

Urban greenery mitigates the negative effect of urban density on older adults' life satisfaction: Evidence from Shanghai, China

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ABSTRACT

The influence of high-density environment on urban residents is controversial, and its effect varies with specific contexts. Meanwhile, urban planners and policy-makers are increasingly aware that urban greenery may mitigate the detrimental effects of crowded environments on quality of life in high-density cities. However, little empirical evidence is available in the context of China. This study aims to examine the complex relationship between urban density, urban greenery, and older people's life satisfaction, with survey data collected from 1,594 older adults in 129 neighborhoods in Shanghai, China. Urban density was assessed using floor area ratio and building coverage ratio respectively, and urban greenery was measured by street view greenery, greening rate, Normalized Differential Vegetation Index (NDVI), and accessibility to nearest parks. Results from structural equation modeling showed that higher urban density was related to lower life satisfaction, and a reduced sense of community was a significant pathway between higher urban density and lower life satisfaction. Furthermore, eye-level greenery cushioned the negative effect of urban density on life satisfaction. Our findings highlighted the necessity of optimizing high-density neighborhood environments and promoting eye-level greenery in high-density urban areas to create aging-friendly cities.

1. Introduction

High-density urban developments have been advocated and implemented in many parts of the world (Boyko & Cooper, 2011; Xia, Yeh, & Zhang, 2020; Zhu, 2012). In numerous Asian countries, it is considered as a rational approach to balance the needs of land scarcity and population growth (Bardhan, Kurisu, & Hanaki, 2015; Wang & Shaw, 2018). For instance, the number of cities with more than one million population in China increased from 90 in 2000 to 161 in 2019 (National Bureau of Statistics, 2019). Despite the well-documented merits, urban over-density may negatively affect residents' daily life, including such problems as traffic congestion, air/noise pollution, limited communal space, and alienation of neighbors (Boyko & Cooper, 2011; Cao, 2016;

Cramer, Torgersen, & Kringlen, 2004; Sun, Zhao, Webster, & Lin, 2020). Meanwhile, China is experiencing a rapidly aging population, and currently has the largest elderly population in the world (Feng, Tang, & Chuai, 2018; Miao & Wu, 2016). The number of Chinese people over 60 years old reached approximately 264 million in 2020, accounting for 18.7% of the total population (National Bureau of Statistics, 2019).

Life satisfaction is a crucial measure of wellbeing and reflects a favorable attitude towards one's life (Collins, Gleib, & Goldman, 2009; Wang, Schwanen, & Mao, 2019). While it is widely documented that life satisfaction is shaped by individual attributes, attitudes, social relationships and experience (Cao, Wu, & Yuan, 2018; Liu et al., 2019; Lombardo, Jones, Wang, Shen, & Goldner, 2018), the effect of neighborhood built environments on life satisfaction has attracted scholarly

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attention only very recently (Ettema & Schekkerman, 2016; Mouratidis, 2018; Wang & Wang, 2016). Among various components of the built environment, urban density is considered as an important determinant of life satisfaction (Bardhan et al., 2015; Zhang, Van den Berg, Van Dijk, & Weitkamp, 2017), and people who live in high-density neighborhoods tend to report lower life satisfaction (Cao, 2016). Although several previous studies proposed possible pathways linking urban density to subjective wellbeing (Boyko & Cooper, 2011), little empirical research has been conducted on these potential pathways (Bergefurt et al., 2019). Since urban density may simultaneously impose positive and negative impacts on life satisfaction through different pathways, and the overall effects vary in different contexts (Cao, 2016), it is necessary to unravel the underlying mechanisms.

Policy-makers and planners are increasingly aware of the benefits of greenspace provision in high-density cities (He, Lu, Xie, & Helbich, 2021). Creating adequate urban greenery (e.g., preserved natural areas, parks, tree-lined streets, and gardens) has become indispensable in high-density urban areas (Peschardt & Stigsdotter, 2013). It is believed that greenspaces provide venues for restoration, recreation, and social interaction, and alleviate the potential harm arising from over-densification (Haaland & van Den Bosch, 2015; Lindal & Hartig, 2015; Liu et al., 2019). However, little empirical research has been conducted to examine whether greenery mitigates the negative effect of over-densification on individual life satisfaction, especially in the rapidly urbanizing and aging Chinese context.

To address these knowledge gaps, this study aims to investigate the linkages between urban density and life satisfaction among older adults in Shanghai. It contributes to the literature in the following three ways. First, it examines the association between excessively dense urban environments and the life satisfaction of older adults in China. Second, it is one of the first studies to comprehensively unravel the mechanisms underlying the association between urban density and life satisfaction. Third, the study enhances our knowledge of the buffering effect of urban greenery on older adults faced with the drawbacks of over-densification. The findings not only have valuable implications for urban planning decision-making in megacities of China, but also guide the planning of high-density mega-cities in other developing countries.

2. Literature review

There is a consensus that higher levels of life satisfaction are of great importance to successful aging (Miao & Wu, 2019), as they are concerned with the overall evaluation of daily life. Recently, much attention has been paid to identifying the determinants of life satisfaction among the elderly, such as interpersonal relationships, medical resources, and neighborhood social and physical characteristics (Engel et al., 2016; Feng et al., 2018). As older adults have relatively low mobility and spend most of their time in the immediate residential context (Xie, An, Zheng, & Li, 2018), their quality of life may be more subject to the residential neighborhood environment.

Urban density is, arguably, the most important planning parameter, and it heavily influences the overall urban form and the individual's daily life (Mouratidis, 2019; Tratalos, Fuller, Warren, Davies, & Gaston, 2007). Despite the many benefits (e.g., shorter commuting distance to destinations, efficient land use, walkable environments) of high-density development strategies, over-densified urban environments may negatively influence the individual's life, such as traffic congestion, air/noise pollution, and limited communal space (Cao, 2016; Sun, Lin, & Yin, 2021). Thus, the association between urban density and life satisfaction is inconclusive in different contexts. For instance, several studies suggested that high density is negatively associated with life satisfaction, as it is related to crowded streets, and noisy and polluted living conditions (Boyko & Cooper, 2011). By contrast, Du, Wood, Ditchman, and Stephens (2017) found that people living in high-rise neighborhoods in Chicago were more satisfied with life than those living in low-density suburban neighborhoods. They speculated that this is due to higher

accessibility and safety in downtown areas. There are also studies that highlight that residents living in neighborhoods with different density levels have similar levels of life satisfaction (Feng et al., 2018; Mouratidis, 2019).

It is likely that high urban density has both positive and negative impacts on life satisfaction through different pathways, and its overall effect relies on whether the advantages outweigh the potential harm. The significance and strength of different pathways vary in different settings, which may explain the varying results in different studies (Boyko & Cooper, 2011; Cao, 2016). Potential positive pathways include encouraging active behaviors (e.g., walking and cycling) (Boyko & Cooper, 2011), and increased access to various destinations (Cao, 2016). On the other hand, there are also some negative pathways via which high urban density may lead to low life satisfaction, such as traffic congestion and noise (Cao, 2016), feelings of loneliness (Bergefurt et al., 2019), crowdedness (Wang & Shaw, 2018), and fear of crime (Sun & Webster, 2019). The impacts of urban density on life satisfaction could be comprehended better if researchers decompose different pathways on life satisfaction.

As another important element in urban areas, the multiple benefits of greenspaces have been widely recognized (Ambrey & Fleming, 2014; Hartig, Mitchell, De Vries, & Frumkin, 2014; Liu, Xiao, Liu, Yao, & Wang, 2021). Numerous studies show that people who are frequently exposed to greenspace tend to have higher levels of life satisfaction (Tsurumi & Managi, 2015; Fleming, Manning, & Ambrey, 2016; White, Alcock, Wheeler, & Depledge, 2013). Moreover, some studies have attempted to disentangle the complex relationship between urban greenery and urban density. First, in parallel with the urban densification process, urban ecosystems are generally diminished, such as the removal of greenspace and the reduction in sizes (Jim, 2004; Nordh, Hartig, Hagerhall, & Fry, 2009). Second, greenspace is deemed an effective intervention to buffer the negative influence of crowded urban environments (Mesimäki, Hauru, & Lehvävirta, 2019; Nordh et al., 2009; Thwaites, Helleur, & Simkins, 2005). Given that urban dwellers in high-density contexts tend to have hectic lifestyles and are under myriad pressures, the provision of greenspace is believed to reduce environmental stressors arising from over-densification (Peschardt & Stigsdotter, 2013). To be specific, greenspace provides settings for recreation, restoration, and social interaction among neighbors, thereby enhancing residents' life satisfaction (Haaland & van Den Bosch, 2015; Lindal & Hartig, 2015). However, no studies have examined the potential moderating role of greenspace in alleviating the negative influence of high urban density on life satisfaction, especially in high-density cities. Based on the evidence of prior studies and the abovementioned reviews, a theoretical framework linking urban density, urban greenery, and life satisfaction was proposed in this study (Fig. 1). It highlighted underlying mechanisms between urban density, urban greenway, and life satisfaction, which may help us better understand the complexity of this topic.

Last but not least, it should be noted that the definition of urban density and greenery is essential when investigating the association between the neighborhood environment and life satisfaction (Boyko & Cooper, 2011). Prior studies defined urban density in various ways, such as population density (Feng et al., 2018), floor area ratio (Xia et al., 2020), and building coverage ratio (Haaland & van Den Bosch, 2015). Similarly, different metrics of greenery exposure were also used in prior studies, such as accessibility to the nearest park (Ma, Dong, Chen, & Zhang, 2018), neighborhood overall vegetation levels (White, Pahl, Wheeler, Depledge, & Fleming, 2017), and eye-level greenery exposure (Yang et al., 2019). Nevertheless, whether the inconsistent results of urban density and greenery on individual life satisfaction stem from different measurements remains unclear. It is necessary to compare the associations between different metrics of urban density, urban greenery, and older adults' life satisfaction simultaneously.

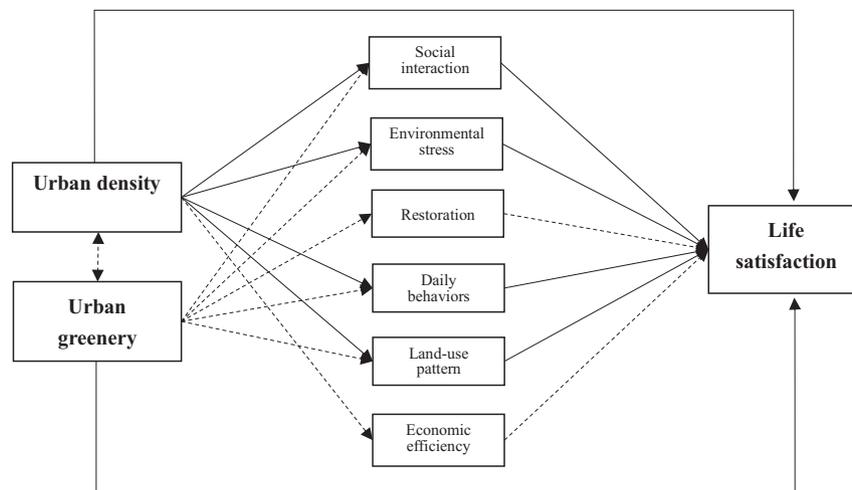


Fig. 1. Theoretical framework concerning complex relationship between urban density, urban greenery, and life satisfaction (arrows with solid lines would be examined in this study).

3. Methods

3.1. Data

Shanghai is one of the most densely populated cities globally, with a total population of 24.18 million in 2017 and an average population density of 3,854 persons/km² in the urban area (Shanghai Statistics Bureau, 2019). Simultaneously, Shanghai faces serious challenges relating to population aging, as the population over the age of 60 has reached 4.83 million, accounting for 20% of the total population (Shanghai Research Center on Aging, 2017). Hence, Shanghai serves as an ideal city to investigate the association between urban density and life satisfaction among the older adults.

We used the first wave of the Shanghai Urban Neighborhood Survey (SUNS) conducted in 2017 by the Centre for Data and Urban Sciences (CENDUS) at Shanghai University. The SUNS covered all the districts/counties in Shanghai. It employed multistage probability proportional to size sampling (PPS) with implicit stratification (Miao, Wu, & Sun, 2019). To select representative samples, the main stratification took into consideration the types of area (downtown, new town, or suburban areas) and socio-economic status. Samples were obtained through three stages: the primary sampling unit (PSU) was a sub-district or town; the secondary sampling unit (SSU) was an urban neighborhood or village, and the tertiary sampling unit (TSU) was the household. The household survey was carried out in July 2017 by interviewing households in 174 neighborhoods/villages throughout the metropolitan (see Fig. S1). In each neighborhood/village, 30 households were selected and all eligible household members were interviewed face-to-face. Eventually, the survey interviewed 8,631 individuals aged 15 or above in 5,102 households. Following previous studies in China (Yang, Zhang, & Wang, 2018), we used 60 as the age threshold for the older adults in this study. After removing cases with missing values, our working sample consisted of 1,594 older adults from 129 neighborhoods/villages (Fig. 2).

3.2. Variables

3.2.1. Life satisfaction

Following previous studies (Diener, Emmons, Larsen, & Griffin, 1985), we adopted the Satisfaction with Life Scale (SWLS) to measure the levels of respondents' life satisfaction. The SWLS consists of five items. Using the Likert scale, respondents ranked each question from 1 (strongly disagree) to 7 (strongly agree) based on their self-rated status. The scores for the five questions were added together (5–35), and the total score was treated as a continuous variable.

3.2.2. Urban density

Building coverage ratio (BCR) and floor area ratio (FAR) are two important indicators of urban density in Chinese urban planning (Xia et al., 2020). This study used building data obtained in 2017 from Gaode Map (<https://lbs.amap.com/>). Building data in Shanghai was obtained through the Application Programming Interface (API) of Gaode Map. This dataset provided detailed information on building space coordinates, footprints, and the number of floors. We measured FAR as the ratio of total floor area of all buildings to the area of the neighborhood (Yang et al., 2022), and BCR as the proportion of the areas of all building footprints within the neighborhood. An interquartile range (IQR) increase in average urban density was reported in the analysis.

3.2.3. Urban greenery

The level of urban greenery was assessed with 1) a satellite-derived metric, 2) a streetscape metric, and 3) the distance to the nearest park.

1) The satellite-derived metric was used to measure the greening rate and Normalized Difference Vegetation Index (NDVI). The full stack of Sentinel-2A surface reflectance products from 1st August 2015 to 31st July 2016 archived in Google Earth Engine was collected to map the satellite-based urban greenery distribution. Four bands with a spatial resolution of 10-m were finally utilized (e.g., Bands 2–4: blue, red, green, and Band 8: near-infrared) after conducting a pixel-based quality inspection to exclude the cloud- or shadow-contaminated pixels. The greening rate was then extracted by using a three-endmember linear spectral unmixing (LSU) model (Song, Chen, & Kwan, 2020). This model effectively addresses the inevitable issue of mixed pixels, which occurs for land-cover products derived from medium-resolution visible remote-sensing images. Furthermore, this approach can provide ratio-based land-cover maps with more detailed information. To exclude the agricultural vegetation, the LSU-based greenery map was overlaid with the land-cover map of Finer Resolution Observation and Monitoring of Global Land Cover (FROM-GLC) of 2015 (Li et al., 2017). The areas covered by agricultural vegetation were then removed.

Based on land surface reflectance of red and near-infrared (NIR) parts of the spectrum (Huete, Didan, van Leeuwen, Miura, & Glenn, 2010), NDVI¹ was calculated to represent the configuration and quality of greenspace. It ranged between −1 and 1, with higher values indicating a higher level of green vegetation.

¹ NDVI = (NIR − RED) / (NIR + RED).

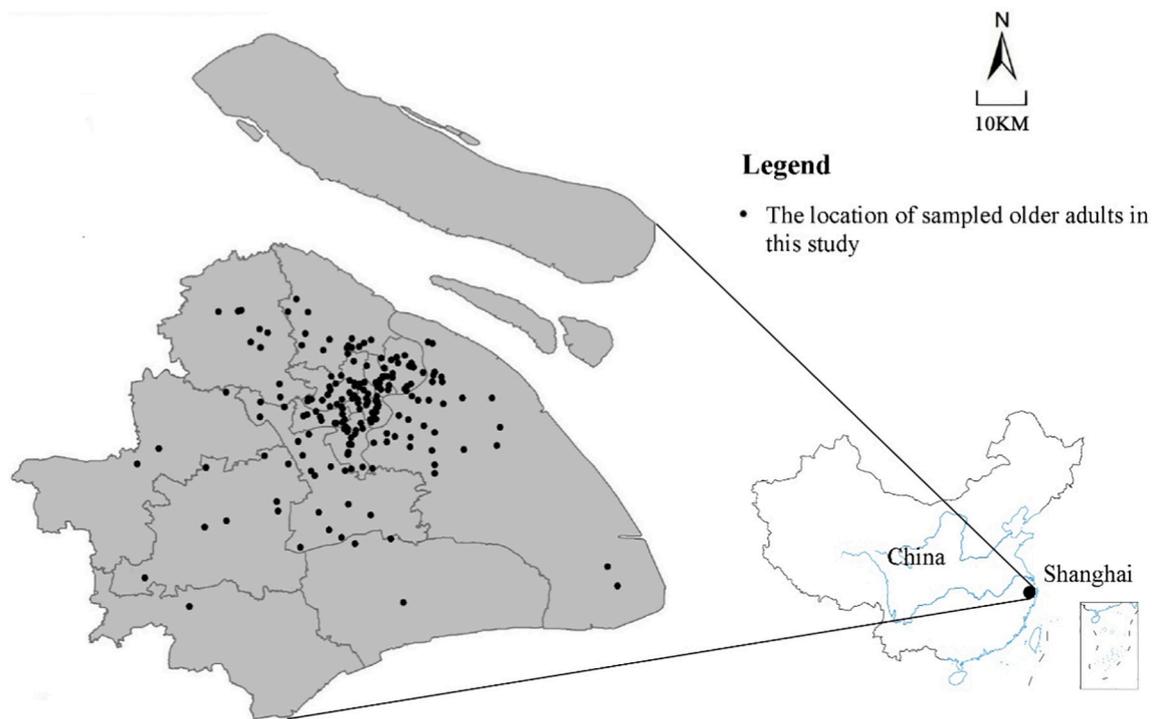


Fig. 2. The location of sampled older adults in this study.

2) We used deep learning techniques and street-view images (SVIs) to develop an index of streetscape greenery (Helbich et al., 2019; Yang, Ao, Ke, Lu, & Liang, 2021). The SVIs were collected from Baidu Maps, a web mapping service application and technology (Ye, Zeng, Shen, Zhang, & Lu, 2019). Specifically, we created sampling points every 30 m along the road networks based on Open Street Map (OSM). Then streetscape images (1024 × 1024 pixels) in four orthometric directions from each sampling point were collected through the API of Baidu Maps (<https://lbsyun.baidu.com/>). The Pyramid Scene Parsing Network (PSPNet) was performed to segment the images into 21 foreground objects (e.g., buildings, vegetation, and sky). A collection of images from the Cityscape dataset (<https://www.cityscapes-dataset.com>) was used to train the model (Fig. 3). The results obtained from training suggested a good validity for assessing the ratio of greenery (Cordts et al., 2016). The greenery level of each sampled point was calculated as the proportion of vegetation contained in images in four cardinal directions. The average value of all sampled point-generating points within the buffer zone was used to represent the level of street greenery in the neighborhood. The index of streetscape greenery ranged from 0 to 1.

Regarding the buffer, the centroid of each neighborhood (the administrative scope of a residential or village committee) was captured in ArcGIS 10.5. Then a neighborhood buffer was defined as a 1 km circular buffer around the centroid of neighborhoods. We reported a one-interquartile range (IQR) increase in the average level of greenery from satellite images and SVIs within the neighborhood.

3) Based on the POIs provided by Baidu Map and the Shanghai Parks Directory from Shanghai Landscaping and City Appearance Administrative Bureau, the geographical location of each park was identified. The distance from the centroid of residential neighborhoods to the entrance of the nearest park was calculated based on street networks.

3.2.4. Mediators

This study investigates the effects of four mediators on the relationship between urban density and life satisfaction. The first is self-reported loneliness measured by De Jong's six items in a 7-point

Likert scale (Gierveld & Tilburg, 2006; Yang et al., 2018). The sum of the six items was added together, ranging from 6 to 42, and a higher score indicating a higher level of loneliness. The second mediator is the sense of community. It was measured based on participants' responses to the question: "to what extent do you feel you belong to this community?". The question has five response categories from 1 "strongly disagree" to 5 "strongly agree", the higher value representing an increased sense of belonging (Dallago et al., 2009; Hidalgo & Hernandez, 2001). The third mediator is the frequency of physical activity and it was measured on a 7-point Likert scale, ranging from 1 to 7 (1 = never, 7 = almost every day).

In addition, we calculated the neighborhood walk score metric (<https://www.walkscore.com>), which has been validated for its effectiveness in measuring neighborhood amenability to pedestrians (Carr, Dunsiger, & Marcus, 2010; Su et al., 2019). In this study, the measurement was modified to measure 15-min walkable neighborhoods able to be walked within 15 min, which has been advocated in China recently. It contained four procedures: (1) Assigning raw weights for six selected amenities selected for importance, including education, medical care, municipal administration, finance and telecommunication, commercial services, and elderly care; (2) Calculating distances from the center of a neighborhood to the selected amenities, according to the optimal route based on the street network provided by Baidu Map; (3) Computing the total scores based on the distances and modifying the scores according to decay factors, and (4) The initial score was normalized into 0–100, and higher scores correspond to neighborhoods that are more conducive to walking. For detailed information on walk score metrics, see reference (Weng et al., 2019).

3.2.5. Covariates

Several neighborhood environmental attributes were controlled for this study. Road network data was derived from Open Street Map in 2017 (<https://www.openstreetmap.org/>), and street connectivity was defined as the density of road intersections (Yang, He, Lu, Ren, & Huang, 2021). We also measured the density of bus stops within neighborhoods using Point of Interest (POIs) data from Gaode Map in 2018 (<https://lbs.amap.com/>), one of the largest map providers in China.

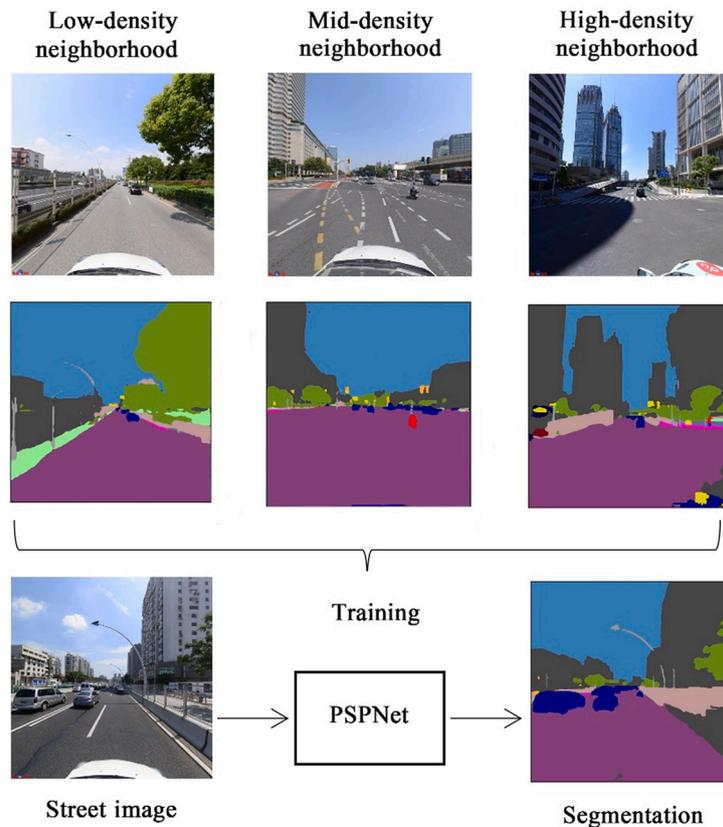


Fig. 3. Street view image segmentation through PSPNet.

Models were also adjusted for covariates concerning individual characteristics. Specifically, we controlled older adults’ monthly incomes (continuous variable), gender (dichotomous variable), age (continuous variable), marital status (categorical variable), education attainment (categorical variable), *hukou*² status (categorical variable), employment status (categorical variable), self-rated health (categorical variable), social interaction among neighbors (categorical variable), and Shanghai medical insurance coverage (categorical variable). Self-rated health was measured based on individual responses to the question “In general, how would you rate your health?”, and was based on a 5-point Likert scale, ranging from 1 (poor) to 5 (very good). The level of social interaction among neighbors was measured using the frequency of visits or chats with neighbors last year, which ranged from 1 (almost never) to 9 (almost every day). The summary statistics of variables are shown in Table 1.

3.3. Data analysis

To assess the association and pathways between urban density and life satisfaction, we adopted Structural Equation Modelling (SEM) and followed a three-step procedure for the analysis. First, we examined the linkages between SWLS scores, floor area ratio, the neighborhood greenery level (either streetscape metric, satellite-derived metric, or distance to nearest park), and four hypothesized mediators (sense of neighborhood, loneliness, the walk score, and physical activity), adjusting for covariates of individual characteristics. Second, we examined the direct and indirect effects of floor area ratio on SWLS scores. Third, we added interaction terms between urban greenery and

² *Hukou* refers to permanent residency rights in local area, and influences associated social welfare and government-provided services, ranging from education attainment, medical service, and employment.

Table 1
Descriptive statistics of variables.

Variables	Proportion/mean (SD)
<i>Dependent variable</i>	
SWLS Score (5–35)	22.82 (5.81)
<i>Independent variables</i>	
Street view greenery (0–1) median (IQR)	0.16 (0.07)
Greening rate (0–1) median (IQR)	0.32 (0.14)
NDVI median (IQR)	0.12 (0.08)
Distance to the nearest park (km)	0.97 (0.83)
Floor area ratio median (IQR)	1.91 (1.80)
Building coverage ratio (0–1) median (IQR)	0.30 (0.22)
<i>Mediators</i>	
Walk score	12.21 (21.61)
Sense of community (1–5)	3.42 (0.92)
Loneliness (6–42)	18.00 (5.90)
Physical activity (0–7)	3.68 (2.36)
<i>Controlled variables</i>	
Male	48.68%
Junior high school or below (Yes = 1)	47.24%
Married (Yes = 1)	83.25%
Age	68.45 (6.80)
Logarithm of monthly income (CNY)	8.00 (1.16)
Local medical insurance coverage (Yes = 1)	79.05%
Whether being employed (Yes = 1)	7.97%
Shanghai <i>hukou</i> (Yes = 1)	91.47%
Physical health (1–5)	2.20 (0.85)
Number of road intersection	26.68 (22.33)
Number of bus stops	41.36 (39.53)
n	1594

floor area ratio to the SEM. We assumed that urban greenery might buffer the negative effect of over-densification on older adults’ life satisfaction (Fig. 4). In addition, we conducted several sensitivity checks to ensure the robustness of observed results. It included using the alternative metric of urban density (building coverage ratio) and testing

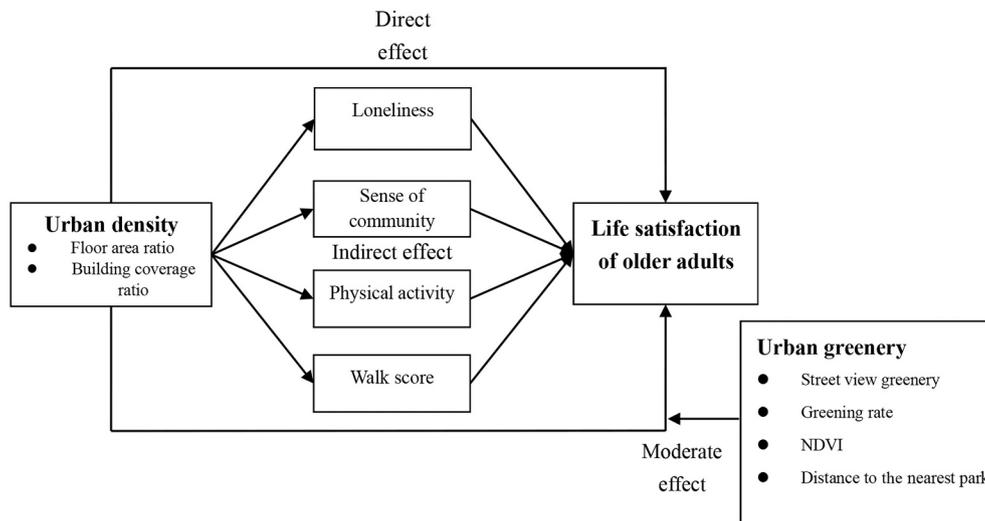


Fig. 4. Analysis framework of this study.

the dose-response relationship between urban density and life satisfaction among older adults. The fitness was measured by the standardized root mean square residual (SRMSR), root mean square error of approximation (RMSEA) and comparative fit index (CFI). These analyses were performed using STATA 15.0.

4. Results

4.1. Descriptive results

Table 1 shows the descriptive statistical results of all variables. The average value of the SWLS score was 22.82 (SD ± 5.81), which revealed that the sampled older adults in Shanghai showed relatively higher life satisfaction compared with some recent studies (Liu et al., 2019). The average neighborhood building coverage ratio and floor area ratio were 0.30 and 1.91. In addition, the average neighborhood street view

Table 2
Structural equation modelling: the association between floor area ratio, street view greenery, and life satisfaction.

Variable	Model 1				
	SWLS estimate (S.E.)	Loneliness estimate (S.E.)	Sense of community estimate (S.E.)	Physical activity estimate (S.E.)	Walk score estimate (S.E.)
<i>Independent variables</i>					
Floor area ratio	-0.876*** (0.274)				
Street view greenery	0.334* (0.186)	-0.300 (0.197)	0.030 (0.031)	0.002 (0.004)	-3.326*** (0.532)
Loneliness		-0.162*** (0.024)			
Sense of community		1.414*** (0.147)			
Physical activity		0.102* (0.058)			
Walk score		0.010 (0.009)			
<i>Control variables</i>					
Age	0.144*** (0.021)	0.036* (0.022)	0.019*** (0.003)	0.005 (0.009)	0.083 (0.059)
Male (ref: female)	-0.347 (0.270)	0.716** (0.289)	-0.031 (0.046)	0.341*** (0.118)	-0.161 (0.779)
High school and above (ref: Middle school or less)	-0.112 (0.281)	-1.085*** (0.300)	-0.101** (0.048)	0.321*** (0.121)	1.000 (0.809)
Married (ref. = single, divorced, or widowed)	0.677*** (0.368)	-2.092*** (0.390)	0.172*** (0.062)	0.044 (0.159)	-1.794 (1.054)
Shanghai hukou (ref: non-local hukou)	-1.507** (0.560)	0.017*** (0.601)	0.014 (0.096)	0.008 (0.245)	1.821 (1.624)
Medical welfare coverage in Shanghai (ref: no medical insurance)	-0.506 (0.379)	-0.517 (0.406)	-0.053 (0.065)	-0.008 (0.165)	1.381 (1.096)
Logarithm of monthly income	-0.021 (0.122)	-0.489*** (0.130)	-0.028 (0.021)	0.093* (0.053)	0.318 (0.350)
Employed (ref: retired)	0.132 (0.516)	-0.731 (0.549)	0.219** (0.087)	-0.817*** (0.224)	2.330 (1.482)
Physical health	1.263*** (0.162)	-1.312*** (0.167)	0.094*** (0.027)	0.633*** (0.068)	0.434 (0.450)
Street connectivity	-0.002 (0.006)	0.006 (0.011)	0.001 (0.002)	0.002 (0.004)	0.192*** (0.029)
Bus stops	-0.002 (0.006)	-0.005 (0.006)	0.001 (0.001)	-0.005* (0.002)	0.197*** (0.016)
Constant	9.481 (1.984)	27.273 (1.986)	1.806 (0.316)	0.046 (0.809)	0.418 (5.362)
SRMSR				0.008	
RMSEA				0.047	
CFI				0.990	
n				1594	

* $p < 0.1$.
 ** $p < 0.05$.
 *** $p < 0.01$.

greenery level were 0.16. In terms of satellite-derived metrics, the mean score of greening rate and NDVI were 0.32 and 0.12 respectively. Accessibility to nearest parks is 0.97 km (SD ± 0.83). The average age of respondents was 68.45 years old; almost half had an educational level of high school or above, and 79.2% had participated in medical insurance in Shanghai. Furthermore, more than 90% were married and unemployed. The average logarithm annual individual income per household member was 8.00 CNY.

4.2. Association and pathways between floor area ratio and life satisfaction

Table 2 shows the association between the floor area ratio, life satisfaction and four potential mediators (e.g., loneliness, sense of community, physical activity, and walk score) (Model 1). The floor area ratio was positively correlated with individual life satisfaction levels, and respondents who were surrounded by a neighborhood environment featuring a higher building coverage ratio reported significantly lower SWLS scores than those in neighborhoods with lower densities (−0.876, $p < 0.01$). Simultaneously, higher levels of street greenery were positively associated with life satisfaction among older adults (0.334, $p < 0.1$). In addition, a series of controlled variables also showed significant correlation between life satisfaction, advanced age, Shanghai hukou, married status, and better physical health, which was significant in predicting life satisfaction levels. Unexpectedly, none of these built environment attributes controlled was significant in predicting life satisfaction.

Table 2 also shows that the floor area ratio was negatively related to a sense of community (−0.164, $p < 0.01$), but positively related to the walk score (9.367, $p < 0.01$). These findings suggested that higher levels of density tend to decrease the sense of community and create walkable environment.

Model 1 in Table 4 shows the mediating effects between the floor area ratio and life satisfaction. This association was mediated by a sense of community (−0.061, $p < 0.01$), and the effect of sense of community accounted for 7.6% of the total proportion of overall associations. While loneliness and frequency of physical activity directly influenced life satisfaction, they did not exert significant mediating effects. The results were consistent with those shown in Model 1.

To evaluate the association between different aspects of urban greenery and life satisfaction among the elderly, street view greenery was replaced by NDVI, greening rate, and accessibility to nearby parks separately. After controlling for covariates and mediators, the overall association was shown in Table 3. Results revealed that the association between NDVI and life satisfaction is significant, while significant effects of greening rate or accessibility to nearest parks was not observed. These results highlighted that different metrics of urban greenery have unidentical associations with older adults' life satisfaction.

4.3. The buffering effect of urban greenery on life satisfaction against over-densification

Table 5 illustrates the extent to which the strength of the association between floor area ratio and life satisfaction can be moderated by the level of urban greenery. We added interaction items respectively (Models 5-8). Model 5 showed the significant moderation effect of street-view greenery. This result suggested that a higher level of perceived street greenery exposure helps alleviate the negative influence of urban density on life satisfaction in a high-density context. However, the significant moderation effect of other aspects of urban greenery on life satisfaction could not be observed (Model 6-8). To summarize, street view greenery not only directly correlated with older adults' life satisfaction, but also had a moderating effect on the relationship between urban density and life satisfaction.

Table 3

The association between floor area ratio, other urban greenery metrics, and life satisfaction.

Variable	Model 2	Model 3	Model 4
	SWLS estimate (S.E.)	SWLS estimate (S.E.)	SWLS estimate (S.E.)
<i>Independent variables</i>			
Greening rate	0.933*** (0.558)	−0.111 (0.628)	
NDVI			
Distance to the nearest park			−0.057 (0.185) −0.969***
Floor area ratio	−0.981*** (0.270)	−0.920*** (0.277)	−0.188*** (0.268)
Loneliness	−0.162*** (0.023)	−0.164*** (0.024)	−0.188*** (0.024)
Sense of community	1.409*** (0.148)	1.420*** (0.148)	1.432*** (0.147)
Physical activity	0.107* (0.057)	0.112* (0.057)	0.109* (0.059)
Walk score	0.004 (0.009)	0.007 (0.009)	0.003 (0.009)
SRMSR	0.008	0.008	0.015
RMSEA	0.047	0.047	0.069
CFI	0.990	0.989	0.968
n	1594		

Note: We contained covariates and mediators in the models.

* $p < 0.1$.
*** $p < 0.01$.

Table 4

The direct and indirect effects of floor area ratio on life satisfaction.

Model 1					
Mediator	Indirect effect				Direct effect
	Loneliness estimate (S.E.)	Sense of community estimate (S.E.)	Physical activity estimate (S.E.)	Walk score estimate (S.E.)	Estimate (S.E.)
SWLS	0.002 (0.045)	−0.061*** (0.067)	0.023 (0.017)	0.020 (0.086)	−0.876*** (0.274)

*** $p < 0.01$.

4.4. Robustness tests

There are various definitions of urban density that may exert different effects on individual lives (Boyko & Cooper, 2011). We conducted a sensitivity check to test the robustness of our results by replacing floor area ratio to the building coverage ratio. After using alternative urban density metrics, the correlation patterns among building coverage ratio, urban greenery and life satisfaction were consistent with previous models (Table S1).

In addition, given that urban density may have an inverted U-shaped relationship with individual active behaviors and health outcomes (e.g., older adults may have lower life satisfaction when living in either extremely densely populated areas or extremely sparsely populated areas) (Christiansen et al., 2016; Sarkar, Webster, & Gallacher, 2017). We conducted another sensitivity check by adding the quadratic form of urban density to model specifications. Results of the check suggested absence of the inverted U-shaped relationship. The results are available from the authors upon request.

5. Discussion

Improving individuals' life satisfaction is the ultimate goal for policymakers (Cao, 2016), and how urban density influences life satisfaction has attracted much attention recently. However, considering that urban density is the most controversial issue in urban planning (Ewing & Hamidi, 2015), prior findings on this topic varied with different

Table 5
The moderating role of urban greenery on the linkage between floor area ratio and life satisfaction.

Variable	Model 5	Model 6	Model 7	Model 8
	SWLS estimate (S.E.)	SWLS estimate (S.E.)	SWLS estimate (S.E.)	SWLS estimate (S.E.)
<i>Independent variables</i>				
Street view greenery	0.030 (0.266)			
Greening rate		-0.205 (0.701)		
NDVI			0.594 (0.679)	
Distance to the nearest park				-0.099 (0.184)
Floor area ratio	-1.947*** (0.624)	-0.914*** (0.263)	-1.164*** (0.282)	-0.722** (0.395)
<i>Interaction items</i>				
Floor area ratio × street view greenery	0.526** (0.276)			
Floor area ratio × greening rate		0.197 (0.657)		
Floor area ratio × NDVI			0.594 (0.589)	
Floor area ratio × distance to the nearest park				-0.617 (0.357)
SRMSR	0.008	0.009	0.010	0.011
RMSEA	0.060	0.048	0.063	0.066
CFI	0.973	0.982	0.965	0.966
n			1594	

Note: We contained control variables and mediators in the models.

** $p < 0.05$.
*** $p < 0.01$.

geographical and cultural contexts, and observed results were far from reaching consensus (Boyko & Cooper, 2011). Our results confirmed that higher urban density in the Chinese megacities is negatively associated with older adults' life satisfaction, and these findings supplemented the evidence from western contexts (Cao, 2016; Mouratidis, 2019). The study area had adequate density variation. The center of Shanghai was one of the most densely populated areas globally, and there were also less densified areas scattered around suburban areas. Results confirmed that the negative effects were amplified in the densified area and exceeded the potential benefits. Notably, our findings were inconsistent with a recent study in Nanjing, China (Feng et al., 2018). The plausible explanation was due to the sited area of that study, which was located in the urban center. By contrast, the current study sampled more representative neighborhoods with differing levels of urban density.

This study also highlighted that we should be cautious when generalizing the findings on this topic from a single study to other settings. As the potential threats and benefits vary in different contexts, the essence of "high-density" development is distinct in different countries. Higher-density development refers to compaction in North America, which has the potential to promote the efficiency of land use and other facilities, compared with urban sprawl (Hamidi, Sabouri, & Ewing, 2020). Therefore, the necessity of high-density development has been advocated. By contrast, due to scarce land resources, densified development has become a necessity rather than a choice in Asian cities (Zhu, 2012). If more densified planning was proposed, the undesirable urban environment would be detrimental to residents. In the future, more evidence is needed in smaller cities with lower density and quantifying optimal urban density in Asian contexts to balance economic efficiency and social sustainability.

Previous studies proposed potential mediators through which urban

density influences subjective wellbeing (Boyko & Cooper, 2011), while specific evidence was lacking (Cao, 2016). As hypothesized, a sense of community mediated the urban density-wellbeing association, consistent with previous studies (Zhang, Zhang, Zhou, & Yu, 2018). Unexpectedly, loneliness, physical activity, and walk scores did not mediate the urban density-wellbeing association. This was possibly because older adults are physically active and interact with friends regardless of urban density level. For instance, older adults still conducted adequate physical activity and maintain the social connection, even in low-density neighborhoods. In addition, it seemed that the benefits of convenient and accessible environments created by high-density development fail to promote overall life quality.

Lastly, a dearth of studies has asked whether inconsistent results stem from different measurements (Liu et al., 2021). This study showed that two urban density metrics exert similar effects, while different metrics of urban greenery showed varying associations with life satisfaction among the elderly. Street greenery and NDVI were significantly associated with life satisfaction from the observed direct effect. It was assumed that different metrics represent different exposure opportunities to urban greenery (Helbich et al., 2019). For one thing, older adults may be unconsciously and continuously exposed to street greenery through daily activities on streets (e.g., walking for transportation or recreational activities) (Liu et al., 2020). However, they may only visit parks for specific purposes. Thus, accessibility to nearby parks failed to capture the whole spectrum of daily exposure to urban greenery. Furthermore, NDVI represented the overall levels of healthy vegetation in certain areas, which was linked to the attractiveness of greenery (Rhew, Vander Stoep, Kearney, Smith, & Dunbar, 2011). By contrast, a greening rate only represented the amount of land allocated to greenery, even though such land may have low-quality vegetation or even be barren. Consequently, NDVI better represented the overall conditions of urban greenery compared with the greening rate. Moreover, results verified that eye-level greenery could cushion the adverse effects of urban density on older people's life satisfaction. To summarize, these results further unraveled the relationship between different urban greenery metrics and life satisfaction. Given that making tailored planning policies is necessary, the findings shed light on the necessity of optimizing the over-densified urban environment and promoting human-perceived greenery in high-density megacities.

6. Conclusion

Using a large and representative survey in Shanghai, this study was one of the first to systematically unravel the mechanisms underlying the association between urban density and life satisfaction. The structural equation modeling was applied to examine the complex relationship between urban density, urban greenery, and older people's life satisfaction. The results showed that higher urban density was related to lower life satisfaction among older adults, and a sense of community mediated the relationship between urban density and life satisfaction. Moreover, eye-level greenery alleviated the negative effect of urban density on life satisfaction, while the buffering effects of other greenery metrics were not observed. This finding enhanced our knowledge of the buffering effect of urban greenery on older adults faced with the drawbacks of over-densification.

The findings of this study have urban planning and public policy implications, which may assist in optimizing physical environments and promoting governance in high-density cities. Local governments need to be cautious regarding the construction of high-density residential neighborhoods due to the potential adverse effects of over-densification. Also, neighborhood committees in high-density areas should improve residents' attachment to their neighborhoods using different approaches. Furthermore, the importance of human-perceived greenery should be further emphasized. There are still numerous high-density older neighborhoods with few public greenspaces, planners thus are recommended to create more vertical and street greenery when carrying

out urban renewal projects. This study also highlighted that the conventional indicator for greenspace planning (e.g., greening rate) in China might be ineffective or misleading. Multiple greenery indicators (e.g., street view greenery, NDVI) are expected to be incorporated jointly to inform better policy-making and urban planning practices.

We also listed several limitations and provided insights for further empirical research. First, the cross-sectional nature of the data failed to infer causal relationships between urban density and life satisfaction. Future study is advised to adopt longitudinal research design. Second, residential selection bias might lead to an overestimation of the urban density and life satisfaction linkage. For instance, older adults with high socio-economic status were more likely to be satisfied with their lives while simultaneously living in lower-density neighborhoods. Thus, the observed density-satisfaction associations may be alternatively explained by individual factors. Third, we used self-reported measures of the frequency of physical activity and symptoms of loneliness, and future studies should use objective measures of physical activity and loneliness levels. Fourth, as some streets were not covered by SVIs, we failed to capture all human-perceived greenery. In the future, street-scene photos taken on those sidewalks uncovered by SVIs could be combined.

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CRediT authorship contribution statement

Dongsheng He: Conceptualization, Methodology, Software, Visualization, Writing – original draft. **Jia Miao:** Data curation, Formal analysis, Writing – review & editing. **Yi Lu:** Writing – review & editing. **Yimeng Song:** Investigation, Writing – review & editing. **Long Chen:** Investigation. **Ye Liu:** Conceptualization, Methodology, Supervision, Writing – review & editing.

Declaration of competing interest

None.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.cities.2022.103607>.

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