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Association between residential greenness and metabolic syndrome in Chinese adults

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ABSTRACT

Background: Residing in greener areas has several health benefits, but no study to date has examined the effects of greenness on metabolic syndrome (MetS). We aimed to assess associations between residential greenness and MetS prevalence in China, and to explore whether air pollution and physical activity mediated any observed associations.

Methods: We analyzed data from 15,477 adults who participated in the 33 Communities Chinese Health Study during 2009. We defined MetS according to standard guidelines for Chinese populations. Residential greenness was estimated using the Normalized Difference Vegetation Index (NDVI), the Soil Adjusted Vegetation Index (SAVI), and the Vegetation Continuous Field (VCF). We used generalized linear mixed models to assess the associations between greenness and MetS, and mediation analyses to explore potential mechanisms underlying the associations.

Results: Higher greenness levels were associated with lower odds of MetS [e.g., for every interquartile range increase of $NDVI_{500\text{-m}}$, $SAVI_{500\text{-m}}$, and $VCF_{500\text{-m}}$, the adjusted odds ratio of MetS was 0.81 (95% confidence interval: 0.70–0.93), 0.80 (95% confidence interval: 0.69–0.93), and 0.91 (95% confidence interval: 0.83–1.00), respectively]. The direction and the magnitude of the associations persisted in several sensitivity analyses. Stratified analyses showed that age and household income modified the associations, with greater effect estimates observed in participants younger than 65 years old or those with higher household income. Particulate matter with an aerodynamic diameter ≤10 μm, nitrogen dioxide, and ozone mediated 2.1–20.3% of the

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associations between greenness and MetS; no evidence of mediation was observed for physical activity.
Conclusions: Our findings suggest a beneficial association for residential greenness and MetS in Chinese urban dwellers, especially for participants younger than 65 years old and those with higher household income. Particulate matter with an aerodynamic diameter ≤10 μm, nitrogen dioxide and ozone, but not physical activity, may only partially mediate the association.

1. Introduction

Metabolic syndrome (MetS), characterized by a cluster of metabolic disorders (i.e., elevated blood pressure and blood glucose levels, dyslipidemia, and abdominal obesity; hereafter referred to as "MetS components"), has been linked to increased risks for cardiovascular morbidity and mortality (O'Neill and O'Driscoll, 2015). It is estimated that about 20–30% of the global population has MetS, and the prevalence keeps growing (O'Neill and O'Driscoll, 2015; Pucci et al., 2017). China is also experiencing this increase in MetS prevalence. The most recent nationwide meta-analysis in 2016 estimated that the prevalence of MetS was 24.5% (about 300 million Chinese people) in China (Li et al., 2016). Better understanding of risk factors and potential intervention strategies is therefore needed to mitigate the growing MetS burden in China. There have been well-documented individual-level guidelines for preventing MetS — including weight reduction, increased physical activity, and healthy diet. Meanwhile, there is growing awareness that environmental factors may also be crucial protective factors for preventing MetS.

Accumulating evidence suggests that living in greener areas is beneficially associated with many health indicators (Markevych et al., 2017; Twohig-Bennett and Jones, 2018), including MetS components: hypertension (Dzhambov et al., 2018; Yang et al., 2019a), diabetes or impaired fasting glucose (Astell-Burt et al., 2014a; Dadvand et al., 2018; Yang et al., 2019b; den Braver et al., 2018), dyslipidemia (Kim et al., 2016; Yang et al., 2019c), and adiposity (Persson et al., 2018). However, previous studies mainly focused on the individual MetS components, and only three explored the complex, multiple conditions that constitute MetS (de Keijzer et al., 2019; Dengel et al., 2009; Paquet et al., 2013). Comparing with individual MetS components, these conditions co-occur in an individual would be associated with much greater risk of cardiovascular morbidity and mortality. Thus, exploration of the relationship between greenness and MetS would have more important public health significance. Potential mechanisms for the beneficial effects of greenness on human health included reduced exposure to environmental hazards (e.g. air pollution, noise, and air temperature) and psychophysiological stress, encouraging physical activity, and facilitating social cohesion (Markevych et al., 2017). These factors can also be independently or interactively involved in the pathophysiologic pathways of MetS (Eckel et al., 2005).

During the past four decades, China has experienced rapid urbanization (Guan et al., 2018), which poses a great challenge for urban dwellers' access to greenspace (Nieuwenhuijsen et al., 2017), and has also caused severe air pollution (Chen et al., 2018a). In addition, lifestyle changes like motorized transport to work and reduced leisure time has caused an epidemic of physical inactivity in China (Kohl et al., 2012). If there are beneficial effects of greenness on MetS and the effects are mediated by air pollution and physical activity, then China might have the potential to realize public health benefits by developing more urban greenspaces.

We hypothesized that: (1) living in areas with higher greenness levels is associated with lower odds of MetS, and (2) a lower air pollution and more physical activity could mediate the association between greenness and MetS.

2. Methods

2.1. Study area

From April 1 to December 31, 2009, we conducted a large population-based cross-sectional study (the 33 Communities Chinese Health Study, 33CCHS) in Liaoning province, Northeastern China (Yang et al., 2019a). Liaoning province has dry and cold winters, but wet and warm summers. The province has a population of over 20 million, of which about 64% live in urban areas. The province is also an important industrial area in Northeastern China. Given abundant industrial and traffic emissions as well as household solid fuel combustion for heating in the winter months, severe air pollution has been observed in the area (Chen, et al., 2018a). In addition, greenness levels in urban areas of Liaoning province, like most Chinese cities, are relatively low due to high-density buildings and limited land availability. Greenspace in these urban areas mainly comprises of community gardens (i.e., gardens within the communities), parks, road greenbelts, and other open spaces. Among them, community gardens that typically consist of trees (e.g., poplar, willow, pine, and ginkgo), lawn, and flowers, serve as a crucial greenspace type and have been frequently used by the community residents for physical activity and social contact. Moreover, the prevalence of MetS is reported to be high (39.0%) in the province (Yu et al., 2014).

2.2. Study participants

Using a random number generator, we employed a four-stage stratified cluster sampling scheme to select potential participants (Fig. S1). First, three cities (Shenyang, Anshan, and Jinzhou) were randomly selected from the 14 cities in Liaoning province. Second, three communities from each of 11 total districts (five districts in Shenyang and three each in Jinzhou and Anshan) were randomly selected, which yielded 33 study communities in total. Third, 700–1000 households were randomly selected from each community. Fourth, one adult aged 18–74 years was randomly selected from each household without replacement. The following individuals were excluded from the study sample: pregnant women; people who resided at the current area for less than five years; or people with severe pre-existing disease(s) (e.g. terminal cancer).

A total of 28,830 individuals were invited to participant in the study, of whom 24,845 finished the study and returned questionnaires, generating a response rate of 86.2%. In the current analysis, we excluded 9368 individuals who refused to provide a venous blood sample, yielding 15,477 participants. The study protocol was reviewed and approved by the Human Studies Committee of Sun Yat-Sen University. Each participant gave written informed consent.

2.3. Outcome assessment

We measured blood pressure (BP) according to the guidelines of the American Heart Association (Pickering et al., 2005). Briefly, all study participants were asked not to consume tobacco, coffee, or tea, and not to undertake exercise for more than 30 min before BP measurement. After at least five minutes' rest in a quiet room and with the participants sitting upright, we measured systolic blood pressure (SBP) and diastolic blood pressure (DBP) three times using a standardized mercuric-column sphygmomanometer, with an interval of two minutes. The first reading was taken on both arms, and the second and third readings were taken on the arm showing greater BP measurements. The average of the three consecutive pairs of BP measurements was recorded and used in the analysis.

We measured study participants' height and weight to the nearest 0.5 cm and 0.1 kg, respectively, according to the standard protocol developed by WHO (World Health Organization, 1995). Body mass index was calculated as weight divided by the square of height. Waist circumference (WC) was measured to the nearest 0.5 cm, using a tape with insertion buckle at one end, and was recorded (World Health Organization, 1995).

We collected a blood sample after participants fasted for 12 h. A Hitachi Autoanalyzer (Type 7170A; Hitachi Ltd.; Tokyo, Japan) was employed to determine serum levels of fasting blood glucose (FBG), triglycerides (TG), and high-density lipoprotein cholesterol (HDL-C). All assays were performed according to the manufacturer's instructions.

We adopted the Joint Interim Societies' definition of MetS for Chinese populations in our analysis, which was defined as having three or more of the following components: (1) a WC ≥85 cm for men or ≥80 cm for women; (2) a FBG level ≥100 mg/dL (or 5.6 mmol/L); (3) a TG ≥150 mg/dL (or 1.7 mmol/L); (4) an HDL-C ≤40 mg/dL (1.0 mmol/L) for men or ≤50 mg/dL (1.3 mmol/L) for women; and (5) a SBP ≥130 mmHg or DBP ≥85 mmHg (Alberti et al., 2009). In sensitivity analyses, we also defined MetS using recommendations by (1) the National Cholesterol Education Program/Adult Treatment Panel III Criteria (NCEP/ATP III) (Grundy et al., 2005), (2) the Chinese Diabetes Society (CDS) (Joint Committee for Developing Chinese Guidelines on Prevention and Treatment of Dyslipidemia in Adults, 2016), (3) the International Diabetes Federation (IDF) (Alberti et al., 2005), and (4) the American Heart Association (AHA) (Grundy et al., 2005). Further, we calculated continuous Metabolic Syndrome Severity Score (MetSSS) according to the formulas suggested by Wiley and Carrington (2016).

2.4. Exposure assessment

The residential geographical codes of our study population were community-level and were used for assigning greenness exposure data. In our current study, the size of the study communities ranged from 0.25 to 0.64 km^2. We geocoded the residential locations based on the centroid of the community using the xGeocoding software (http://www.gpsspg.com/xgeocoding/).

To estimate residential greenness exposure, we calculated three indicators: the Normalized Difference Vegetation index (NDVI), the Soil Adjusted Vegetation Index (SAVI), and the Vegetation Continuous Fields (VCF). Both NDVI and SAVI were derived from the Landsat 5 Thematic Mapper satellite images at a 30-m by 30-m resolution (http://earthexplorer.usgs.gov). NDVI was calculated as near-infrared minus red reflectance divided by near-infrared plus red reflectance (Weier and Herring, 2011). SAVI was calculated by additionally incorporating a correction factor to minimize the effects of soil background on the vegetation. Both NDVI and SAVI values fall in a range of −1 to +1, with higher number representing greener areas. We downloaded Landsat 5 Thematic Mapper satellite images with a minimum of cloud cover obtained during August 2010, which is the greenest month in northern China and the closest year to the study period. We did not remove water pixels from the satellite images. VCF indicates the percent of each pixel covered by woody vegetation with a height greater than 5-m. It was calculated as the annual average value for the year 2009 based on a satellite image collected by the Moderate Resolution Imaging Spectroradiometer aboard the Terra satellite at a 250-m by 250-m resolution. We defined residential greenness as the average of NDVI, SAVI, or VCF in circular buffers of 500-m and 1000-m around each community centroid. We used NDVI, SAVI, and VCF values in the 500-m buffer in the main analysis. However, effect estimates for the three greenness metrics in 1000-m buffer were also reported in sensitivity analyses. Calculations for all the three metrics were carried out in ArcGIS 10.4 (ESRI, Redlands, CA, USA).

2.5. Confounders and potential mediators

We used the literature to identify common predictors of greenness exposure and MetS as potential confounding variables, and incorporated these into a directed acyclic graphing (DAG, Fig. S2) to select a minimally sufficient set of variables for adjustment (Greenland et al., 1999), employing DAGitty v2.3 software (www.dagitty.net). From the DAG (Fig. S2), we considered the following variables as confounders: gender (men or women), age (in years), ethnicity (Han or "others"), education level (< 9 years *vs.* ≥9 years), household income levels (< 10,000 Yuan or ≥10,000 Yuan), and district-level gross domestic product (GDP, in Chinese Yuan) and population density (person/km^2) (Fig. S2). These variables were assessed by questionnaire, with the exception of district-level GDPs and population density, which were obtained from cities' Statistical Yearbook.

Evidence has documented that greenness can reduce air pollution levels (Hirabayashi and Nowak, 2016) and encourage physical activity (McMorris et al., 2015; Astell-Burt et al., 2014b), which are both correlated with MetS (Zhang et al., 2017; Yang et al., 2018b). Therefore, air pollution and physical activity are suggested to be on the pathway between greenness exposure and MetS, and we considered them as potential mediators (Fig. S2). PM_1, $PM_{2.5}$, PM_{10}, SO_2, NO_2, and O_3 assessment has been described in detail elsewhere (Chen et al., 2018b; Yang et al., 2018a). Briefly, we obtained two types of daily aerosol optical depth (AOD) data (i.e., Deep Blue (DB) and Dark Target (DT)) from the Aqua Atmosphere Level 2 Product Collection 1 at a 0.1° × 0.1° spatial resolution, and combined them to employ an Inverse Variance Weighting method. We then developed a generalized additive model to link the AOD data with ground-monitored PM_1 and $PM_{2.5}$ measurements, land use information, meteorological data, and other spatial predictors. Finally, a 10-fold cross-validation process was performed to test the validity of PM_1 and $PM_{2.5}$ predictions, and the results showed the adjusted R^2 and root-mean-squared error were 71% and 13.0 μg/m^3, and 75% and 15.1 μg/m^3, and respectively. Daily PM_{10}, SO_2, NO_2, and O_3 concentrations were obtained and calculated using data generated from air monitoring stations (Yang et al., 2018a). Finally, we calculated three-year (2006–08) average air pollutants concentrations and then assigned them to the study participants. Information on physical activity was collected using self-reported questionnaire (exercised ≥180 min per week or exercised < 180 min per week).

2.6. Statistical analysis

Given the clustered structure of our data, we used generalized linear mixed models with a random intercept for community to evaluate the association between greenness and MetS prevalence. The results are presented as odds ratio (ORs) with corresponding 95% confidence intervals (CIs) per interquartile range (IQR) increment in NDVI and SAVI. We fitted two models: a crude model, and a multivariate model adjusted for variables listed in covariates section. Consistent with previous studies (Yeager et al., 2018; Dzhambov et al., 2018), we introduced NDVI and SAVI as continuous linear terms in the models.

We performed several sensitivity analyses. First, we used other four MetS definitions to assess the impact of possible outcome misclassification. Second, we repeated the analyses using larger buffers of NDVI and SAVI (i.e., 1000-m). Third, we categorized greenness metrics into quartiles to explore potential non-linear associations. Fourth, we estimated the greenness-MetS associations by excluding participants with cardiovascular diseases (defined as self-reported heart disease and stroke), hypotension (SBP < 90 mmHg or DBP < 60 mmHg) (Lim et al., 2003), or underweight (BMI < 18.5 kg/m^2) (Flegal et al., 2005) to assess the impact of existing disorders. Fifth, we repeated the analyses by additional adjusting for smoking, alcohol consumption, controlled diet of low calories, and sugar-sweetened soft drink intake to reduce potential residual confounding. Sixth, we performed linear regression to explore the association of greenness with continuous MetSSS. Finally, we performed Poisson regression models to assess the relationship between greenness and the number of MetS components, and regression coefficients from the models were exponentiated to express as relative risks.

We also tested the effect modification effects by age, gender, and household income levels on the association between greenness and MetS. First, we performed stratified analyses by age (≥65 years *vs.* < 65 years), gender (men *vs.* women), and household income levels (≥10,000 Yuan *vs.* < 10,000 Yuan). Then, we evaluated the presence of interactions on the additive scale by calculating the relative excess risk due to interaction (RERI) (Andersson et al., 2005). An RERI of 0 indicates no interaction.

Finally, we assessed the potential mediating effects of air pollutants and physical activity on greenness and MetS using the existing R mediation package created by Imai et al. (2010) and calculated standard errors by generating 5000 bootstrap iterations. Briefly, this method compared the exposure effect estimate from the full model that included the greenness, mediator and all covariates (multivariate model) with the exposure effect estimates obtained from a univariate model where exposure is regressed on the mediator (the mediation model). The mediators were tested one-at-a-time. These analyses were performed using the function *mediate* implemented in the R package.

All analyses were performed in SAS 9.4 (SAS Institute, Inc. Cary, NC, USA) or R software (version 3.4.3, R foundation for Statistical Computing, Vienna, Austria). A two-tailed P value < 0.05 was used as the threshold for statistical significance.

3. Results

3.1. Population characteristics

Mean (SD) age of the study participants was 45.0 (13.5) years, and 47.3% were women. Most participants (94%) were of Han ethnicity and had a household income ≥10,000 Yuan per year (79.6%). The prevalence of MetS was 30.4%. Participants with MetS were more likely to be aged ≥65 years, men, Han ethnicity, have a lower level of household income and education, and exercise more regularly when compared to participants without MetS (Table 1). The basic characteristics of the participants in the current analysis were similar (although not the same) to those who were excluded (Table S1).

3.2. Greenness exposure

There was large spatial heterogeneity in levels of greenness among the study communities. For instance, the $NDVI_{500\text{-}m}$ levels ranged from 0.18 to 0.80, $SAVI_{500\text{-}m}$ from 0.10 to 0.48, and $VCF_{500\text{-}m}$ from 2.17 to 33.63%. NDVI and SAVI were strongly correlated, with r_s ranging from 0.89 to 0.98 (Table S2). However, the correlations between NDVI/SAVI and VC were low, which may be due to specifics of the study area where community gardens with grasses, short trees, and shrubs are prevailing greenspaces. Also, we observed low correlations between all the studies greenness metrics and air pollutants. Compared with participants without MetS, those with MetS lived in areas with lower greenness (Table 1).

3.3. Greenness exposure and MetS prevalence

In the crude model, higher greenness was significantly associated with lower odds of MetS (Table 2). When adjusted for age, gender, ethnicity, household income, education, and district-level gross domestic product and population density, the associations were slightly attenuated but remained statistically significant; for a IQR increase in $NDVI_{500\text{-}m}$, $SAVI_{500\text{-}m}$, and $VCF_{500\text{-}m}$, the adjusted OR of MetS was 0.81 (95% CI: 0.70–0.93), 0.80 (95% CI: 0.69–0.93), and 0.91 (95% CI: 0.83–1.00), respectively (Table 2).

We repeated analyses using other four MetS definitions and found that the effect estimates were similar to those of the main analysis, although the association between $VCF_{500\text{-}m}$ and MetS using the NCEP/ATP III definition did not reach statistical significance (Table 3). In analyses using larger buffer (1000-m) of the greenness metrics, the associations persisted in magnitude and direction (Table 2). When greenness levels were categorized into quartiles, we observed that compared with participants in the first quartile group of exposure, those in the second, third, and fourth quartile groups had lower odds for MetS, and P values for trend were statistically significant (Table S3). We repeated analyses excluding participants with cardiovascular diseases (Table S4), hypotension (Table S5), or those who were underweight (Table S6), and found that the effect estimates did not substantially change. When the main models were additionally adjusted for smoking, alcohol consumption, low calorie diet, or sugar-sweetened soft drink, the results were similar (Table S7). We also observed that higher greenness levels were significantly associated with lower MetSSS (Table S8) and with lower number of MetS components (Table S9).

Table 1
Descriptive statistics of study participants (n = 15,477).

Variables	MetS (n = 4701)	Non-MetS (n = 10,776)	P value
Sociodemographic factors (covariates)			
Age, No. (%)			< 0.001
< 65 years	4185 (89.0)	9958 (92.4)	
≥65 years	516 (11.0)	818 (7.6)	
Gender, No. (%)			< 0.001
Men	2738 (58.2)	5418 (50.3)	
Women	1963 (41.8)	5358 (49.7)	
Ethnicity, No. (%)			< 0.001
Han	4482 (95.3)	10,072 (93.5)	
Others	219 (4.7)	704 (6.5)	
Education			< 0.001
< 9 years	3761 (80.0)	8137 (75.5)	
≥9 years	940 (20.0)	2639 (24.5)	
Household income per year, Yuan, No. (%)			< 0.001
< 10,000	1047 (22.3)	2097 (19.5)	
≥10,000	3654 (77.7)	8679 (80.5)	
District-level per capita GDP, Yuan, Mean (SD)[a,b]	73,786 (30,213)	73,640 (30,974)	0.964
District-level population density, Person/km^2, Mean (SD)[b]	8771 (4560)	8799 (4581)	0.888
Exposures			
$NDVI_{500\text{-}m}$, Mean (SD)[c]	0.31 (0.11)	0.33 (0.13)	< 0.001
$NDVI_{1000\text{-}m}$, Mean (SD)[c]	0.32 (0.10)	0.33 (0.12)	< 0.001
$SAVI_{500\text{-}m}$, Mean (SD)[c]	0.17 (0.07)	0.19 (0.08)	< 0.001
$SAVI_{1000\text{-}m}$, Mean (SD)[c]	0.18 (0.07)	0.19 (0.07)	< 0.001
$VCF_{500\text{-}m}$, %, Mean (SD)[c]	6.66 (4.75)	7.36 (5.86)	< 0.001
$VCF_{1000\text{-}m}$, %, Mean (SD)[c]	6.57 (3.26)	6.97 (4.00)	< 0.001
Candidate mediators			
Regular exercise (n, %)			< 0.001
No	3076 (65.4)	7469 (69.3)	
Yes	1625 (34.6)	3307 (30.7)	
$PM_{2.5}$, Mean (SD)[c]	83.90 (14.82)	82.59 (14.51)	< 0.001
NO_2, Mean (SD)[b]	36.10 (5.54)	35.35 (5.45)	< 0.001

Abbreviations: GDP, gross domestic product; MetS, metabolic syndrome; NDVI, normalized difference vegetation index; NO_2, nitrogen dioxide; $PM_{2.5}$, particle with aerodynamic diameter ≤2.5 μm; SAVI, soil adjusted vegetation index; SD, standard deviation; VCF, vegetation continuous field.

[a] 1 US Dollar = 6.84 Yuan in 2009.

[b] Based on values from 11 districts.

[c] Based on values from 33 communities.

Table 2
Associations between per IQR[a] increase in greenness metrics and metabolic syndrome prevalence (n = 15,477).

Greenness metrics	Crude OR (95% CI)	*P* value	Adjusted OR (95% CI)[b]	*P* value
$NDVI_{500\text{-m}}$	0.78 (0.68 to 0.91)	0.001	0.81 (0.70 to 0.93)	0.003
$NDVI_{1000\text{-m}}$	0.81 (0.70 to 0.93)	0.004	0.83 (0.72 to 0.95)	0.006
$SAVI_{500\text{-m}}$	0.78 (0.67 to 0.90)	0.001	0.80 (0.69 to 0.93)	0.003
$SAVI_{1000\text{-m}}$	0.80 (0.69 to 0.93)	0.004	0.82 (0.71 to 0.94)	0.006
$VCF_{500\text{-m}}$	0.90 (0.82 to 0.99)	0.025	0.91 (0.83 to 1.00)	0.038
$VCF_{1000\text{-m}}$	0.95 (0.89 to 1.00)	0.068	0.95 (0.89 to 1.00)	0.068

Abbreviations: CI, confidence interval; IQR, interquartile range; NDVI, normalized difference vegetation index; OR, odds ratio; SAVI, soil adjusted vegetation index; VCF, vegetation continuous field.
[a] IQR: $NDVI_{500\text{-m}}$, 0.17; $NDVI_{1000\text{-m}}$, 0.15; $SAVI_{500\text{-m}}$, 0.11; $SAVI_{1000\text{-m}}$, 0.10; $VCF_{500\text{-m}}$, 4.52%; $VCF_{1000\text{-m}}$, 1.97%.
[b] Adjusted for age, gender, ethnicity, household income, education, and district-level of gross domestic product and population density.

Table 3
Associations between per IQR[a] increase in greenness metrics and MetS prevalence using different definitions (n = 15,477).

Definitions	$NDVI_{500\text{-m}}$	*P* value	$SAVI_{500\text{-m}}$		$VCF_{500\text{-m}}$	*P* value
	Adjusted OR (95% CI)[b]		Adjusted OR (95% CI)[b]	*P* value	Adjusted OR (95% CI)[b]	
JISC (main definition)	0.81 (0.70 to 0.93)	0.003	0.80 (0.69 to 0.93)	0.003	0.91 (0.83 to 1.00)	0.038
NCEP/ATPIII	0.83 (0.71 to 0.96)	0.010	0.82 (0.70 to 0.95)	0.010	0.93 (0.85 to 1.02)	0.144
CDS	0.79 (0.71 to 0.88)	< 0.001	0.78 (0.70 to 0.87)	< 0.001	0.90 (0.84 to 0.98)	0.009
IDF	0.81 (0.68 to 0.95)	0.011	0.81 (0.68 to 0.96)	0.015	0.90 (0.81 to 1.00)	0.041
AHA	0.81 (0.70 to 0.92)	0.002	0.80 (0.70 to 0.93)	0.003	0.91 (0.83 to 1.00)	0.042

AHA, American Heart Association; CDS, Chinese Diabetes Society; CI, confidence interval; IDF, the International Diabetes Federation; IQR, interquartile range; JISC, Joint Interim Societies Criteria; NCEP/ATPIII, the US National Cholesterol Education Programme Adult Treatment Panel III guidelines; NDVI, normalized difference vegetation index; OR, odds ratio; SAVI, soil adjusted vegetation index, VCF, vegetation continuous field.
[a] IQR: $NDVI_{500\text{-m}}$, 0.17; $SAVI_{500\text{-m}}$, 0.11; $VCF_{500\text{-m}}$, 4.52%.
[b] Adjusted for age, gender, ethnicity, household income, education, and district-level of gross domestic product and population density.

3.4. Stratified analyses

In stratified analyses by age, the association between greenness and MetS prevalence was stronger in younger participants (Table 4). For example, the estimated OR per IQR increase in $NDVI_{500\text{-m}}$ was 0.78 (95% CI: 0.68 to 0.90) and 1.09 (95% CI: 0.88 to 1.35) in participants aged < 65 years and those aged ≥65 years, respectively, and the interaction was statistically significant ($P = 0.046$). We also observed a significant interaction between $VCF_{500\text{-m}}$ and household income, in which greater association was shown in participants with higher household income. No significant modification effects were observed for the remaining sub-categories.

3.5. Mediation analyses

In mediation analyses, we observed that PM_{10}, NO_2, and O_3 explained 2.1–20.3% of the association between greenness ($NDVI_{500\text{-m}}$ and $SAVI_{500\text{-m}}$) and MetS (Table 5). However, no mediating effect was observed for physical activity.

4. Discussion

4.1. Key findings

We observed that exposure to higher greenness levels were

Table 4
Associations between per IQR[a] increase in greenness metrics with metabolic syndrome, stratified by potential modifiers (n = 15,477).

Group	$NDVI_{500\text{-m}}$	RERI (95%CI)	$P_{additive}$	$SAVI_{500\text{-m}}$	RERI (95% CI)	$P_{additive}$	$VCF_{500\text{-m}}$	RERI (95% CI)	$P_{additive}$
	Adjusted OR (95% CI)[b]			Adjusted OR (95% CI)[b]			Adjusted OR (95% CI)[b]		
Age		−0.26 (−0.52 to −0.01)	0.046		−0.35 (−0.62 to −0.08)	0.011		−0.24 (−0.51 to 0.02)	0.076
< 65 years	0.78 (0.68 to 0.90)			0.77 (0.67 to 0.90)			0.89 (0.81 to 0.98)		
≥65 years	1.09 (0.88 to 1.35)			1.10 (0.88 to 1.37)			1.09 (0.96 to 1.25)		
Gender		0.07 (−0.07 to 0.20)	0.309		0.05 (−0.09 to 0.19)	0.484		0.06 (−0.09 to 0.21)	0.433
Men	0.71 (0.56 to 0.90)			0.73 (0.58 to 0.91)			0.86 (0.66 to 1.13)		
Women	0.83 (0.72 to 0.97)			0.82 (0.70 to 0.97)			0.91 (0.83 to 1.00)		
Household income		0.10 (−0.05 to 0.26)	0.206		0.08 (−0.08 to 0.23)	0.312		0.21 (0.05 to 0.37)	0.010
< 10,000 Yuan	0.85 (0.72 to 1.01)			0.85 (0.71 to 1.01)			0.93 (0.84 to 1.04)		
≥10,000 Yuan	0.80 (0.69 to 0.92)			0.79 (0.68 to 0.91)			0.90 (0.82 to 0.99)		

Abbreviations: CI, confidence interval; IQR, interquartile range; NDVI, normalized difference vegetation index; OR, odds ratio; RERI, relative excess risk due to interaction; SAVI, soil adjusted vegetation index, VCF, vegetation continuous field.
[a] IQR: $NDVI_{500\text{-m}}$, 0.17; $SAVI_{500\text{-m}}$, 0.11; $VCF_{500\text{-m}}$,4.52%.
[b] Adjusted for age, gender, ethnicity, household income, education, and district-level of gross domestic product and population density, except the variable that were stratified.

Table 5
Mediation of association between greenness and metabolic syndrome by air pollutants and physical activity (n = 15,477).

Exposures	Potential mediators	β (95% CI)[a]	Proportion mediated (95% CI)[a]	*P* value
$NDVI_{500\text{-m}}$				
	PM_1	−0.010 (−0.021 to 0.002)	4.5 (−1.3 to 10.2)	0.131
	$PM_{2.5}$	−0.007 (−0.020 to 0.007)	3.3 (−3.7 to 10.3)	0.355
	PM_{10}	−0.040 (−0.058 to −0.023)	20.3 (9.2 to 31.4)	< 0.0001
	NO_2	−0.023 (−0.032 to −0.013)	11.3 (5.4 to 17.1)	< 0.001
	SO_2	0.024 (−0.001 to 0.049)	−17.5 (−35.6 to 0.7)	0.059
	O_3	−0.004 (−0.006 to −0.001)	2.1 (0.6 to 3.6)	< 0.0001
	Physical activity	0.003 (0.000 to 0.006)	−1.5 (−3.1 to 0.0)	0.056
$SAVI_{500\text{-m}}$				
	PM_1	−0.009 (−0.022 to 0.003)	4.6 (−1.8 to 10.9)	0.157
	$PM_{2.5}$	−0.006 (−0.021 to 0.008)	3.0 (−4.0 to 10.0)	0.404
	PM_{10}	−0.036 (−0.054 to −0.018)	17.4 (7.1 to 27.7)	0.001
	NO_2	−0.020 (−0.031 to −0.010)	9.5 (3.8 to 15.2)	0.001
	SO_2	0.013 (−0.003 to 0.027)	−10.0 (−22.0 to 2.3)	0.112
	O_3	−0.006 (−0.009 to −0.003)	3.5 (1.4 to 5.5)	0.001
	Physical activity	0.003 (0.000 to 0.006)	−1.6 (−3.2 to 0.0)	0.050
$VCF_{500\text{-m}}$				
	PM_1	−0.0002 (−0.0007 to 0.0003)	0.7 (−1.3 to 2.8)	0.496
	$PM_{2.5}$	−0.0001 (−0.0003 to 0.0001)	1.1 (−0.9 to 3.0)	0.299
	PM_{10}	−0.0008 (−0.0017 to 0.0001)	3.2 (−0.5 to 6.9)	0.088
	NO_2	0.0001 (−0.0002 to 0.0004)	−0.5 (−1.7 to 0.6)	0.360
	SO_2	0.002 (0.000 to 0.004)	−8.9 (−18.8 to 0.9)	0.074
	O_3	0.001 (−0.001 to 0.004)	−5.9 (−18.4 to 6.6)	0.356
	Physical activity	0.0001 (−0.0002 to 0.0003)	−0.5 (−2.1 to 1.1)	0.531

Abbreviations: CI, confidence interval; NDVI, normalized difference vegetation index; NO_2, nitrogen dioxide; $PM_{2.5}$, particle with aerodynamic diameter ≤2.5 μm; SAVI, soil adjusted vegetation index; VCF, vegetation continuous field.
[a] Adjusted for age, gender, ethnicity, household income, education, and district-level of gross domestic product and population density.

consistently associated with significantly lower odds of MetS, and that the associations were robust in sensitivity analyses using other definitions of MetS and greenness or selected adjustment set. Stronger associations were observed in participants aged 65 years or younger and those with higher household income. In addition, we observed that air pollutants, but not physical activity, partly mediated the association between greenness and MetS.

4.2. Comparisons with other studies and interpretations

We are aware of only one prior study concerning the effects of greenness on MetS. In that cohort study, de Keijzer et al. (2019) explored longitudinal association between long-term exposure to greenness and incident MetS in 6076 UK adults aged 35–55 years. They observed that both high NDVI and VCF levels were associated with a lower risk of MetS, which was consistent with our current findings. Similarly, two cross-sectional studies focused on alternative indicators of cardiometabolic risk factors, and both observed beneficial associations between the indicators and greenness exposure (Dengel et al., 2009; Paquet et al., 2013). Specifically, a study of 3754 Australian adults reported an association between higher $NDVI_{1000\text{-m}}$ levels and a lower number of cardio-metabolic risk factors (hypertension, high WC, high TG, low HDL-C, and high FBG) (Paquet et al., 2013). The other study of 188 American adolescents observed that more land use dedicated to parks was negatively associated with MetS cluster score (Dengel et al., 2009). There are many studies that focused on greenness and individual MetS components. Specifically, in a recent systematic literature search, we found there have been 13 cross-sectional or cohort studies investigating greenness and blood pressure or hypertension, of which 10 reported that higher greenness levels were associated with lower risk of hypertension or lower blood pressure levels (summarized in Yang et al., 2019b). There have also been 10 studies concerning greenness and diabetes (Maas et al., 2009; Bodicoat et al., 2014; Astell-Burt et al., 2014a; Dalton et al., 2016; Ngom et al., 2016; Brown et al., 2016; Clark et al., 2017; Lee et al., 2017; Ihlebaek et al., 2018; Yang et al., 2019b), and eight of them reported that living in greener areas was associated with lower risk of diabetes (Maas et al., 2009; Bodicoat et al., 2014; Astell-Burt et al., 2014a; Dalton et al., 2016; Ngom et al., 2016; Brown et al., 2016; Clark et al., 2017; Yang et al., 2019b). In addition, of five studies focusing on associations between blood lipids and greenness (Markevych et al., 2016; Brown et al., 2016; Kim et al., 2016; Yang et al., 2019c), three reported significant inverse associations (Brown et al., 2016; Kim et al., 2016; Yang et al., 2019c). Collectively, the existing evidence, albeit inconsistent, generally suggests that higher greenness levels were associated with lower odds of MetS and its components.

Our findings were also consistent with several proposed hypotheses for the beneficial effects of greenness. Higher air pollutant levels have been linked to an increased risk of MetS (Yang et al., 2018b), and green spaces (trees in particular) can help to remove air pollutants (Hirabayashi and Nowak, 2016), although the evidence remains mixed (Markevych et al., 2017). Therefore, we hypothesized that greenness can benefit MetS via reducing air pollution levels. However, we found that PM_{10}, NO_2, and O_3 mediated only 2.1–20.3% of the association for NDVI/SAVI and MetS prevalence. When we alternatively measured greenness using VCF, the mediating effects of all air pollutants became non-significant, which might be caused by low VCF levels in our study area. Our current findings indicate that only a small part of the greenness-MetS association might be mediated by air pollution. Physical activity is a protective factor for MetS (Zhang et al., 2017), and living in close proximity to green areas can motivate people to exercise more regularly (McMorris et al., 2015; Astell-Burt et al. 2014b). A study of Chinese adults reported that almost half of the association for NDVI and hypertension was mediated by exercise (Jia et al., 2018). However, in our study, we did not observe mediation by physical activity. A possible explanation may be that participants might have modified their physical activity pattern as a part of a treatment plan, as the participants with MetS exercised more regularly than those without MetS in our study. Previous evidence also indicated that green space can alleviate mental stress, lower noise and air temperature levels, and facilitate social cohesion (Markevych et al., 2017), which are also correlated with the development of MetS (Eckel et al., 2005).

Vegetation is also a known source of volatile organic compounds (VOCs) (Copeland et al., 2012), which have been linked to MetS (Shim et al., 2019). However, these data are unavailable in our study and thus we cannot investigate them.

In subgroup analysis, we observed that age significantly modified the association for greenness and MetS prevalence with stronger effect estimates observed in participants aged < 65 years. No prior study has explored age-specific effects of greenness on MetS. A few studies investigated such effects on other health outcomes, but the evidence was mixed (Jia et al., 2018). For example, in a previous cross-sectional study of a Chinese population, Jia and colleagues reported that the association between greenness and hypertension was greater in middle aged adults than that in older adults, which is consistent with our results. However, an Austrian study did not find age to modify the association between greenness and blood pressure (Dzhambov et al., 2018). Nevertheless, our findings may reflect that younger people may be more likely to visit and use outdoor greenspace to a greater extent than older people, and thus benefit more from greenspace. In addition, age is strongly associated with MetS, which might have masked any moderate beneficial effects of greenness.

We also observed an indication of a stronger association between greenness and MetS among participants with higher household income than those with lower household income. Contrary to our results, de Keijzer et al. (2019) did not detect a significant modification effect of socioeconomic status on greenness and incident MetS. However, our results are not unexpected, as individuals with higher income levels might live in communities with higher quality greenspaces [e.g., in our study mean levels of $VCF_{500\text{-}m}$ in participants with higher household income (7.21%) were higher than those with lower household income (6.88%)] or be more likely to use greenspaces than those with lower income. However, detailed data on the type and use of greenspace were not available, which limited us to further directly assess these. Future studies with more detailed greenspace information are needed to validate our results.

4.3. Strengths and limitations

A major strength of our study is its population-based design, large sample size, and high response rate, which increases the representativeness of study sample and provided sufficient statistical power to detect modest associations with greenness. In addition, we measured individual MetS components according to standardized methods to increase the accuracy and precision of study outcomes. Moreover, we performed a series of sensitivity analyses and demonstrated that our effect estimates were robust.

Our study also faces several limitations. The cross-sectional design limited our ability to infer temporality between the exposure and the outcome. However, the possibility of reverse-causality (i.e., participants with MetS may choose to live in communities with less greenness) is low, especially considering that we have excluded participants who lived at the current area for less than five years. Second, greenness exposure assessment was based on community centroids but not personal address, that is, we only had 33 unique greenness exposure values. This may have misclassified exposure for some participants. However, such misclassification is likely to be random, which usually biases effect estimates towards the null hypothesis (Hutcheon et al., 2010). Thus, the associations for greenness and MetS may have been greater if we collected individual-level greenness exposure data. Misclassification was also possible for air pollution assessment, which might explain why air pollution (community-based) was detected as a mediator, while physical activity (individual-level) was not. Third, the cluster sampling strategy aggregated data into communities, which might have caused the modifiable area unit problem (i.e., the choice of community boundaries affects the results) and have biased our estimates. However, 500-m and 1000-m buffer results were similar in our study, which indicates that impact of the modifiable area unit problem was probably modest. Fourth, NDVI and SAVI are sensitive to season and cannot distinguish the types of greenspace, which prevents us from finding out what aspects of the greenspace are most correlated with MetS. In addition, we did not collect data on actual greenspaces use, such as time and frequent spent in green space, which might have caused exposure misclassification. Also, our greenness exposure assessment was limited to residential locations and was static, while participants might have visited multiple places for their daily activities (e.g., work, leisure). Therefore, as suggested by Helbich (2018), a dynamic exposure assessment considering participants' daily mobility patterns would be more accurate. Moreover, pixels covering blue spaces were not excluded from the satellite images, thus, our exposure estimates can be partially influenced in presence of water. Fifth, physical activity, the potential mediator, was assessed using a dichotomous question, and more detailed information like exercise duration, time, intensity, and location were not available. The binary physical activity data limited our mediation models options and might have misclassified physical activity to a degree sufficient to obfuscate mediation effects. Air pollution assessment precedes greenness calculations, which might have affected the mediation analyses, although greenness levels are usually stable in a certain period. In addition, while we calculated greenness metrics in 500 m and 1000 m buffers, air pollutants were not estimated within the same buffers, which might have also affected our mediation analyses. Further, mediators can work together, whereas we did not test serial mediation via air pollution and physical activity. Finally, confounders were also assessed using a questionnaire, thus recall bias or misclassification with residual confounding was possible. In addition, although we have considered a set of confounders, the potential for unmeasured confounding cannot be avoided.

5. Conclusion

Our study showed that higher residential greenness levels are associated with lower odds of MetS, especially in people aged 65 years or younger or those had higher income. PM_{10}, NO_2, and O_3 only partially mediate the association, indicating that other more important mechanisms may underpin the association between greenness and MetS. However, due to the cross-sectional nature, community-based exposure assessment, and other limitations of our study, future well-designed longitudinal studies with individual-level exposure assessment are needed to validate our results.

CRediT authorship contribution statement

Bo-Yi Yang: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization, Funding acquisition. **Kang-Kang Liu:** Conceptualization, Methodology, Software, Writing - original draft, Writing - review & editing. **Iana Markevych:** Methodology, Software, Writing - original draft, Writing - review & editing. **Luke D. Knibbs:** Validation, Writing - review & editing, Software. **Michael S. Bloom:** Conceptualization, Methodology, Software, Writing - review & editing. **Shaymali C. Dharmage:** Conceptualization, Supervision, Writing - review & editing. **Shao Lin:** Methodology, Validation, Writing - review & editing, Resources. **Lidia Morawska:** Conceptualization, Validation, Investigation, Writing - review & editing. **Joachim Heinrich:** Conceptualization, Validation, Investigation, Writing - review & editing, Supervision. **Bin Jalaludin:** Conceptualization, Validation, Investigation, Writing - review & editing, Supervision. **Meng Gao:** Methodology, Validation, Writing - review & editing, Software. **Yuming Guo:** Conceptualization, Validation, Investigation, Writing - review & editing, Supervision. **Yang Zhou:** Methodology, Software, Validation, Data curation, Writing - review & editing, Visualization. **Wen-Zhong Huang:** Methodology, Software, Validation, Data curation, Writing - review & editing, Visualization. **Hong-Yao Yu:** Methodology, Software, Validation, Data curation, Writing - review &

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Declaration of Competing Interest

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

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Appendix A. Supplementary material

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