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Establishing associations between residential greenness and markers of adiposity among middle-aged and older Chinese adults through multilevel structural equation models

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ABSTRACT

Objectives: Residential greenness may prevent overweight/obesity, but the matter has not been investigated among middle-aged and older adults in China. This study 1) assessed associations between residential greenness and markers of adiposity among middle-aged and older Chinese adults and 2) investigated physical activity, sedentary behaviours, particulate matter (PM) with a diameter of <2.5 μm ($PM_{2.5}$) concentrations, and perennial mean temperature as mediators of the associations.
Methods: We used data from the World Health Organization's Study on Global Ageing and Adult Health (SAGE) between 2007 and 2010. Overweight/obesity and abdominal obesity were measured by body mass index and waist circumference. Exposure to neighbourhood greenness was measured by the normalized difference vegetation index (NDVI). Multilevel structural equation models were fitted to investigate the associations between neighbourhood greenness, the four potential mediators, and the prevalence of overweight/obesity and central obesity.
Results: The results showed that greenness was inversely associated with the odds of overweight/obesity (odds = 0.73, 95% confidence interval (CI) 0.58–0.92) and abdominal adiposity (odds = 0.55, 95% CI 0.33–0.91). The greenness-overweight/obesity association varied significantly by sex and age, and the greenness-central obesity varied significantly by sex, age, and education. We found some indication that $PM_{2.5}$ concentrations had a suppressive effect on the greenness-adiposity associations. There was no evidence that physical activity, sedentary behaviours, and perennial mean temperature mediated the associations between neighbourhood greenness and markers of adiposity.
Conclusions: Exposure to higher levels of residential greenness was associated with lower odds of overweight/obesity and abdominal obesity among middle-aged and older Chinese adults. However, underlying mechanisms explaining these associations remain unclear requiring longitudinal studies and natural experiments.

1. Introduction

China's rapid urbanization has been accompanied by an increase in Chinese people's exposure to obesogenic environments and their shift toward an obesogenic lifestyle (Gong et al., 2012). For example, the popularity of fast foods, sedentary occupations, and motorized transportation modes has increased both the prevalence of physical inactivity and the daily caloric intake among Chinese people. Overweight and obesity are recognized as global epidemics (NCD-RisC, 2016) and modifiable risk factors for chronic diseases include cardiovascular disease, type 2 diabetes, and cancer (Guh et al., 2009). The prevalence of obesity among Chinese adults increased from 0.8% in 1975 to 6.8% in 2016 for females, and from 0.2% to 6.1% for males.[1]

A growing body of research has investigated how residential greenness is related to the risk of overweight/obesity in high income countries (Halonen et al., 2014; Lovasi et al., 2013; Persson et al., 2018; Sarkar,

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[1] http://ncdrisc.org/obesity-prevalence-map.html.

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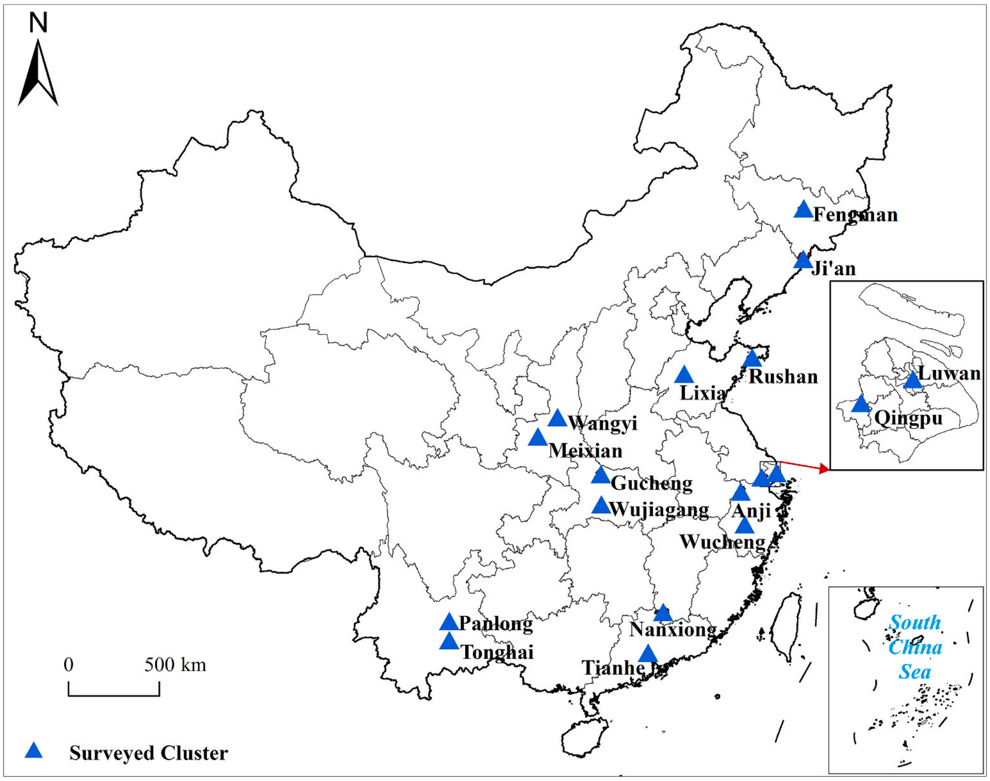

Fig. 1. SAGE-China wave 1 sampling sites.

2017), but the results have been inconsistent. While some studies observed that more greenness in the living environment or closer proximity to green space was significantly associated with a reduced probability of being overweight/obese (Coombes et al., 2010; Ghimire et al., 2017; Halonen et al., 2014; Nielsen and Hansen, 2007; Pereira et al., 2013; Sanders et al., 2015a; Sarkar, 2017; Xu et al., 2015), others only found associations for specific population subgroups (e.g., women and boys) (Persson et al., 2018; Sanders et al., 2015b), reported no associations (Michael et al., 2014; Mowafi et al., 2012; Muller et al., 2018; Potestio et al., 2009), or even observed a counterintuitive positive relationship between residential greenness and overweight/obesity (Cummins and Fagg, 2012; Dempsey et al., 2018; Wilhelmsen et al., 2017). Furthermore, most studies on the nexus between greenness and overweight/obesity have focused either on adults in general (Ghimire et al., 2017; Persson et al., 2018; Sarkar, 2017) or on children (Lovasi et al., 2013; Potestio et al., 2009; Sanders et al., 2015b); only a few have assessed older adults (Dempsey et al., 2018).

Conceptually, greenness near home is beneficial for human health and wellbeing. Different pathways have been suggested for this (Hartig et al., 2014; Liu et al., 2019; Markevych et al., 2017; Twohig-Bennett et al., 2018). First, exposure to greenness may decrease the risk of being overweight or obese by providing accessible and attractive spaces that facilitate physical activity and reduce sedentary behaviours (Coombes et al., 2010; Markevych et al., 2017; McCormack et al., 2010; Sarkar, 2017). Second, greenness can reduce psychological stress and relieve mental fatigue, which may diminish negative emotions and their effects (Feng and Astell-Burt, 2019; Halonen et al., 2014; Harding et al., 2014; Kondo et al., 2019; Parsons, 1991). Some studies have indicated that negative emotional states are related to overweight/obesity, because negative emotions may lead to changes in dietary behaviours and cortisol reactivity, resulting in weight gain (Block et al., 2009; Harding et al., 2014). In addition, exposure to greenness may improve sleep quality, thereby maintaining endocrine function and protecting people against adiposity (Gildner et al., 2014). Third, greenness can mitigate exposure to environmental threats (e.g., air pollution, transport noise, extreme temperatures). Suggested mechanisms include the filtering effects of vegetation, diffraction or absorption of sound waves and solar radiation, evapotranspiration of plants, and microclimate regulation (Markevych et al., 2017), which may reduce cortisol levels, insulin resistance, and chronic inflammation and hence promote the maintenance of a healthy body weight (Dadvand et al., 2012; O'Callaghan-Gordo et al., 2017; Pyko et al., 2017).

Previous studies in high-income countries have reported that living in a greener neighbourhood is conducive to maintaining a normal body weight (Feng and Astell-Burt, 2019; Ghimire et al., 2017; Lachowycz and Jones, 2011; Lovasi et al., 2013; Nielsen and Hansen, 2007; Pereira et al., 2013; Sarkar, 2017; Xu et al., 2015). Only one study has disentangled the association between exposure to neighbourhood greenery and markers of adiposity in China (Huang et al., 2019b). However, the results of this study are tentative because: a) survey data on only 3 out of 333 prefectures were used; b) important area-level co-exposures (e.g. climate and urbanicity) and individual-level confounders (e.g., socioeconomic status and behavioural risk factors) remained unadjusted, increasing the risk of poor generalizability and selection bias; and c) the greenness–adiposity associations were exclusively assessed in Chinese urban areas even though urban–rural differences in living environment, nutritional intake, and lifestyle are likely to confound the adiposity–-greenness association.

To address these research gaps, the present study investigated the dose–effect relationships between residential greenness and markers of adiposity among Chinese adults aged 50 or above. We paid attention to the mediating role of physical activity, sedentary behaviours, $PM_{2.5}$ concentrations, and perennial mean temperature. We further explored whether these associations were modified by demographic, socioeconomic, and regional attributes. We hypothesized that neighbourhood greenness is negatively associated with the odds of both overweight/obesity and abdominal obesity, and that these associations could be partially mediated by physical activity, sedentary behaviours, $PM_{2.5}$ concentrations, and perennial mean temperature.

2. Materials and methods

2.1. Study population

The research was based on Chinese data from the first wave of the World Health Organization's longitudinal Study on Global Ageing and Adult Health (SAGE), which was carried out between 2007 and 2010 in six low- or middle-income countries in different parts of the world, namely, China, Ghana, India, Mexico, the Russian Federation, and South Africa. Data on individuals aged 50 and above (as the primary sample) and individuals aged 18–49 years (as a comparison sample) were collected (Kowal et al., 2012). Face-to-face interviews and physical examinations were conducted to collect information on socio-demographics, health and wellbeing outcomes, behavioural risk factors, health services utilization, etc.

The wave 1 of SAGE in China was conducted between 2007 and 2010. SAGE employed a multistage cluster sampling technique to select households and participants (Kowal et al., 2012; Lin et al., 2017; Wu et al., 2013). The Chinese dataset contained data on 15, 050 individuals from 127 secondary sample units (villages/enumeration areas) nested within 64 primary sample units (townships/neighbourhoods) (Fig. 1). In this study, a neighbourhood was defined as a village/enumeration area, which is the smallest administrative division in rural/urban China. We focused on those aged ≥50 years (N = 13, 367) and further restricted our analyses to respondents with complete information on adiposity measurement and individual-level confounders. Thus, our final analytical sample comprised 12, 112 participants.

2.2. Outcome variables

During the interviews, height (cm), weight (kg), and waist circumference (cm) measurements were made by trained staff using standardized protocols. Body mass index (BMI) and waist circumference (WC) were used to measure general obesity and abdominal obesity. BMI was calculated by dividing weight (kg) by the square of height (m^2). Overweight or obesity was defined as BMI ≥24, in accordance with the Chinese standards (Sun et al., 2017). Abdominal obesity was defined as having a WC of ≥80 cm for females and of ≥90 cm for males (WHO, 2008).

2.3. Greenness exposure assessment

We utilized a remote sensing-based normalized difference vegetation index (NDVI) to quantify the level of neighbourhood greenness. NDVI data were derived from Landsat 5 Thematic Mapper (TM) images with a spatial resolution of 30 × 30 m obtained from the United States Geological Survey (USGS) Earth Explorer.[2] We used nine cloud-free images of the study areas from 1 May to 30 September (i.e., the greenest period) in 2007–2010. NDVI was computed as the ratio of the difference between the near-infrared and red visible reflectance to their sum for the same image (Persson et al., 2018; Tucker, 1979). NDVI ranges from −1 to 1, with larger positive numbers representing denser vegetation. Negative NDVI values were set to zero, as done elsewhere (Helbich, 2019). Neighbourhood greenness was computed as the average NDVI values within a radius of 500 m, 1 km, 1.5 km, 2 km and 3 km circular buffer around the centroid of the participants' village/enumeration area. The 1 km buffer served as baseline (Ekkel and de Vries, 2017; Huang et al., 2019a; Liu et al., 2019; Maas et al., 2006); the others were used for robustness tests.

2.4. Mediators

We tested the following four potential mediators. First, physical activity was measured through the Global Physical Activity Questionnaire (GPAQ), which has 15 items measuring the intensity of work-, transport-, and leisure-related physical activity in a typical week. We took into account transport- and leisure-related physical activity in our analysis. Based on the intensity, frequency and duration of physical activity, the total amount of time spent on transport- and leisure-related activities was computed as follows: *(duration of transport-related physical activity × frequency of transport-related physical activity) + (duration of moderate-intensity leisure-related physical activity × frequency of moderate-intensity leisure-related physical activity) + (2 × (duration of vigorous intensity leisure-related physical activity × frequency of vigorous intensity leisure-related physical activity))*. Time spent on transport- and leisure-related activities was considered a continuous variable.

Second, sedentary behaviours were assessed by the following question: 'How much time do you usually spend sitting or reclining (not including time spent sleeping) on a typical day?' We calculated the total amount of time spent sitting or reclining. This variable was included continuously.

Third, we used annual mean concentrations of particulate matter that have a diameter of less than 2.5 μm ($PM_{2.5}$) within a 1 km circular buffer around the centroid of the participants' residential neighbourhood as a proxy for the level of ambient air pollution. We estimated the average concentrations of $PM_{2.5}$ in the period 2007–2010 (Huang et al., 2019b; Lin et al., 2017). $PM_{2.5}$ data with a resolution of 1 km were obtained from the Atmospheric Composition Analysis Group. This dataset estimates ground-level $PM_{2.5}$ concentrations over China based on remote sensing data (e.g., Moderate Resolution Imaging Spectroradiometer) and regional ground-based observations (van Donkelaar et al., 2019).

Fourth, data on perennial temperature per meteorological station were retrieved from annual surface observation data[3] collected in China in 1981–2010. Ordinary kriging was used as the interpolation method to produce predictions at non-observed locations, and then zonal statistics were applied to determine the average perennial mean air temperature per circular buffer for each neighbourhood.

2.5. Covariates

Based on previous studies and our theoretical framework (Halonen et al., 2014; Huang et al., 2019a, 2019b; Liu et al., 2019; Lovasi et al., 2013; Persson et al., 2018; Sarkar, 2017), we adjusted for a series of individual- and neighbourhood-level variables. At the individual level, we adjusted for sex (male, female), age (50–64, ≥65 years), marital status (married/cohabiting, never married/separated/divorced/widowed), education (no schooling, primary or secondary school, high school or above), household permanent income (Kowal et al., 2012) (i.e., an asset-based income index based on the WHO to assess household permanent income with the median income of the included households as cut-off; low, high), car ownership (yes, no), household financial situation (moderate or below, good or very good), work status (unemployed, employed), household food expenditure each week (the total amount of household expenditure (in yuan) on food divided by household size), the season of questionnaire data collection (spring, summer, autumn, winter) and poor mental health. Poor mental health was captured through two questions on a five-point Likert scale: 'Overall in the last 30 days, how much of a problem did you have (1) with feeling sad, low or depressed and (2) with worry or anxiety?' Participants' answers ranged from 'none' (score 1) to 'extreme/cannot handle' (score 5). The scores on these two items were summed, giving a total score ranging from 2 to 10; a higher score indicates pronounced poor mental health. We also included region of residence (south China (i.e., Guangdong, Yunnan, Zhejiang, and Shanghai), north China (i.e., Jilin, Shandong, Shanxi, and Hubei)), and urbanicity of residence (urban area,

[2] https://earthexplorer.usgs.gov/.

[3] http://data.cma.cn/en/?r=data/detail&dataCode=A.0029.0005.

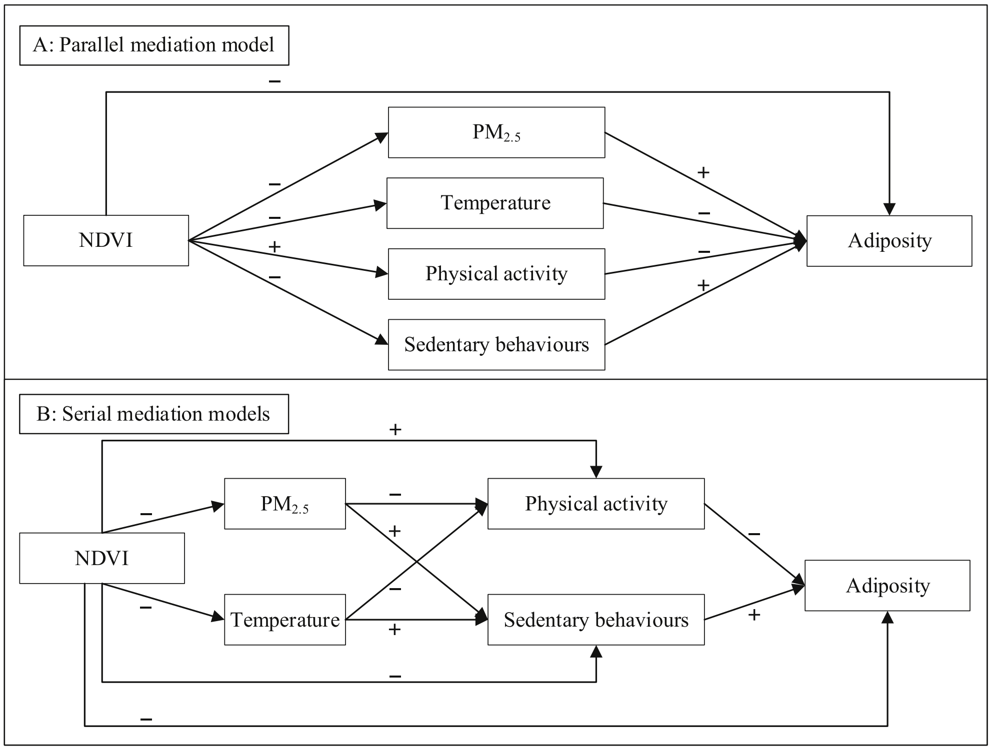

Fig. 2. Conceptual diagrams of two approaches for modelling pathways associating greenspace with adiposity. Note. "+" indicate positive associations and "-" indicate inverse associations.

rural area).

We included two area-level covariates. We used average population density within a 1 km circular buffer centred on participants' residential neighbourhood as a surrogate for urbanicity. Population density data for 2010 were obtained from the Resource and Environment Data Cloud Platform[4] and had a 1 km resolution. We employed county-level gross domestic product (GDP) per capita (in Yuan) as a proxy for area-level socioeconomic conditions. County-level GDP per capita was collected from each city's Statistical Yearbooks.

2.6. Statistical analysis

We used generalized structural equation modelling to fit two-level structural equation models (SEMs) with a logit link for binary responses (e.g., overweight/obesity and abdominal obesity) and an identity link for continuous responses (e.g., time spent on transport- and leisure-related physical activity, time spent on sedentary behaviours, $PM_{2.5}$ concentrations, and perennial mean temperature) (Fig. 2). Because participants were nested within neighbourhoods, we added a neighbourhood level random effect. We employed a latent variable at the neighbourhood level to account for the multilevel structure.

We used two types of SEMs (i.e., a parallel mediation model and a serial mediation model) to test the pathways that linked neighbourhood greenness to adiposity. First, we fitted the parallel mediation model (Fig. 2A) with four potential mediators, in which the four mediators were added together into the model and were assumed to work independently. Second, we fitted the serial mediation model (Fig. 2B), in which the four mediators were allowed to intertwine with each other and were supposed to work together (Dzhambov et al., 2020; Wang et al., 2020). We used a maximum likelihood estimator to obtain the estimated parameters. We used *nlcom* command to compute the indirect effects and standard errors. The Akaike's Information Criterion (AIC) and Bayesian Information Criterion (BIC) were used to assess the model fit.

Three steps were taken. 1) We fitted multilevel SEMs to estimate the relationship between the markers of adiposity (overweight/obesity and abdominal obesity), exposure to neighbourhood greenness, and the four mediators. 2) We performed stratified analyses by sex, age, education, household income, household financial situation, and urbanicity of residence to examine the heterogeneity of the health benefit of greenness. 3) We carried out a series of sensitivity checks by refitting the SEMs: a) we used different buffers radii (500 m, 1.5 km, 2 km, and 3 km) for greenness; b) we replaced greenness, originally a continuous measure, with a categorical variable based on quartiles; and c) we evaluated the greenness–adiposity relationships by restricting respondents to those who had i) a BMI of $\geq$18.5 kg/m^2 (being underweight (BMI <18.5 kg/m^2) may lead to frailty among middle-aged and older adults), ii) had no difficulty walking 100 m, iii) had lived in their current residential area for over 10 years, and iv) had no chronic disease, including self-reported diagnosed angina or hypertension. The multilevel SEMs were performed with Stata 14. The significance level was set to 0.05.

3. Results

3.1. Characteristics of the participants

A total of 12, 112 respondents were included (Table 1). The mean BMI and WC was 24.03 kg/m^2 (standard deviation (SD) = 5.00 kg/m^2) and 84.38 cm (SD = 10.55 cm), while 45.24% of the participants were classified as being overweight/obese and 49.22% had abdominal obesity. Characteristics of the study population are summarized in Table 1.

3.2. Association between neighbourhood greenness and markers of adiposity

Multivariate models did not indicate multicollinearity among the

[4] http://www.resdc.cn/.

Table 1
Descriptive statistics of the study population.

Variables	All participants	Participants with overweight/obesity	Participants without overweight/obesity	p-value
	(N = 12 112)	(N = 5 479)	(N = 6 633)	
BMI (kg/m^2) (mean (SD))	24.03 (5.00)	27.33 (5.59)	21.30 (1.85)	0.00[a]
Waist circumference (cm) (mean (SD))	84.38 (10.55)	90.57 (9.19)	79.26 (8.69)	0.00[a]
Sex (%)				0.00[b]
Female	53.17	57.49	49.60	
Male	46.83	42.51	50.40	
Age (years) (%)				0.00[b]
≥65	39.38	37.31	41.10	
50-64	60.62	62.69	58.90	
Marital status (%)				0.00[b]
Married	83.69	85.80	81.95	
Unmarried	16.31	14.20	18.05	
Education (%)				0.00[b]
No schooling	23.82	21.03	26.13	
Primary or secondary school	59.17	60.83	57.80	
High school or above	17.01	18.14	16.07	
Household permanent income (%)				0.00[b]
Low (≤−0.02)	50.92	43.99	56.64	
High (>−0.02)	49.08	56.01	43.36	
Car ownership (%)				0.03[b]
No	72.87	71.91	73.66	
Yes	27.13	28.09	26.34	
Household financial situation (%)				0.00[b]
Bad or very bad or moderate	85.24	83.98	86.28	
Good or very good	14.76	16.02	13.72	
Work status (%)				0.00[b]
Not employed	60.62	64.74	57.21	
Employed	39.38	35.26	42.79	
Region of residence (%)				0.00[b]
North China	51.53	57.00	47.01	
South China	48.47	43.00	52.99	
Urbanicity of residence (%)				0.00[b]
Rural areas	51.26	44.59	56.78	
Urban areas	48.74	55.41	43.22	
Household food expenditure (yuan/week) (mean (SD))	135.79 (182.06)	146.58 (171.34)	126.89 (190.01)	0.00[a]
The season of questionnaire data collection (%)				0.28[a]
Spring	23.12	23.25	23.01	
Summer	24.83	25.57	24.21	
Autumn	26.76	26.28	27.15	
Winter	25.29	24.90	25.63	
Poor mental health (mean (SD))	2.48 (1.06)	2.41 (0.99)	2.53 (1.11)	0.00[a]
NDVI (median (IQR))	0.40 (0.32)[c]	0.39 (0.33)[d]	0.43 (0.31)[d]	0.00[a]
Time spent on transport- and leisure physical activity (minutes) (mean (SD))	323.62 (533.55)	333.38 (579.22)	315.57 (492.55)	0.07[b]
Time spent on sedentary behaviours (minutes) (mean (SD))	224.17 (139.41)	235.53 (142.75)	214.78 (135.88)	0.00[a]
$PM_{2.5}$ concentrations ($\mu g/m^3$) (mean (SD))	47.53 (17.06)	49.25 (17.78)	46.10 (16.31)	0.00[a]
Perennial mean temperature (°C) (mean (SD))	14.27 (4.36)	13.91 (4.52)	14.57 (4.20)	0.00[a]
Population density (population per km^2) (mean (SD))	4681.45 (9418.25)	5182.40 (9704.29)	4267.45 (9418.25)	0.00[a]
GDP per capita (Yuan) (mean (SD))	36039.99 (20585.52)	39714.74 (20904.44)	33004.57 (19812.29)	0.00[a]

Note: results are presented as proportions for categorical variables and as means (standard deviation (SD)) for continuous variables.
[a] *t*-test.
[b] Pearson's chi-squares test.
[c] Based on values from 127 neighbourhoods.
[d] Based on values from 12 112 study participants.

variables; the variance inflation factors were below the critical value of 5. The results of the multilevel SEMs for parallel mediation are presented in Fig. 3 (the detailed results of multilevel SEMs are provided in Table S1). The AIC and BIC values for the parallel mediation model were 200 950.06 and 201 312.67. In the case of overweight/obesity (Fig. 3A1), we found a significant negative association between residential greenness and overweight/obesity (odds = 0.73, 95% CI 0.58–0.92). Time spent on transport- and leisure-related physical activity (odds = 1.00, 95% CI 1.00–1.00) and sedentary behaviours (odds = 1.00, 95% CI 1.00–1.00) was positively associated with overweight/obesity, while $PM_{2.5}$ concentrations (odds = 0.99, 95% CI 0.99–1.00) was negatively associated with overweight/obesity. There were no significant associations between overweight/obesity and perennial mean temperature (odds = 0.98, 95% CI 0.95–1.00). We also found that residential greenness was negatively associated with $PM_{2.5}$ concentrations ($\beta = -18.37$, 95% CI -19.14 to -17.61) and perennial mean temperature ($\beta = -3.06$, 95% CI -3.24 to -2.88). No significant relationships appeared between NDVI and time spent on transport- and leisure-related physical activity ($\beta = 47.06$, 95% CI -33.05–127.16) and amount of time spent on sedentary activity ($\beta = -0.62$, 95% CI –31.20–29.96). Table 2 shows that a significant indirect effect existed between NDVI and overweight/obesity through $PM_{2.5}$ concentrations, but the direction of the indirect effect was in the reverse direction of the direct effect. This finding indicates that our observed association between residential greenness and overweight/obesity could be suppressed by $PM_{2.5}$ concentrations.

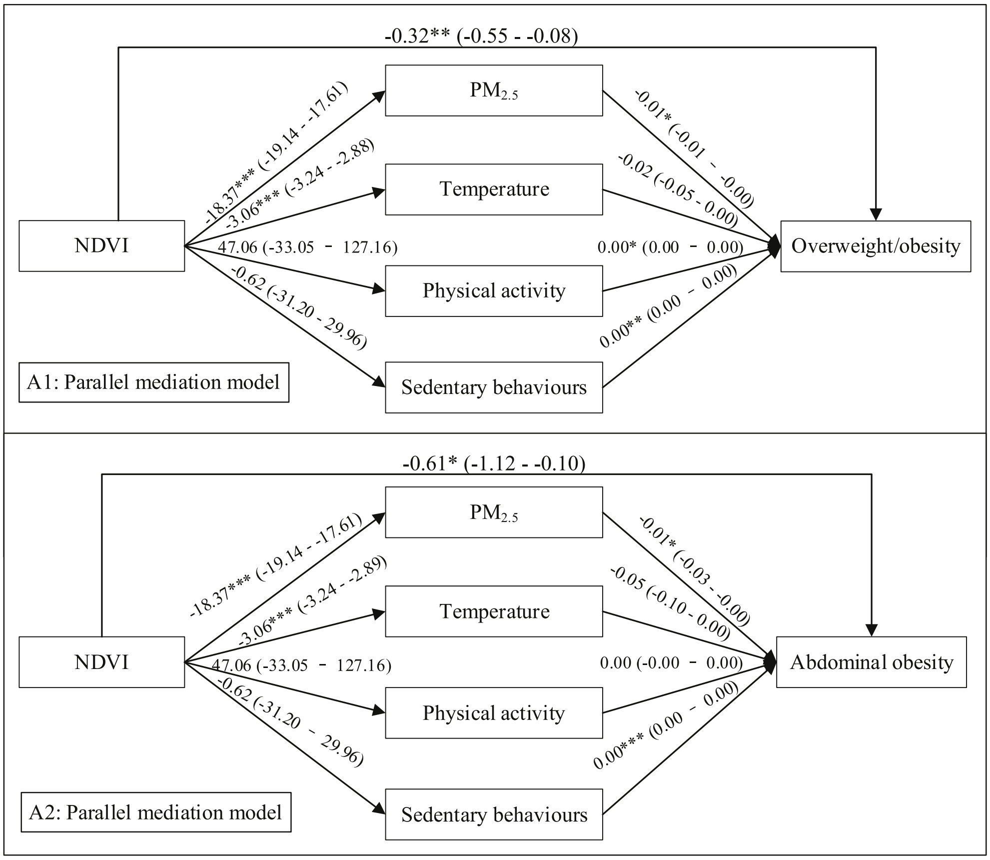

Fig. 3. Results of the multilevel SEMs for parallel mediation
Note: Linear regression coefficients (β) with the 95% CIs of the multilevel SEMs are reported. The models were adjusted for sex, age, marital status, education, household permanent income, car ownership, household's financial situation, work status, household food expenditure, poor mental health, the season of questionnaire data collection, region of residence, urbanicity of residence, population density, and GDP per capita. Full numeric results of multilevel SEMs were presented in Table S1. Significance levels: *$p < 0.05$, **$p < 0.01$, ***$p < 0.00$.

In the case of abdominal obesity (Fig. 3A2), we observed a significant negative association between residential greenness and abdominal obesity (odds = 0.55, 95% CI 0.33–0.91). We also found that time spent on sedentary behaviours was positively associated with central obesity (odds = 1.00, 95% CI 1.00–1.00), while $PM_{2.5}$ concentrations was inversely associated with abdominal obesity (odds = 0.99, 95% CI 0.97–1.00). No significant associations appeared between NDVI and time spent on transport- and leisure-related physical activity (odds = 1.00, 95% CI 1.00–1.00) and perennial mean temperature (odds = 0.95, 95% CI 0.91–1.00). Table 2 suggest that the association between NDVI and abdominal obesity could be suppressed by $PM_{2.5}$ concentrations.

The results of the multilevel SEMs for serial mediation are shown in Fig. 4 (the detailed results of the multilevel SEMs are provided in Table S2). The AIC and BIC scores for serial mediation model are 294 223.22 and 294 748.63 respectively. The AIC and BIC of the parallel mediation model are smaller than those of the serial mediation model, which suggests that the former model has a higher model fit than the latter. Residential greenness was negatively and directly associated with overweight/obesity (Fig. 4B1) and abdominal obesity (Fig. 4B2). $PM_{2.5}$ concentrations was inversely associated with time spent on transport- and leisure physical activity (β = −2.49, 95% CI -4.12 to -0.85). There were no significant associations between $PM_{2.5}$ concentrations and time spent on sedentary behaviours (β = −0.51, 95% CI -1.15–0.12) and between perennial mean temperature and time spent on both transport- and leisure-related physical activity (β = 6.59, 95% CI -0.79–13.97) and sedentary activity (β = 1.58, 95% CI -1.24–4.40). Table 3 indicates that there was no evidence that NDVI could affect adiposity by the serial pathways.

Table 2
Association between neighbourhood greenness and the odds of adiposity: parallel mediation model.

Pathways	Outcome: Overweight/obesity		Outcome: Abdominal obesity	
	Indirect effect	Direct effect	Indirect effect	Direct effect
	β (95% CI)	B (95% CI)	β (95% CI)	β (95% CI)
NDVI → Time spent on transport- and leisure physical activity → Adiposity	0.00 (−0.00–0.01)	−0.32** (−0.55 to −0.08)	−0.00 (−0.00–0.00)	−0.61* (−1.12 to −0.10)
NDVI → Time spent on sedentary behaviours → Adiposity	−0.00 (−0.01–0.01)	−0.32** (−0.55 to −0.08)	−0.00 (−0.02–0.02)	−0.61* (−1.12 to −0.10)
NDVI → $PM_{2.5}$ concentrations → Adiposity	0.12* (0.01–0.22)	−0.32** (−0.55 to −0.08)	0.25* (0.03–0.48)	−0.61* (−1.12 to −0.10)
NDVI → Perennial mean temperature → Adiposity	0.07 (−0.01–0.14)	−0.32** (−0.55 to −0.08)	0.14 (−0.02–0.30)	−0.61* (−1.12 to −0.10)

Note: Linear regression coefficients (β) with the 95% CIs of the multilevel SEMs are reported. The models were adjusted for sex, age, marital status, education, household permanent income, car ownership, household's financial situation, work status, household food expenditure, poor mental health, the season of questionnaire data collection, region of residence, urbanicity of residence, population density, and GDP per capita. Full numeric results of multilevel SEMs were presented in Table S1. Significance levels: *$p < 0.05$, **$p < 0.01$, ***$p < 0.00$.

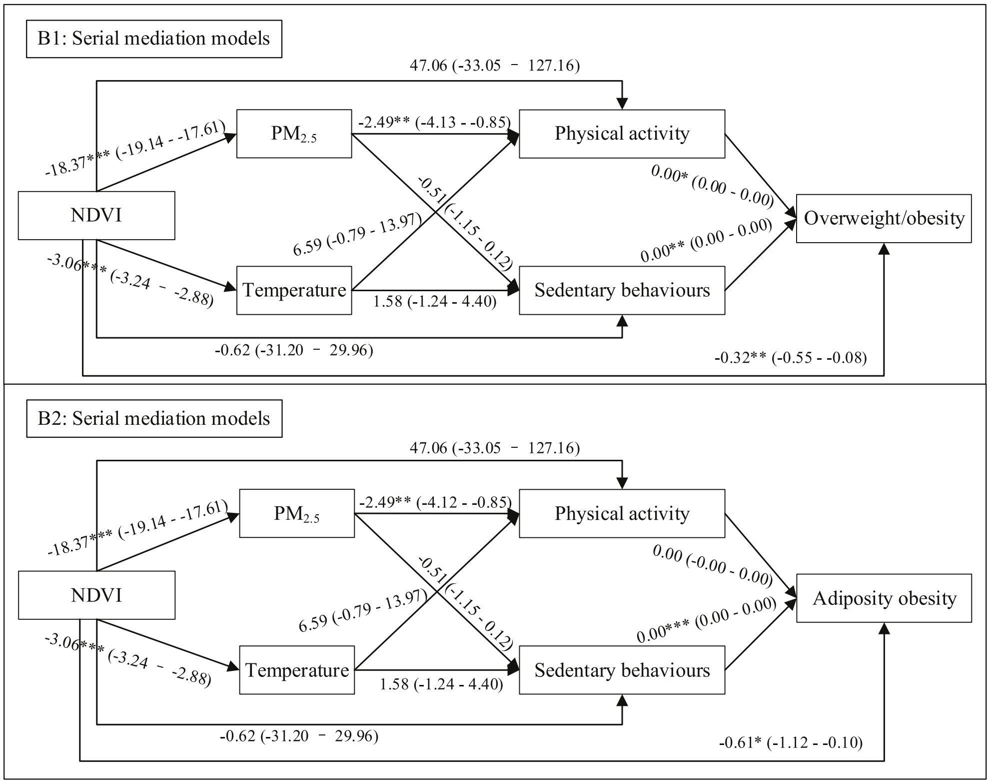

Fig. 4. Results of the multilevel SEMs for serial mediation
Note: Linear regression coefficients (β) with 95% CIs of the multilevel SEMs are reported. The models are adjusted for sex, age, marital status, education, household permanent income, car ownership, household's financial situation, work status, household food expenditure, poor mental health, the season of questionnaire data collection, region of residence, urbanicity of residence, population density, and GDP per capita. Full numeric results of multilevel SEMs were presented in Table S2. Significance levels: $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.00$.

3.3. *Stratified analyses*

Stratified analyses were performed to establish whether the greenness–adiposity relationships were modified by sex, age, education, household permanent income, household financial situation. or urbanicity of residence after adjusting for all covariates (Fig. 5). We observed a significant negative association between greenness and overweight/obesity among females, older participants, those who had a primary or secondary school education, those whose households had a higher income, those whose households had a poorer financial situation, and those who lived in rural areas. We also found a significant negative relationship between greenness and abdominal obesity among females, younger participants, those who had a lower education, and those whose households had a poorer financial situation. We further investigated whether the difference between effects across subgroups was significant by adding interaction terms between modifiers (e.g., age) and exposure (i.e., NDVI) to model specifications. The coefficients of interaction terms suggested that the association between greenness and overweight/obesity differed significantly by sex ($p < 0.000$) and age ($p < 0.000$) but not by education, income, financial situation, and urbanicity of residence. The coefficients also suggested that the association between greenness and abdominal obesity varied significantly by sex ($p < 0.000$), age ($p < 0.005$), and education ($p < 0.009$) but not by other individual/household attributes. The coefficients of the interaction terms are available from the authors upon request.

3.4. *Sensitivity tests*

The results of the sensitivity analyses are shown in Fig. 6. The direction and statistical significance of greenness on the two markers of adiposity based on NDVI with 500 m, 1.5 km, 2 km, and 3 km buffers were congruent with the association in the main analyses using a 1 km buffer. Assessing the quartiles of greenness, rather than greenness as a continuous variable, we found similar associations. Further, the magnitude of the coefficients and their statistical significance did not change substantially after restricting the sample to those with a BMI of $\geq$18.5 kg/m^2, those who had no difficulty walking 100 m, those without cardiovascular diseases, and those who had lived in their current residential area for more than 10 years.

All models have been adjusted for all other variables shown in Table 1.

BMI $\geq$ 18.5 kg/m^2, No difficulty walking, Without cardiovascular diseases, and Non-movers represent, respectively, the estimates of NDVI and markers of adiposity associations after excluding participants who were underweight (BMI <18.5 kg/m^2), participants who had difficulty walking 100 m, participants who had cardiovascular diseases (defined as self-reported angina or hypertension) and participants who had lived in their current residential area for less than 10 years.

4. Discussion

4.1. *Main findings*

To the best of our knowledge, this study was the first to examine the relationship between residential greenness and adiposity markers among middle-aged and older Chinese people using nationally representative survey data. Our results showed that exposure to more greenness in the residential neighbourhood was directly associated with lower odds of overweight/obesity and abdominal adiposity. Parallel mediation models suggest that the association between residential greenness and adiposity could be supressed by $PM_{2.5}$ concentrations. However, there was no evidence that physical activity, sedentary behaviours, $PM_{2.5}$ concentrations, or perennial mean temperature mediate the greenness–adiposity associations. Stratified analyses indicated stronger negative associations between greenness and the odds of overweight/obesity for females and older participants. We also found a stronger negative association with the odds of abdominal adiposity among females, younger participants, and those who had a lower education.

Table 3
Association between neighbourhood greenness and the odds of adiposity: serial mediation model.

Pathways	Outcome: Overweight/obesity		Outcome: Abdominal obesity	
	Indirect effect	Direct effect	Indirect effect	Direct effect
	β (95% CI)	β (95% CI)	β (95% CI)	β (95% CI)
NDVI → PM2.5 concentrations → Time spent on transport- and leisure physical activity → Adiposity	0.00 (−0.00–0.01)	−0.32** (−0.55 to −0.08)	0.00 (−0.00–0.00)	−0.61* (−1.12 to −0.10)
NDVI → PM2.5 concentrations → Time spent on sedentary behaviours → Adiposity	0.00 (−0.00–0.01)	−0.32** (−0.55 to −0.08)	0.01 (−0.00–0.02)	−0.61* (−1.12 to −0.10)
NDVI → Perennial mean temperature → Time spent on transport- and leisure physical activity → Adiposity	−0.00 (−0.00–0.00)	−0.32** (−0.55 to −0.08)	−0.00 (−0.00–0.00)	−0.61* (−1.12 to −0.10)
NDVI → Perennial mean temperature → Time spent on sedentary behaviours → Adiposity	−0.00 (−0.01–0.00)	−0.32** (−0.55 to −0.08)	−0.00 (−0.01–0.00)	−0.61* (−1.12 to −0.10)

Note: Linear regression coefficients (β) with 95% CIs of the multilevel SEMs are reported. The models are adjusted for sex, age, marital status, education, household permanent income, car ownership, household's financial situation, work status, household food expenditure, poor mental health, the season of questionnaire data collection, region of residence, urbanicity of residence, population density, and GDP per capita. Full numeric results of multilevel SEMs were presented in Table S2. Significance levels: *$p < 0.05$, **$p < 0.01$, ***$p < 0.00$.

4.2. Available evidence on the direct effects of residential greenness on adiposity

Our results are in line with earlier studies that suggested a negative association of greenness with overweight/obesity in either children or adults in general (Coombes et al., 2010; Feng and Astell-Burt, 2019; Ghimire et al., 2017; Halonen et al., 2014; Huang et al., 2019b; Klompmaker et al., 2018; Lovasi et al., 2013; Nielsen and Hansen, 2007; Pereira et al., 2013; Sanders et al., 2015a; Sarkar, 2017; Xu et al., 2015). However, evidence from cross-sectional studies on the greenness–overweight/obesity associations in middle-aged and older adults is scarce and shows inconsistent findings (Astell-Burt et al., 2014; Dempsey et al., 2018; Michael et al., 2014; Pereira et al., 2013). For example, a study in Perth, Australia, found that exposure to higher levels and a greater variation of neighbourhood greenness was associated with a lower likelihood of overweight/obesity throughout adulthood (Pereira et al., 2013). Another Australian study found a protective effect of proximity to greenery against the risk of overweight/obesity only in middle-aged to older women (Astell-Burt et al., 2014). However, results from an Ireland study have questioned whether the greenness–overweight/obesity association is linear and suggested a u-shaped association, whereby those living in neighbourhoods with the lowest and highest levels of green space were more likely to be obese (Dempsey et al., 2018). In addition, a study among older women in Portland, USA, suggested that access to parks was not associated with BMI (Michael et al., 2014).

Consistent with previous evidence on adults (Huang et al., 2019b; Persson et al., 2018; Sarkar, 2017), we found a significant negative association between greenness and the prevalence of abdominal adiposity among middle-aged or older adults. Abdominal adiposity – a proxy for visceral fat distribution – is thought to be a better predictor of cardiovascular disease and mortality than BMI (Pischon et al., 2008). Epidemiologic studies have primarily focused on BMI as the proxy for overweight/obesity (Lachowycz and Jones, 2011); only a few have examined the association between greenness exposure and WC or central obesity and produced relatively consistent results (Huang et al., 2019b; Persson et al., 2018; Sanders et al., 2015a; Sarkar, 2017). For example, a cross-sectional study in UK found that adults living in greener areas were more likely to have a smaller WC (Sarkar, 2017). Similarly, another cross-sectional study in China reported that more greenness was associated with a lower likelihood of abdominal obesity among adults in urban communities (Huang et al., 2019b). Meanwhile, a longitudinal study in Stockholm (Sweden) showed that pronounced long-term exposure to greenness was related to lower odds of abdominal adiposity (Persson et al., 2018), while another longitudinal study found that children in Australia who lived in the greenest neighbourhood were more likely to have a smaller WC than those who lived in the least green areas (Sanders et al., 2015a).

4.3. Stratified analyses

Results from stratified analyses showed that the greenness-overweight/obesity association varied significantly by sex and age, and the greenness-central obesity varied significantly by sex, age, and education. In the case of overweight/obesity, we found that the negative association of neighbourhood green space was significant in females. The results were consistent with earlier work that found that females benefit more from exposure to greenness than do males (Huang et al., 2019b; Persson et al., 2018; Sarkar, 2017). It is likely that older Chinese females visit green spaces more frequently and spend more time there taking care of their grandchildren etc. than do older males (Huang et al., 2019a). We also observed that the inverse greenness–overweight/obesity association was stronger for those aged ≥65 years. This finding confirms previous Chinese results (Huang et al., 2019b). A possible explanation is that older people are more likely to use nearby rather than remote green spaces as a result of limited functional ability (Huang et al., 2019b; Maas et al., 2006; Yen et al., 2009).

In the case of abdominal obesity, we found significant evidence that greenness was negatively associated with abdominal adiposity among females, younger adults aged 50–64 years, and lower educated adults. We observed that the greenness-abdominal obesity association was significant in younger adults aged 50–64 years. This result is partially consistent with the UK Biobank study that showed that the inverse association between residential greenness and WC was stronger for adults aged 50–60 years (Sarkar, 2017). A possible explanation is that middle-aged and older adults are more able and more willing to contact with green spaces near their residence for physical exercise and social interaction compared with older adults. Our findings indicated – consistent with prior work (Persson et al., 2018) – that lower educated participants benefit more from greenness than those with a higher education level. This could mean that lower SES groups rely more on their immediate residential environment and public facilities due to financial stress (Huang et al., 2019a; Persson et al., 2018).

4.4. Potential mechanisms

Several mechanisms through which greenness may affect an individual's obesity outcome have been proposed (Lachowycz and Jones, 2011; Markevych et al., 2017; Persson et al., 2018; Sarkar, 2017). Exposure to greenness may encourage physical activity and reduce sedentary behaviours, support restoration from stress and block negative emotions, facilitate neighbourhood cohesion and residential satisfaction, and filter out air pollutants and reduce extreme temperature (Liu et al., 2019). However, our study examined four pathways (i.e.,

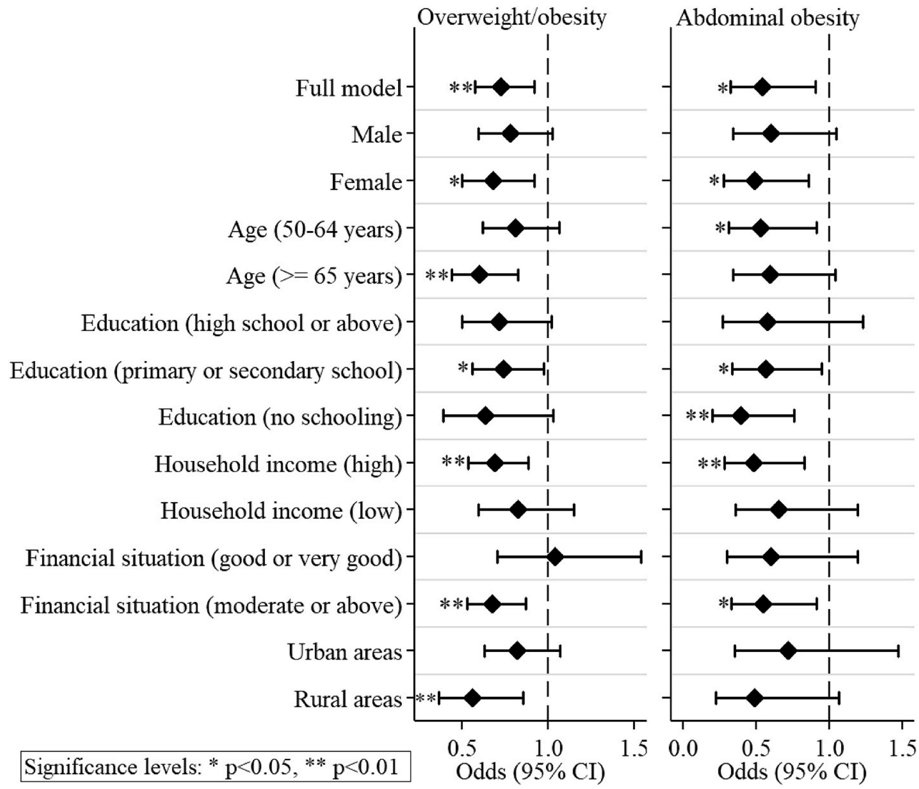

Fig. 5. Results of stratified multilevel SEMs on the relationship between residential greenness and the odds of adiposity. Stratification was based on sex, age, education, household income, household's financial situation, and urbanicity of residence adjusting for all other variables in Table 1. Note: Symbols show odds, bars show 95% CI.

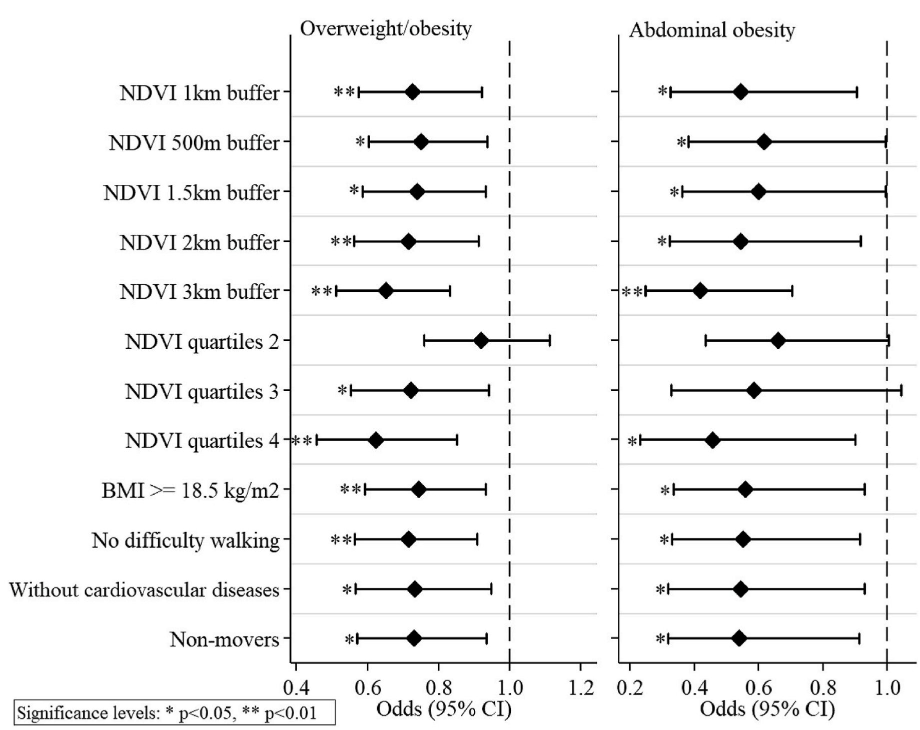

Fig. 6. Results of sensitivity tests with the multilevel SEMs on the relationship between residential greenness and the odds of adiposityNote
Symbols show odds, bars show 95% CI.

physical activity, sedentary behaviours, $PM_{2.5}$ concentrations, and perennial mean temperature) associating residential greenness with two markers of adiposity. Parallel mediation models suggest that $PM_{2.5}$ concentrations may exert a suppressive effect on the associations between residential greenness and adiposity. We found that neighbourhood greenness could mitigate air pollution, while $PM_{2.5}$ concentrations was inversely associated with adiposity. This counterintuitive result can be explained as follows: the relatively coarse spatial scale (neighbourhood level) of $PM_{2.5}$ concentrations combined with coarse spatial resolution of $PM_{2.5}$ data (with a resolution of 1 km) did not capture fine-scale $PM_{2.5}$ gradients, which could lead to a measurement error in air pollution exposure. In addition, there was no evidence that physical activity, sedentary behaviours, or perennial mean temperature could mediate the associations between neighbourhood greenness exposure and markers of adiposity. Serial mediation models also indicated that none of the four potential mediators could mediate the associations between residential greenness and the two indicators of adiposity. The possible reasons are as follows. Firstly, the middle-aged and older Chinese adults generally spent less time on transport- and leisure-related physical activities and more time sitting down or reclining. In our sample, nearly half of the participants did not meet the WHO-recommended amount of moderate to vigorous physical activity, and two thirds of participants spent at least 180 min on sedentary behaviours every day. Secondly, half of the participants lived in rural areas, where vegetation is for agricultural purposes and unsuitable for transport- and leisure-related physical activities. Thirdly, the spatial scale of our geographic variables was very coarse, and thus we might fail to detect fine spatial contrasts in greenness. Lastly, the cross-sectional design used in the present study may not allow for detecting complex and temporal mediation relationships and the direction of causality (Dzhambov et al., 2020). These results indicated that other potential mediators (e.g., increases stress recovery, enhances social cohesion, and reduces noise pollution) might exist in the pathway associating greenness with the odds of adiposity.

4.5. Strengths and limitations

The present research had three particular strengths. First, it provided a comprehensive picture of the greenness–adiposity association among Chinese middle-aged and older adults using a nationally representative survey collected in 64 township-level units, taking into account co-exposures that vary substantially across the country (e.g., air pollution, temperature, urbanicity). Second, our models were well adjusted for demographic attributes, socioeconomic status, urbanicity of residence, etc. Third, we used multilevel SEMs instead of single-level models with Baron and Kenny's approach to assess the mediating roles of physical activity, sedentary behaviours, $PM_{2.5}$ concentrations, and perennial mean temperature. Our SEMs addressed the problem of estimation bias introduced by neglecting neighbourhood-level residuals.

Our research also had some limitations. First, the cross-sectional design precluded us from inferring causation, and we cannot rule out reverse causality. Second, residential self-selection may have affected the greenness–obesity relationships: people who like to exercise may prefer to live in greener neighbourhoods, which are conducive to maintaining a healthy weight. Thus, it could be that the association between greenness exposure and overweight/obesity is over-estimated. Third, we used circular buffers centred on the centroid of participants' village/enumeration area rather than participants' home address, which may have induced an exposure measurement error. However, the size of village/enumeration areas in China is normally small well aligning with 1 km circular buffers covering most villages/enumeration areas. Fourth, we used a static exposure assessment of residential greenness, therefore neglecting participants' greenness exposure in their daily activity (e.g., green spaces on the daily commuter routes and green spaces in the vicinity of the workplace, etc.). Fifth, we were not able to consider participants' frequency of using greenspace due to the lack data. We cannot exclude the possibility that this may have affected our exposure assessment. Finally, due the absence of absolute fit indices for SEMs with binary outcomes, we were unable to assess the overall goodness-of-fit of our models.

5. Conclusion

Our results suggested that exposure to higher levels of residential greenness was associated with lower odds of overweight/obesity and abdominal obesity among middle-aged and older Chinese adults. Subgroup analyses identified groups that are potentially susceptible due to their demographic traits and education level. There was some indication that $PM_{2.5}$ concentrations may exert a suppressive effect on the greenness-adiposity associations, and there was no evidence that physical activity, sedentary behaviours, or perennial mean temperature mediate the greenness–adiposity associations. Further longitudinal studies and natural experiments are needed to assess underlying mechanisms in order to better understand the health-supportive effects of neighbourhood greenery.

Ethics

Ethical approval for the study was obtained from the WHO Ethical Review Committee, the Chinese Centre for Disease Control and Prevention Ethical Review Committee, and the Biomedical Research Ethics Committee of Sun Yat-sen University. Informed consent was obtained from each respondent prior to interview and examination.

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Declaration of competing interest

The authors declare that they have no conflicts of interests.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijheh.2020.113606.

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