pattavina, A., Byrne, J. M., & Garcia, L. (2006). An examination of citizen involvement in crime prevention in high-risk versus low-to moderate-risk neighborhoods. *Crime & Delinquency, 52*(2), 203–231.
Perkins, D. D., Florin, P., Rich, R. C., Wandersman, A., & Chavis, D. M. (1990). Participation and the social and physical environment of residential blocks: Crime and community context. *American Journal of Community Psychology, 18*, 83–115.
Potgieter, L. J., Gaertner, M., O'Farrell, P. J., & Richardson, D. M. (2019). Does vegetation structure influence criminal activity? Insights from Cape Town, South Africa. *Frontiers of Biogeography, 11*(1).
Ranson, M. (2014). Crime, weather, and climate change. *Journal of Environmental Economics and Management, 67*(3), 274–302.
Raphael, S., & Winter-Ebmer, R. (2001). Identifying the effect of unemployment on crime. *The Journal of Law and Economics, 44*(1), 259–283.
Rocque, M., Posick, C., & Hoyle, J. (2015). *Age and Crime. The Encyclopedia of Crime and Punishment, 7*, 1–8.
Sahraoui, Y., Youssoufi, S., & Foltête, J. C. (2016). A comparison of in situ and GIS landscape metrics for residential satisfaction modeling. *Applied Geography, 74*, 199–210.
Seto, M. C., & Lalumiere, M. L. (2010). What is so special about male adolescent sexual offending? A review and test of explanations through meta-analysis. *Psychological Bulletin, 136*(4), 526.
Shams, I., & Barker, A. (2019). Barriers and opportunities of combining social and ecological functions of urban greenspaces–Users' and landscape professionals' perspectives. *Urban Forestry & Urban Greening, 39*, 67–78.
Sohn, D. W. (2016). Residential crimes and neighborhood built environment: Assessing the effectiveness of crime prevention through environmental design (CPTED). *Cities, 52*, 86–93.
Stretesky, P. B., Schuck, A. M., & Hogan, M. J. (2004). Space matters: An analysis of poverty, poverty clustering, and violent crime. *Justice Quarterly, 21*(4), 817–841.
Sukartini, N. M., Auwalin, I., & Rumayya, R. (2021). The impact of urban green spaces on the probability of urban crime in Indonesia. *Development Studies Research, 8*(1), 161–169.
Sule, A. I., Titiloye, M. A., & Arulogun, O. S. (2019). Knowledge, perception and experience of sexual entrapment among undergraduate students of the University of Ibadan, Nigeria. *Gates Open Research, 3*.
Taylor, R. B., Haberman, C. P., & Groff, E. R. (2019). Urban park crime: Neighborhood context and park features. *Journal of Criminal Justice, 64*, Article 101622.
Thompson, A., & Tapp, S. N. (2023). Crime Victimization. *NCJ, 2022*, 307089.
USDA Forest Service. (2021). *USFS Landscape Change Monitoring System Conterminous United States version 2020–5*. Utah: Salt Lake City.
Venter, Z. S., Shackleton, C., Faull, A., Lancaster, L., Breetzke, G., & Edelstein, I. (2022). Is green space associated with reduced crime? A national-scale study from the Global South. *Science of the Total Environment, 825*, 154005.
Villanueva, K., Knuiman, M., Nathan, A., Giles-Corti, B., Christian, H., Foster, S., & Bull, F. (2014). The impact of neighborhood walkability on walking: Does it differ across adult life stage and does neighborhood buffer size matter? *Health & Place, 25*, 43–46.
Wagner, A. J. (2023). Owning the Police: Crime Data, Copyright, and Public Information. *The Journal of Civic Information, 5*(3), 1–16.
Waltermaurer, E., & Akers, T. (2014). *Epidemiological Criminology: Theory to Practice.* Routledge.
Wang, H., & Tassinary, L. G. (2019). Effects of greenspace morphology on mortality at the neighborhood level: A cross-sectional ecological study. *The Lancet Planetary Health, 3*(11), e460–e468.
Wang, H., & Tassinary, L. G. (2024). Association between greenspace morphology and prevalence of non-communicable diseases mediated by air pollution and physical activity. *Landscape and Urban Planning, 242*, Article 104934.
Wang, H., Tassinary, L. G., & Newman, G. D. (2024). Developing the health effect assessment of landscape (HEAL) Tool: Assessing the health effects of community greenspace morphology design on non-communicable diseases. *Landscape and Urban Planning, 244*, Article 104990.
Wang, L., Zhou, Y., Wang, F., Ding, L., Love, P. E., & Li, S. (2021). The influence of the built environment on people's mental health: An empirical classification of causal factors. *Sustainable Cities and Society, 74*, Article 103185.
Welsh, B. C., Mudge, M. E., & Farrington, D. P. (2010). Reconceptualizing public area surveillance and crime prevention: Security guards, place managers and defensible space. *Security Journal, 23*, 299–319.
Wheeler, A. P., & Steenbeek, W. (2021). Mapping the risk terrain for crime using machine learning. *Journal of Quantitative Criminology, 37*, 445–480.
Wilson, J. Q., & Kelling, G. L. (1982). Broken windows. *Atlantic monthly, 249*(3), 29-38.
World Health Organization. (2014). *Health Care for Women Subjected to Intimate Partner Violence or Sexual Violence: A Clinical Handbook* (No. WHO/RHR/14.26). World Health Organization.
Xu, W., Jiang, B., Sullivan, W. C., Webster, C., Lu, Y., Chen, N., & Chen, B. (2024). Racial disparities in environmental exposures and SARS-CoV-2 infection rates: A detailed population-weighted analysis. *Sustainable Cities and Society, 101*, Article 105135.
Yang, W., Li, Y., Liu, Y., Fan, P., & Yue, W. (2024). Environmental factors for outdoor jogging in Beijing: Insights from using explainable spatial machine learning and massive trajectory data. *Landscape and Urban Planning, 243*, Article 104969.
Yang, X., Tan, X., Chen, C., & Wang, Y. (2020). The influence of urban park characteristics on bird diversity in Nanjing, China. *Avian Research, 11*, 1–9.
Zhang, X., Melbourne, S., Sarkar, C., Chiaradia, A., & Webster, C. (2020). Effects of greenspace on walking: Does size, shape and density matter? *Urban Studies, 57*(16), 3402–3420.
Zhou, H., Liu, L., Lan, M., Zhu, W., Song, G., Jing, F., & Gu, X. (2021). Using Google Street View imagery to capture micro built environment characteristics in drug places, compared with street robbery. *Computers, Environment and Urban Systems, 88*, Article 101631.
Zhu, Y., Ding, J., Zhu, Q., Cheng, Y., Ma, Q., & Ji, X. (2017). The impact of green open space on community attachment—A case study of three communities in Beijing. *Sustainability, 9*(4), 560.