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Neighbourhood green space and loneliness in middle-aged and older adults: Evidence from WHO Study on Global Ageing and Adult Health in China

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ABSTRACT

Loneliness may contribute to chronic diseases, while neighbourhood green space is increasingly understood to benefit health. However, whether green space is associated with loneliness is less understood, especially for an ageing population. This study aims to explore the relationship between different measures of green space and loneliness among middle-aged and older adults (N = 8383) based on a national cohort. Loneliness was measured with a yes-or-no (binary) self-reported question, while the availability of residential green space was assessed with the normalised difference vegetation index (NDVI) and proportion of neighbourhood public parks. Multi-level logistic regression models, stratified and mediation analysis were used to test whether green space availability was associated with loneliness. The results showed that both forms of residential green space were negatively associated with the risk of loneliness, even after adjustments for covariates. These associations were partially mediated by social cohesion and modified by socioeconomic status and age; residents who were males, at least 60 years old, had lower incomes, or had no high school degree showed protective associations of residential green space on loneliness in some stratified models. These findings indicate that residential green space plays an important role in loneliness risk reduction in middle-aged and older adults, so policymakers can consider urban greening as part of their comprehensive plans to support the mental health of ageing adults.

1. Introduction

China has the largest ageing population in the world (Chen et al., 2022). This country had approximately 264 million people aged 60 years or above at the end of 2020, accounting for 19 % of the total population; further, the share of older adults is expected to reach 25 % by 2030 (The State Council of the People's Republic of China, 2017). Due to retirement or living alone, older adults are more likely to suffer from loneliness (Jeste et al., 2020). A prior study found that 28 % of older adults in China have reported feeling lonely (Luo & Waite, 2014). Due to the one-child policy, most couples only have one child in China, which may relate to less support from their offspring during ageing and present unique challenges and risks of loneliness (Hu & Wang, 2023). Loneliness is also linked to a higher risk of cardiovascular disease (Valtorta et al., 2016), mortality (Luo & Waite, 2014), and suicide (Troya et al., 2019). Targeting loneliness in middle-aged and older adults is important for improving healthy ageing around the world.

Nature prescriptions are a form of nonpharmaceutical treatment that involves healthcare professionals recommending time spent in nature to benefit mental well-being (Nguyen et al., 2023), including alleviating feelings of loneliness (Astell-Burt et al., 2023a). Rapid urbanisation and industrialisation are normally accompanied by decreased access to nature, regardless of whether that time is spent intentionally as part of a prescription or nonintentionally as part of everyday life (Kabisch et al., 2015; Zahoor et al., 2023). Increasing the provision of green space to maximise its health benefits has become an important topic for cities and researchers globally (Markevych et al., 2017). While most existing literature has focused on the effect of green space on different chronic diseases and some mental health conditions, it is still unclear how green space is related to loneliness, especially for middle-aged and older adults (Astell-Burt et al., 2022b). Only a handful of studies have tested the relationship between green space and loneliness in developed countries,

such as Australia, Germany, and the U.K. (Astell-Burt et al., 2022b).

1.1. Literature review

The lonelygenic environments conceptual framework has highlighted the importance of environments in influencing loneliness and has called for more empirical evidence on these environments (Feng & Astell-Burt, 2022a,b). Previous studies have pointed out that neighbourhood green space may be a crucial indicator of an urban natural environment related to loneliness (Astell-Burt et al., 2022b). However, the evidence on the link between green space and loneliness is mixed (Astell-Burt et al., 2022b). Some studies pointed out that green space may contribute to less loneliness (Astell-Burt et al., 2022). For instance, Astell-Burt et al. (2022a) found that achieving more urban green space could lower the cumulative incidence of loneliness among Australian adults. Hammoud et al. (2021) suggested that nature exposure was negatively related to momentary loneliness in multiple countries based on smartphone technologies. Maas et al. (2009) reported that green space was negatively related to loneliness in the Netherlands. Other studies did not find evidence to support the prevention of loneliness with green space (Astell-Burt et al., 2022b). For instance, Cao et al. (2019) documented that access to parks was not significantly related to loneliness in the U.S. Li et al. (2021) found that viewing green spaces was not related to loneliness in China. One study in the U.K. also indicated that time noticing nature was positively linked to loneliness (Richardson & Hamlin, 2021). Such inconsistency may be partly due to the variations in geographies, study methodologies, measurement of green space and loneliness, and participants' demographics (Feng & Astell-Burt, 2022a).

Despite these conflicting results, several pathways support the beneficial impacts of green space on loneliness through its ability to restore capacities, build capacities, and reduce harm (Astell-Burt et al., 2022b). Specifically, the 'lean on green' hypothesis suggests that contact with nature can help people build a connection between themselves and natural elements, preventing loneliness's negative effect (Astell-Burt et al., 2022b). This process may also facilitate experiences with animals, which alleviates feelings of loneliness (Astell-Burt et al., 2022b). Hence, spending time in nature with others may strengthen people's sense of place attachment even without direct interaction, contributing to less loneliness (Graham & Glover, 2014). Additionally, green space may increase outdoor physical activity and facilitate social contact in neighbourhoods (Astell-Burt et al., 2022b). Green space may encourage people to do more group activities, such as group walking, as it can offer more public open spaces (Marselle et al., 2013). Physical activity in green space may also have more psychological benefits than that in other contexts (Thompson Coon et al., 2011). Green space in neighbourhoods can also provide comfortable spaces for residents to socialise with others (Maas et al., 2009). Frequent social contact among neighbours usually facilitates a higher level of neighbourhood social cohesion (Wan et al., 2021). In cohesive neighbourhoods, people are more likely to get support from others, which is important to prevent the negative impact of loneliness (Yu et al., 2021). Finally, neighbourhoods with higher levels of green space usually have fewer disorders, and residents may suffer less from incivilities (Engemann et al., 2019). This may further encourage people to engage in outdoor activities (e.g., neighbourhood walking groups and other physical activity initiatives) and mitigate the development of loneliness (Astell-Burt et al., 2022). Still, green space may contribute to more unexpected life pressures for some groups, resulting in more loneliness (Astell-Burt et al., 2022). For instance, green space may contribute to higher property values, which makes housing unaffordable to some residents (Anguelovski et al., 2019). This may lead to loneliness due to the exclusion from their homes (Astell-Burt et al., 2022).

Further complicating the potential for green space to benefit loneliness and other dimensions of health, there is less consensus about the consistency of this relationship amongst sociodemographic groups (Bolte et al., 2019; Ode Sang et al., 2016; Rigolon et al., 2021). The

'equigenesis' theory indicates that residents with low socioeconomic status (e.g., lower incomes or levels of educational attainment) may be more influenced by public infrastructures such as public green space because people with higher socioeconomic status can afford many medical resources, and public infrastructures are only one option (Wang et al., 2021). People with lower socioeconomic status may also have to rely more on public green space since green infrastructure is generally freely available to residents (Wang et al., 2022). Maas et al. (2009) suggested that the link between green space and loneliness was stronger for lower-educated adults and adults with lower incomes. Second, there has been particular interest in sex differences in green space-wellbeing relationships (Sillman et al., 2022). Compared with males, a lower proportion of females use green spaces for activities, so the green space-wellbeing relationship may be more pronounced for males (Sillman et al., 2022). However, females may be occupied within the neighbourhood due to unequal caring responsibilities and different employment patterns, which may result in higher sensitivity to neighbourhood environment exposure in females (Sillman et al., 2022). We are aware of only one prior study suggesting that the green space-loneliness relationship is modified by sex; a longitudinal study identified this relationship was stronger among women than men (Astell-Burt et al., 2023b). Further, older adults may spend more time in their neighbourhoods and have more chances to be exposed to neighbourhood green space; therefore, green space may support loneliness more strongly among older adults (Ode Sang et al., 2016). For instance, van den Berg et al. (2010) suggested that the impact of contacting nature was significantly linked to loneliness for people aged ≥ 62, but such an association was not found for those aged < 62 years.

1.2. Current study

In summary, several research gaps related to green space and loneliness remain. First, although the effect of green space on chronic diseases or other forms of mental health has been explored, few studies have tried to understand the effects of green space on loneliness. Second, most studies have shed light on the function of green space in the general population in the context of developed countries. Less attention has been paid to the ageing population in developing countries. Third, loneliness may be lessened by green space through multiple mechanisms, although these are not firmly established. Fourth, the possible impacts of green space on loneliness may be modified by socioeconomic status and older age, among other factors.

Therefore, this study aims to 1) examine associations between measures of residential green space and loneliness in Chinese middle-aged and older adults; 2) identify mediating pathways (i.e., physical activity and social cohesion) between green space and loneliness; and 3) explore heterogeneous impacts of green space across various socioeconomic groups and demographics. The novelty of this study includes focusing on the green space-loneliness association in a developing country with the largest ageing population and examining the pathways linking green space to loneliness.

2. Methods

2.1. Data and variables

2.1.1. World Health Organization Study on global AGEing and adult health (SAGE) in China

This study used a cross-sectional design using survey data from the 2010 WHO SAGE in China (Kowal et al., 2012). It was conducted across 127 neighbourhoods (Figure S1) within eight provinces/municipalities, concentrating on individuals aged 50 and over. A stratified multi-stage cluster sampling method was used for recruitment. After eliminating respondents with incomplete data, we had a viable sample size of 8383 middle-aged and older adults. More details of the data can be found in Kowal et al. (2012).

2.1.2. Loneliness

Respondents' loneliness was measured by self-reported by asking, 'Did you feel lonely for much of the day yesterday?' The response was restricted to '0 = no' or '1 = yes'. Existing studies have shown that using a single survey item to assess loneliness in older adults is feasible and can achieve acceptable reliability (Kotwal et al., 2022).

2.1.3. Green space

This study used two complementary measures to evaluate respondent's green space exposure. First, the normalised difference vegetation index (NDVI) values were used to measure total vegetative greenness (Tucker, 1979). Satellite images were collected from the Landsat5 satellite (30 m × 30 m). Data in 2010 were collected from the USGS EarthExplorer in the greenest season (June, July or August). NDVI ranges from −1 (ice, water, or snow) to 0 (bare soil, rock, or concrete) to 1 (highest level of leafy green vegetation). The average values of all positive pixels within a 1000-m buffer for the centroid of each neighbourhood were used to determine the NDVI. Second, following past literature (Li et al., 2020), the proportion of public parks was calculated within each neighbourhood based on the Autonavi electronic navigation map. To avoid the inclusion of private gardens, we excluded parks that were below one hectare. NDVI and the proportion of public parks within each neighbourhood were defined as measures of green space availability (Labib et al., 2020).

2.1.4. Covariates

Following previous literature (Astell-Burt et al., 2022b), several individual-level sociodemographic characteristics were controlled, including sex (female vs. males), age (in years), marital status (married vs. others), annual household income per capita (Chinese Yuan), educational attainment (≤ primary school vs. high school vs. ≥ college), employment status (employed vs. others), and household size (persons).

This study also included a series of health-related behaviour variables. First, functional limitation scores were assessed with a 22-item questionnaire (Cronbach's alpha = 0.92) (Table S1) to evaluate the difficulties respondents had when performing daily activities. They were treated as a continuous variable, and higher scores indicate greater limitations. Second, general health was evaluated using a self-reported question (the participants were asked how they would rate their health) and treated as a binary variable (high= 'very good', 'good' or 'moderate'; low = 'bad' or 'very bad'). Third, current smoking and drinking status were also self-reported (current smoker/drinker vs. non-smoker/drinker). Fourth, moderate-to-vigorous physical activity levels (MVPA) were self-reported as the total weekly minutes, and it was considered a potential mediator. The weekly MVPA time was calculated by the total duration of weekly recreational MVPA. Last, social cohesion was measured with nine survey items (Table S2) (Cronbach's alpha = 0.86), which aimed at understanding respondents' involvement in their community. It was considered as another potential mediator. The mean scores of nine items were used for the final analysis. The higher the score, the stronger social cohesion a respondent reported.

2.2. Analysis

Since the SAGE respondents were clustered in neighbourhoods, several multilevel logistic models (Raudenbush and Bryk, 2002) were fitted. Random intercepts (at the neighbourhood level) were used to adjust for the clustered effect. Variance inflation factors (VIF) values < 2.0 showed no multicollinearity among the model variables. A baseline model with only the two green space indicators was fitted first (Model 1). Then, socioeconomic, demographic, and behaviour-related covariates were added to examine how green space was related to participants' loneliness after adjusting for these factors (Model 2).

Several sensitivity tests were conducted. First, as people aged > 85 may have various preferences or perceptions of green space (Helbich et al., 2019), the green space and loneliness relationship was tested among a sub-sample excluding those > 85 years old (Model 4). Functionally restricted participants may have difficulties with outdoor activities and accessing green space. Therefore, this study also checked whether excluding participants who had high functional limitation scores (> 30) affected the associations (Model 5). Next, the main analysis (Model 2) was repeated with robust standard errors to test whether the green space and loneliness association was influenced by heteroscedasticity (Arellano, 1987) (Model 6).

In addition, a series of stratified analyses were conducted to explore differences in associations among sociodemographic groups. A median split was used for income, and models were re-run within lower income (participants at the first and second quartiles based on income) (Models 6) and high income (participants at the third and fourth quartiles based on income) (Model 7). Levels of educational attainment were split by high school degree status (no, Model 8; yes, Model 9). A median split was also used for age, and models were re-run among older participants (60 years or older; Model 10) and younger participants (less than 60 years; Model 11). Last, models were re-run among males (Model 12) and females (Model 13).

Finally, this study examined whether MVPA and social cohesion may mediate relationships between green space and loneliness using a compositional mediation model (Sohn et al., 2021) using the 'ccmm' package (Zhang et al., 2021) (Table 4). This model provides information regarding the impact of green space on loneliness through MVPA and social cohesion (indirect effect). Analyses were based on R 4.2.1 and STATA 15.1 (StataCorp., College Station, TX, USA). The flow chart of the study design is presented in Fig. 1.

3. Results

3.1. Description of SAGE sample

Table 1 summarises the description of the SAGE sample. About 5 % of the respondents reported loneliness. The average proportion of public parks within the neighbourhood and NDVI was 5 % and 0.6, respectively. Overall, about half (52 %) were aged 60 years or above, and 45 % were female. Nearly 88 % of the respondents were married, 19 % attended high school, and 7 % attended college. The average annual household income per capita was 12,453 Chinese Yuan (approximately 1700 USD). The average functional limitation scores and household size were 28 and 3 persons, respectively. About 44 % were employed, 17 % reported low general health, 38 % were smokers, and 36 % were drinkers. The average social cohesion score was 2, and the average weekly MVPA was 89 minutes. Descriptive statistics for each stratified sample (Table S3) were also reported in the supplement file as a reference.

3.2. Associations between green space and loneliness

Table 2 displays the results of green space impacting respondents' loneliness. The fully adjusted model (Model 3) suggested that greenness was negatively related to loneliness (OR = 0.03; 95 % CI = 0.02–0.05), and the proportion of public parks was also negatively related to loneliness (OR = 0.05; 95 % CI = 0.02–0.38).

Table 3 summarises the results of robustness tests on associations between green space and loneliness. Despite some differences in magnitude, green space-loneliness associations remained significant and in the negative direction across models.

3.3. Stratified analysis

Table 4 summarises stratified analyses for associations of green space and loneliness in sociodemographic groups. Greenness was negatively associated with loneliness for respondents with lower and higher income levels (Models 7 and 8). In contrast, the proportion of public parks was only associated with loneliness for lower income levels (Models 7 and 8).
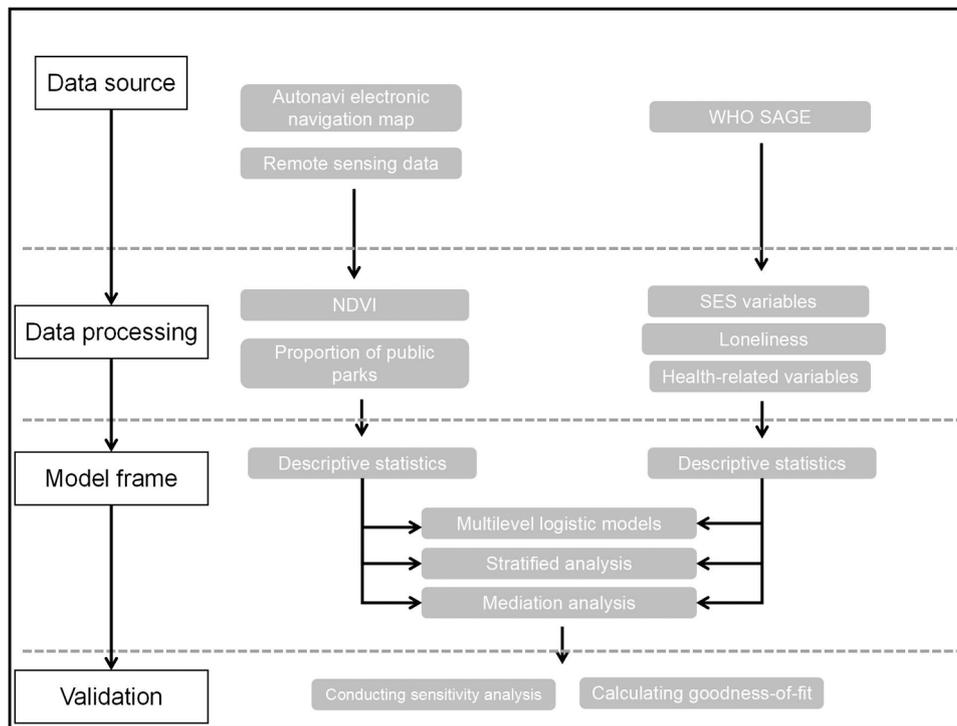
Fig. 1. Flow chart of the study design.

Table 1
Description of sample (N = 8383).

Variables	Mean (S.D.) or Count (Proportion)
Loneliness	
Yes	398 (0.05)
No	7985 (0.95)
Sex	
Male	4652 (0.55)
Female	3731 (0.45)
Age	
< 60 years	4111 (0.48)
60–69 years	2582 (0.31)
70–79 years	1392 (0.17)
≥ 80 years	298 (0.04)
Marital status	
Married	7395 (0.88)
Others	988 (0.12)
Educational attainment	
≤ Primary school	6236 (0.74)
High school	1576 (0.19)
≥ College	571 (0.07)
Annual household income per capita (Chinese Yuan)	12,452.94 (19,418.12)
Functional limitation scores	28.15 (8.27)
Household size	2.74 (1.27)
Employment	
Employed	3647 (0.44)
Others	4736 (0.56)
General Health	
Low	1409 (0.17)
High	6974 (0.83)
Smoking	
Yes	3220 (0.38)
No	5163 (0.62)
Drinking	
Yes	2985 (0.36)
No	5398 (0.64)
Weekly MVPA (mins)	89.12 (268.78)
Social cohesion (1–5)	1.69 (0.39)
Proportion of public parks	0.05 (0.08)
Greenness	0.57 (0.22)

Also, greenness was negatively associated with loneliness for respondents with less than a high school degree and above a high school degree (Models 9 and 10). In contrast, the proportion of public parks was only associated with loneliness for respondents with less than a high school degree (Models 9 and 10). Meanwhile, greenness was negatively associated with loneliness in middle-aged (< 60 years) and older (≥ 60 years) respondents, as well as males and females (Models 11–14). In contrast, the proportion of public parks was associated with loneliness only in older respondents and males (Models 11–14).

3.4. Mediator analysis

Table 5 summarises the mediating effects of MVPA and social cohesion. We observed that greenness and the proportion of public parks were negatively related to loneliness through the promotion of social cohesion. However, no evidence exists that MVPA mediated associations between green space and loneliness.

4. Discussion

4.1. Main findings

This study investigated whether green space was linked to a reduced risk of loneliness in over 8000 middle-aged and older adults in China. This study can contribute to the existing knowledge on this topic in several aspects. First, we examined an older demographic in a developing country. This context and population have been understudied in prior research on green space and loneliness. Second, we compared the effects of different measures of green space, including greenness (NDVI) and the proportion of public parks within a neighbourhood. Third, we examined mediating pathways linking green space to loneliness. Fourth, we explored the heterogeneous impacts of green space on loneliness across socioeconomic groups.

Our results suggest that greenness and the proportion of public parks reduced the risk of loneliness. Two longitudinal studies in Australia also suggested that urban greening and tree canopy are associated with lower risks of loneliness (Astell-Burt et al., 2022a; Astell-Burt et al., 2023b). A

Table 2
Regressing loneliness in green space alone (Model 1) and sociodemographics with green space (Models 2 and 3).

	Model 1 (Base) OR (95 % CI)	Model 2 (Adjusted model) OR (95 % CI)	Model 3 (Adjusted model+potential mediators) OR (95 % CI)
Male (reference = female)		0.94 (0.70,1.27)	0.91 (0.68,1.23)
Age (reference: < 60 years)			
60–69 years		0.91 (0.71,1.18)	0.90 (0.70,1.16)
70–79 years		0.81 (0.58,1.11)	0.78 (0.57,1.08)
≥ 80 years		0.54** (0.29,0.99)	0.49** (0.26,0.92)
Married (reference = others)		0.21*** (0.17,0.27)	0.21*** (0.16,0.27)
Educational attainment (reference: ≤ primary school and below)			
High school		0.80 (0.58,1.10)	0.82 (0.59,1.14)
≥ College		1.58* (0.98,2.55)	1.62** (1.01,2.62)
Employed (reference = Others)		1.01 (0.78,1.29)	1.04 (0.81,1.34)
Low general health (reference = high general health)		2.05*** (1.59,2.64)	2.02*** (1.57,2.61)
Functional limitation scores		1.03*** (1.02,1.04)	1.02*** (1.01,1.03)
Smoker (reference = non-smoker)		0.96 (0.71,1.29)	0.95 (0.70,1.28)
Drinker (reference = non-drinker)		1.27* (0.98,1.64)	1.30** (1.01,1.69)
Household size		0.87*** (0.79,0.95)	0.86*** (0.78,0.95)
Annual household income per capita		0.99*** (0.99,0.99)	0.99*** (0.99,0.99)
Weekly recreational MVPA			0.99 (0.99,1.00)
Social cohesion			0.55 (0.41,0.74)
Greenness	0.04*** (0.03,0.07)	0.03*** (0.02,0.05)	0.03*** (0.02,0.05)
Proportion of public parks	0.01** (0.00,0.10)	0.09** (0.01,0.72)	0.05* (0.02,0.38)
Log-likelihood	-1488.09	-1326.48	-1318.52
AIC	2982.18	2686.97	2675.05

Note: OR = odds ratio; CI = confidence interval; AIC = Akaike information criterion. Significance levels: * p < 0.10, ** p < 0.05, *** p < 0.01.

Table 3
Sensitivity analyses regressing loneliness in green space among respondents ≤ 85 years old (Model 4), those with low or moderate functional limitation scores (Model 5), and robust confidence intervals (Model 6).

	Model 4 (excluding > 85 yrs) OR (95 % CI)	Model 5 (excluding high functional limitations) OR (95 % CI)	Model 6 (robust CIs) OR (95 % CI)
Greenness	0.04*** (0.02,0.06)	0.04*** (0.02,0.07)	0.04*** (0.03,0.05)
Proportion of public parks	0.05** (0.01,0.40)	0.06** (0.01,0.81)	0.05** (0.01,0.25)
Log-likelihood	-1306.16	-932.34	-1318.52
AIC	2650.32	1902.68	2675.05

Note: OR = odds ratio; CI = confidence interval; AIC = Akaike information criterion. Adjusted for all covariates. Significance levels: * p < 0.10, ** p < 0.05, *** p < 0.01.

Table 4
Stratified analysis.

	Model 7 (Low income) OR (95 % CI)	Model 8 (High income) OR (95 % CI)	Model 9 (< High school) OR (95 % CI)	Model 10 (≥ High school) OR (95 % CI)
Greenness	0.03*** (0.01,0.06)	0.04*** (0.02,0.09)	0.02*** (0.01,0.08)	0.04*** (0.02,0.07)
Proportion of public parks	0.01** (0.00,0.46)	0.19 (0.01,2.34)	0.03** (0.00,0.48)	0.10 (0.00,2.94)
Log-likelihood	-797.54	-509.85	-1040.76	-273.68
AIC	1633.08	1057.70	2115.52	583.37
Effect size (Greenness)[a]	-1.93	-1.77	-2.15	-1.77
Effect size (Proportion of public parks)[a]	-2.53	-0.91	-1.93	-1.26

	Model 11 (≥ 60 years) OR (95 % CI)	Model 12 (< 60 years) OR (95 % CI)	Model 13 (Males) OR (95 % CI)	Model 14 (Females) OR (95 % CI)
Greenness	0.03*** (0.02,0.06)	0.04*** (0.02,0.09)	0.03*** (0.01,0.06)	0.04*** (0.02,0.09)
Proportion of public parks	0.02** (0.00,0.71)	0.09 (0.01,1.28)	0.05** (0.00,0.98)	0.09 (0.00,1.74)
Log-likelihood	-728.75	-583.21	-696.46	-607.08
AIC	1493.51	1198.43	1428.93	1250.16
Effect size (Greenness)[a]	-1.93	-1.77	-1.93	-1.77
Effect size (Proportion of public parks)[a]	-2.15	-1.32	-1.65	-1.32

Note: OR = odds ratio; CI = confidence interval; AIC = Akaike information criterion. Adjusted for all covariates. Significance levels: * p < 0.10, ** p < 0.05, *** p < 0.01.
[a] Effect size was calculated using Cohen's D (Ruscio, 2008). The absolute values of Cohen's d of 0.2, 0.5, and 0.8 are considered small, medium and large effect sizes, respectively.

Table 5
Indirect effects of the mediation analyses.

	Mediator	Mediating effect
Greenness	MVPA	0.008 (0.015)
	Social cohesion	-0.137*** (0.049)
Proportion of public parks	MVPA	0.002 (0.010)
	Social cohesion	-0.437*** (0.147)

Note: Significance levels: *p < 0.10, **p < 0.05, ***p < 0.01. Adjusted for all covariates.

cross-sectional study in Germany found that living near public parks was associated with less loneliness (Buecker et al., 2021). Another cross-sectional study in eight higher-income countries found that greater walking times to nearby green spaces were associated with a higher level of loneliness (van Houwelingen-Snippe et al., 2020). However, cross-sectional studies from the Netherlands (van den Berg et al., 2016), the U.S. (Cao et al., 2019) and three higher-income countries (Spain, Netherlands, and U.K.; Zijlema et al., 2017) found no evidence that access to public green space was associated with loneliness. Similarly, cross-sectional studies from Japan (Soga et al., 2021) and the U.K. (Lai et al., 2021) reported no evidence that greenness was related to loneliness.

There are several explanations for why our findings may differ from previous research. First, this study mainly paid attention to middle-aged and older adults, while some previous studies focused on general populations. Existing studies have pointed out that older adults may rely more on neighbourhood amenities for socialising due to their lower levels of mobility (Hong et al., 2018). Second, the definition of urban parks has been inconsistent across different literature, so it is possible that our measurement cannot reflect those in other studies. Third, the spatial resolution and size of NDVI buffers are inconsistent among

different studies. Previous studies usually used small buffers (e.g., 250 m or 300 m), while we used a relatively large buffer (i.e., 1000 m), which may indicate that a relatively large buffer may also be appropriate for measuring middle-aged and older adults' range of daily activities within residential neighbourhoods. This is consistent with the findings of Astell-Burt et al. (2022a), which suggest that the green space-loneliness was significant at a 1600-m buffer but not at 800-m or 400-m buffer.

Our results suggest that social cohesion mediates associations between green space availability and loneliness among middle-aged and older adults. Existing studies have also shown that neighbourhood greenness was associated with different health outcomes by improving neighbourhood social cohesion (Markevych et al., 2017). However, this pathway has rarely been explored for loneliness, especially among middle-aged and older adults (Astell-Burt et al., 2022b). Residential green space availability may promote middle-aged and older adults' social contact with their neighbours (Hanibuchi et al., 2012; Hong et al., 2018). Several previous studies have shown that the ageing population in socially cohesive neighbourhoods tend to have more social support from their neighbours (Choi and Matz-Costa, 2018; Cramm et al., 2013), which might protect them from loneliness.

There is no evidence that physical activity mediates the link between green space and loneliness in the middle and older. Green spaces like parks can provide people with a comfortable open space, thus encouraging more MVPA (Chen et al., 2022, 2024; Luo et al., 2022; Richardson et al., 2013; Wei et al., 2022; Yang et al., 2021, 2023, 2024), which may reduce loneliness (Astell-Burt et al., 2022b). There are several potential reasons for our unexpected findings. First, physical activity was self-reported, and there may have been measurement bias for the duration of physical activity. Also, respondents reported loneliness for yesterday and MVPA in general, so there were temporal differences in these measures. Second, there was no information regarding MVPA type and location in this study, so if middle-aged and older adults preferred to perform physical activity indoors or in certain facilities, the expected pathway from green space to physical activity to loneliness relationships would not have been observed. Last, our measures of green space could not reflect the presence of physical activity-related facilities within neighbourhoods; higher levels of green space availability may not have translated to opportunities for outdoor MVPA among middle-aged and older adults.

This study also found in some stratified models that green space reduced loneliness among those with lower socioeconomic status, levels of educational achievement, and older adults. These findings could be explained by several factors. Middle-aged and older adults with higher incomes may have more choices for socialising and strengthening their social networks than those with lower incomes, who may have to rely more on public amenities due to limited access to other resources (Mitchell et al., 2015; Rigolon et al., 2021). Adults with lower levels of educational attainment tend to have less health-related knowledge, so they may also have to rely on local green space for the exchange of health-related information (Wang et al., 2022). Adults with longer cumulative green space over the life course may witness greater effects than those younger since older adults may have lived longer in their neighbourhoods (Pearce et al., 2016). Last, our results indicated that only green space availability is more protective against loneliness for men than for women. This finding is inconsistent with the conclusion of Astell-Burt et al. (2023b), which indicated that the green space-loneliness association was stronger for females. These differences may be due to differences in cultures, green space type and quality, and study design (cross-sectional vs. longitudinal), warranting future research to elucidate the modifying effects of sex in the green space and loneliness relationship.

4.2. Policy implications

Understanding the relationship between green space and loneliness among middle-aged and older adults has implications for urban policy.

Vegetative cover and the proportion of public parks may be protective against loneliness in middle-aged and older adults. Policymakers can focus on both perspectives when considering green infrastructure. For example, more trees could be planted in residential neighbourhoods to improve greenness, and more public parks could be built to increase availability. Also, since social cohesion partially explains why green space was associated with loneliness, policymakers could promote social cohesion at the same time as neighbourhood greenery. For instance, neighbourhood gardening clubs could be organised to facilitate more social contact among middle-aged and older adults. Policymakers can also attend to the heterogeneous effect of green space across different groups. Green space may have particularly important benefits to the risk of loneliness among older adults and those with lower levels of educational achievement and income, who are also among the most vulnerable groups to health disparities (Rigolon et al., 2021).

4.3. Limitations

There are several limitations to be considered when considering its results. The cross-sectional nature of the SAGE study and data prevented us from inferring causation between green space and loneliness. Future studies should consider using longitudinal or experimental designs to overcome this limitation. Second, loneliness was measured as a binary (lonely or not) question and only asked about feelings on the previous day. This temporal reference, binary outcome, and self-reported data collection may have resulted in measurement biases. Similarly, social cohesion and physical activity were self-reported measures, which may have led to recall and measurement bias, limiting the robustness of our mediation tests. Additionally, this study could not include measures of green space quality, which could have influenced the effects of green space quantity on subjective and mental well-being measures (Wang et al., 2022; Zhang et al., 2023). This study also did not have information on respondents' green space visitation, types of use or perceived quality of parks and other green spaces, which are important for people to maintain social contact and may influence the observed green space-loneliness associations (Astell-Burt & Feng, 2021; Feng & Astell-Burt, 2022b). Last, this study only measured green space in people's residential neighbourhoods and could not investigate the influence of other contexts on loneliness (Wang et al., 2021; Yang et al., 2020).

5. Conclusion

This study examined the link between residential green space and loneliness among Chinese middle-aged and older adults, paying special attention to different measures of green space. The results suggested that the greenness and proportion of public parks was related to a reduced risk of loneliness among middle-aged and older adults. Social cohesion partially mediated links between green space and loneliness risk, while moderate-to-vigorous physical activity did not. Some stratified analyses suggest that older respondents and those with lower incomes or educational achievement levels have particularly beneficial associations with green space. Neighbourhoods might incorporate more urban green spaces to protect their middle-aged and older residents from feeling lonely.

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CRediT authorship contribution statement

Ruoyu Wang: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Yimeng Song**: Methodology. **Linchuan Yang**: Conceptualization, Writing – review & editing, Supervision. **Matthew H. E. M. Browning**:

Writing – review & editing.

Declaration of Competing Interest

Our research manuscript has no conflict of interest.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ufug.2024.128324.

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