Environment International 126 (2019) 727–734

Contents lists available at ScienceDirect

Environment International

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

Community greenness, blood pressure, and hypertension in urban dwellers: The 33 Communities Chinese Health Study

Bo-Yi Yang[a], Iana Markevych[b,c,d], Michael S. Bloom[e], Joachim Heinrich[b,f], Yuming Guo[g], Lidia Morawska[h], Shyamali C. Dharmage[i,j], Luke D. Knibbs[k], Bin Jalaludin[l,m,n,o], Pasi Jalava[p], Xiao-Wen Zeng[a], Li-Wen Hu[a], Kang-Kang Liu[a], Guang-Hui Dong[a,*]

[a] Guangzhou Key Laboratory of Environmental Pollution and Health Risk Assessment, Guangdong Provincial Engineering Technology Research Center of Environmental and Health risk Assessment, Department of Occupational and Environmental Health, School of Public Health, Sun Yat-sen University, Guangzhou 510080, China
[b] Institute and Clinic for Occupational, Social and Environmental Medicine, University Hospital, LMU Munich, Ziemssenstraße 1, 80336 Munich, Germany
[c] Institute of Epidemiology, Helmholtz Zentrum München - German Research Center for Environmental Health, Ingolstädter Landstraße 1, 85764 Neuherberg, Germany
[d] Division of Metabolic and Nutritional Medicine, Dr. von Hauner Children's Hospital, Munich, Ludwig Maximilian University of Munich, Munich, Germany
[e] Departments of Environmental Health Sciences and Epidemiology and Biostatistics, University at Albany, State University of New York, Rensselaer, NY 12144, USA
[f] Comprehensive Pneumology Center Munich, German Center for Lung Research, Ziemssenstraße 1, 80336 Munich, Germany
[g] Department of Epidemiology and Preventive Medicine, School of Public Health and Preventive Medicine, Monash University, Melbourne, VIC 3004, Australia
[h] International Laboratory for Air Quality and Health, Queensland University of Technology (QUT), GPO Box 2434, Brisbane, Queensland 4001, Australia
[i] Allergy and Lung Health Unit, Centre for Epidemiology and Biostatistics, School of Population & Global Health, The University of Melbourne, Melbourne, VIC 3010, Australia
[j] Murdoch Children Research Institute, Melbourne, VIC 3010, Australia
[k] School of Public Health, The University of Queensland, Herston, Queensland 4006, Australia
[l] Centre for Air Quality and Health Research and Evaluation, Glebe, NSW 2037, Australia
[m] Population Health, South Western Sydney Local Health District, Liverpool, NSW 2170, Australia
[n] Ingham Institute for Applied Medical Research, Liverpool, NSW 2170, Australia
[o] School of Public Health and Community Medicine, The University of New South Wales, Kensington, NSW 2052, Australia
[p] Department of Environmental and Biological Sciences, University of Eastern Finland, Kuopio FI 70211, Finland

ARTICLE INFO

Handling Editor: Zorana Andersen

Keywords:
Greenness
Hypertension
Blood pressure
Mediation
Cross-sectional study
Chinese adults

ABSTRACT

Background: Living in greener areas has many health benefits, but evidence concerning the effects on blood pressure remains mixed. We sought to assess associations between community greenness and both blood pressure and hypertension in Chinese urban dwellers, and whether the associations were mediated by air pollution, body mass index, and physical activity.
Methods: We analyzed data from 24,845 adults participating in the 33 Communities Chinese Health Study, which was conducted in Northeastern China during 2009. We measured each participant's blood pressure according to a standardized protocol. We assessed community greenness using two satellite-derived vegetation indexes – the Normalized Difference Vegetation Index (NDVI) and the Soil Adjusted Vegetation Index (SAVI). Particulate matter ≤2.5 μm and nitrogen dioxide were used as proxies of ambient air pollution. We applied generalized linear mixed models to investigate the association between greenness and blood pressure. We also performed mediation analyses.
Results: Living in greener areas was associated with lower blood pressure and hypertension prevalence; an interquartile range increase in both $NDVI_{500\text{-}m}$ and $SAVI_{500\text{-}m}$ were significantly associated with reductions in systolic blood pressure of 0.82 mm Hg (95% CI: −1.13, −0.51) and 0.89 mm Hg (95% CI: −1.21, −0.57), respectively. The same increases in greenness were also significantly associated with a 5% (95% CI: 1%, 8%) and 5% (95% CI: 1%, 9%) lower odds of having hypertension, respectively. These associations remained consistent in sensitivity analyses. The associations were stronger among women than men. Air pollutants and body mass index partly mediated the associations, but there was no evidence of mediation effects for physical activity.
Conclusions: Our findings indicate beneficial associations between community greenness and blood pressure in Chinese adults, especially for women. Air pollution and body mass index only partly mediated the associations.

* Corresponding author at: Guangzhou Key Laboratory of Environmental Pollution and Health Risk Assessment, Guangdong Provincial Engineering Technology Research Center of Environmental and Health Risk Assessment, Department of Preventive Medicine, School of Public Health, Sun Yat-sen University, 74 Zhongshan 2nd Road, Yuexiu District, Guangzhou 510080, China.
E-mail address: donggh5@mail.sysu.edu.cn (G.-H. Dong).

https://doi.org/10.1016/j.envint.2019.02.068
Received 27 November 2018; Received in revised form 10 February 2019; Accepted 25 February 2019
Available online 14 March 2019

1. Introduction

Hypertension has been consistently identified as the leading contributor to cardiovascular disease burden, and its prevalence continues to increase in low- and middle- income countries (Forouzanfar et al., 2016). The prevalence of hypertension reached 27.9% in Chinese adults between 2012 and 2015 according to the most recent national survey data, which represents over 250 million hypertensive individuals (Wang et al., 2018). Effective intervention strategies are therefore needed to stem the rising tide of hypertension in China. The etiology of hypertension is complicated and includes both genetic and environmental factors (Poulter et al., 2015; Staessen et al., 2003). From a public health perspective, identification of environmental factors may be particularly important, as many such factors are modifiable through behavior changes or government level policy changes.

Residing in greener areas has been shown to be beneficially associated with a broad spectrum of health indicators (Twohig-Bennett and Jones, 2018; Nieuwenhuijsen et al., 2017; Dadvand and Nieuwenhuijsen, 2019). The hypothesized mechanisms for the health benefits of living greener areas include reduced harmful environmental exposures (e.g., noise and air pollution), encouraged health-related behaviors (e.g., physical activity), and enhanced psychophysiological recovery (e.g., stress alleviation), and reduced adiposity (Markevych et al., 2017). These proposed mechanisms are similar to those involved in the pathophysiologic pathways of hypertension (Dzhambov and Dimitrova, 2018; Poulter et al., 2015; Staessen et al., 2003; Yang et al., 2018a). Several experimental or observational (mostly cross-sectional) human studies, mainly adopting an experimental or cross-sectional design, have explored the relationship between greenness and blood pressure (Bijnens et al., 2017; Brown et al., 2016; Calogiuri et al., 2016; Dzhambov et al., 2018; Grazuleviciene et al., 2014; Grazuleviciene et al., 2015; Groenewegen et al., 2018; Hartig et al., 2003; Jia et al., 2018; Jendrossek et al., 2017; Lane et al., 2017; Lee et al., 2014; Lee and Lee, 2014; Li et al., 2011; Markevych et al., 2014a; Morita et al., 2011; Ochiai et al., 2015; Park et al., 2010; Parsons et al., 1998; Sung et al., 2012; Tamosiunas et al., 2014; Toda et al., 2013; Tsunetsugu et al., 2013; Tsunetsugu et al., 2007; Ulrich et al., 1991; Vienneau et al., 2017) (those studies are summarized in Table S1). However, the results of those studies were mixed and inconclusive. For example, while some studies reported that exposure to higher greenness levels was associated with lower blood pressure levels or lower odds of hypertension (Dzhambov et al., 2018; Lane et al., 2017; Jia et al., 2018), others reported no association or an association only in sub-populations (e.g., Jendrossek et al., 2017; Tamosiunas et al., 2014; Morita et al., 2011). In addition, most of the previously published studies were conducted in high-income countries; very limited such evidence (Jia et al., 2018; Lane et al., 2017) is available from low-and middle-income countries like China.

China has experienced rapid urbanization during the past four decades (Guan et al., 2018; United Nations, 2015), which poses a critical challenge in providing sufficient green spaces for urban dwellers (Nieuwenhuijsen et al., 2017). Therefore, understanding the associations between greenness and blood pressure in China could provide new and locally-relevant evidence to be used by public health and urban planning authorities. Additionally, due to urbanization, industrialization, and lifestyle changes, the Chinese population experiences severe air pollution (Guan et al., 2016), as well as epidemics of physical inactivity (Kohl III et al., 2012) and obesity (World Bank, 2011). Thus, China is an ideal setting for exploring the effects of greenness on human health and the underlying biological mechanisms. We hypothesized that exposure to greenness would be associated with blood pressure in the Chinese population, and that the associations would be mediated by air pollution, physical activity, and adiposity. We used data from the 33 Communities Chinese Health Study (33CCHS) to test these hypotheses (Yang et al., 2018b, 2018c).

2. Methods

2.1. Study area

Between April 1 and Dec 31, 2009, we conducted the 33CCHS, a large population-based cross-sectional study, in Liaoning province, which is in Northeastern China (Yang et al., 2018b, 2018c). Liaoning province is one of the largest industrial centers in China, with > 20 million permanent residents, over 64% of whom reside in urban areas. Air pollution is a substantial environmental and public issue in Liaoning province, due to abundant industrial and motor vehicle emissions, as well as household solid fuel combustion for heating during the cold winter. The prevalence of hypertension (37.7%) in this area is reported to be the highest in China (Li et al., 2018).

2.2. Study participants

The 33CCHS design, recruitment, and inclusion criteria have been described in detail elsewhere (Yang et al., 2018b, 2018c). Briefly, we used a four-stage stratified clustering sampling scheme to obtain a representative sample of the study population (Fig. 1). First, we selected three cities (Shenyang, Anshan, and Jinzhou) out of 14 provincial cities in Liaoning province. Second, there were a total of eleven city districts in the three cities (five districts in Shenyang, and three each in Anshan and Jinzhou); each district had a single air quality monitoring station. From each district, we randomly selected three communities that were located within a 1-km radius from the air-monitoring station. The size of the study communities ranged from 0.25 to 0.64 km^2, and the distances between the three communities in each district were < 1.5 km. Third, we randomly selected 700–1000 household from each community. Fourth, we randomly selected one adult from each household.

In total, 28,830 potential study participants were invited. Of those, 24,845 (response rate = 86.2%) were included in the current analysis, based on the following six criteria: (1) blood pressure measurements were available; (2) aged 18–74 years; (3) resided at the study address for at least five years; (4) no pre-existing severe illness (e.g. terminal cancer); (5) not pregnant; and (6) completed a valid study

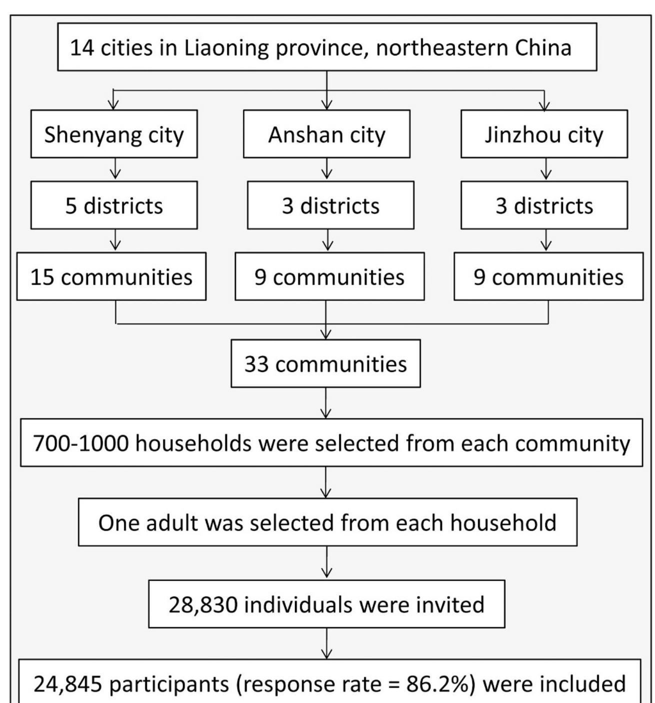

Fig. 1. Sampling strategy for the 33 Communities Chinese Health Study.

questionnaire. The study protocols were approved by the Human Studies Committee of Sun Yat-sen University. All participants gave informed consent prior to data collection.

2.3. Outcome assessment

Systolic blood pressure (SBP) and diastolic blood pressure (DBP) were measured by nurses using the standard mercuric-column sphygmomanometer method. Nurses were trained according to the American Heart Association recommendations to standardize the measurements (Pickering et al., 2005). This protocol was described in detail previously (Yang et al., 2017; Dong et al., 2013). In brief, SBP and DBP were measured with participants in a sitting position, after a minimum of five minute rest, and > 30 min after exercising, tobacco smoking, and consuming tea, coffee, or alcohol. The measurements were repeated three times after an interval of at least 2 min. The average of the three measurements was recorded. Information on anti-hypertensive treatments was collected by questionnaire. Hypertension was defined as mean SBP ≥ 140 mm Hg or DBP ≥ 90 mm Hg, or reported use of anti-hypertensive medicine (Chobanian et al., 2003).

2.4. Exposure assessment

We used the Normalized Difference Vegetation index (NDVI; Tucker, 1979) and the Soil Adjusted Vegetation Index (SAVI; Huete, 1988), which were derived from the Landsat 5 Thematic Mapper satellite images at 30 m × 30 m resolution (http://earthexplorer.usgs.gov), to determine community greenness. The derivation of both NDVI and SAVI indexes are based on land surface reflectance of the visible red and near-infrared parts of the light spectrum. SAVI additionally incorporates a correction factor to minimize soil background. Both NDVI and SAVI values range from −1 to +1, with higher values indicating more greenness. We obtained two cloud-free Landsat 5 Thematic Mapper satellite images during August 2010, the greenest month in Northeastern China and the year closest to our collection of health data from study participants (i.e., between April 1 and Dec 31, 2009). For each study community's centroid, greenness was defined as the average of NDVI or SAVI in 500-m and 1000-m buffers. Considering the small size of the study communities (0.25–0.64 km^2), the short distance between communities in each study district (1.5 km), as well as the radius of buffers used in recent studies (Markevych et al., 2014b; Dadvand et al., 2014), we used NDVI values in the 500-m buffer for the main analysis. However, we also reported other metrics and buffers in sensitivity analyses. These calculations were performed using ArcGIS 10.4 (ESRI, Redlands, CA, USA).

2.5. Potential confounders and mediators

As suggested by Jager et al. (2008), we first considered potential confounders based on the following three criteria: (1) it should be a risk factor for hypertension or elevated blood pressure; (2) it must be antecedent to the greenness exposure (i.e., a "cause" of the greenness exposure) and unequally distributed between exposed and unexposed groups (i.e., groups with different greenness levels); and (3) it must not be an "effect" of greenness exposure, nor be an intermediate factor in the causal pathway of hypertension. Then, we constructed a directed acyclic graph (DAG, Fig. S1) representing the existing literature to select a minimally sufficient set of covariates to adjust for confounding (Greenland et al., 1999), by employing DAGitty v2.3 software (www.dagitty.net). Based on the DAG, the following variables were retained as confounders in our statistical models: age (years), sex (man vs. woman), ethnicity (Han vs. others), household income levels (< 10,000 Yuan vs. > 10,000 Yuan), and district-level gross domestic product (GDP, Chinese Yuan) (Fig. S2). Information on these selected confounders was mainly collected using a questionnaire. GDP in each district was obtained from each city's Statistical Yearbooks.

Also, based on the DAG, air pollution (i.e., $PM_{2.5}$ and NO_2), physical activity, and body mass index (BMI) were selected as candidate mediators. We previously described the $PM_{2.5}$ and NO_2 assessments in detail (Yang et al., 2018b, 2018c). Briefly, we downloaded 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. We then combined DB and DT AOD data using an inverse variance weighting method. Further, we developed a generalized additive model to link AOD data with ground-level $PM_{2.5}$ measurements, meteorological data, land use information, vegetation data, and other spatial predictor (i.e., fire spot, elevation, calendar month). To test the validity of $PM_{2.5}$ predictions, we employed a 10-fold cross-validation procedure, indicating that the adjusted R^2 and root mean squared error were 75% and 15.1 μg/m^3. To incorporate the impact of air pollutants in areas adjacent to each study community, the value of $PM_{2.5}$ at each point was linearly interpolated from the values of the four nearest grid cells. Consequently, different communities that fell into the same grid cell showed different predicted $PM_{2.5}$ values (i.e., contingent on levels from the nearby grid cells). NO_2 concentrations were measured using chemiluminescence and reported hourly by air-monitoring stations (Yang et al., 2017). The continuous NO_2 measures were then averaged into daily concentrations. Using the daily measures, we calculated three-year (2006–08) average $PM_{2.5}$ and NO_2 concentrations for each of the study communities. We collected information on regular physical activity using self-reported questionnaire (yes (exercised ≥180 min per week) vs. no (exercised < 180 min per week)). Body mass index (BMI, kg/m^2) was calculated using measured body weight and height.

2.6. Statistical analysis

Pair-wise correlations between NDVI, SAVI, and air pollutants were tested by the Spearman rank correlation test. Based on recent published studies of greenness and blood pressure (Dzhambov et al., 2018; Lane et al., 2017; Brown et al., 2016), we hypothesized a linear relationship between greenness and blood pressure metrics in the main analysis. Due to the hierarchical structure of our data, we used generalized linear mixed models with a random intercept for community to assess the associations of greenness exposure (per IQR increase in $NDVI_{500m}$ buffer) with SBP and DBP levels (PROC MIXED in SAS) and hypertension prevalence (PROC GLIMMIX in SAS) (Yang et al., 2018b, 2018c). The results generated from PROC MIXED procedure and the PROC GLIMMIX procedure were presented as regression coefficients (β) and odds ratios (ORs), and their corresponding 95% confidence intervals (CIs), respectively. We used two levels of covariate adjustments. Crude models were not adjusted. In the main models, we adjusted for the covariates that were selected using the DAG (i.e., age, sex, ethnicity, income, and district-level GDP).

To test the robustness of our estimates, we performed several sensitivity analyses. First, we repeated the analyses using a 1000-m buffer for NDVI, as well as SAVI in buffers of 500-m and 1000-m. Second, we estimated the greenness-blood pressure association after excluding participants who reported taking anti-hypertensive medicine, participants who had cardiovascular diseases (defined as self-reported heart diseases and stroke), or hypotensive participants (defined as SBP ≤90 mm Hg and DBP ≤60 mm Hg (Lim et al., 2003)). Third, we tested non-linear associations between greenness and blood pressure metrics, by categorizing $NDVI_{500\text{-}m}$ levels into quartiles (Q_1, < 25th percentile; Q_2, between 25th and 50th percentile; Q_3, between 50th and 75th percentile; and Q_4, ≥75th percentile) and examining the effect estimates for each Q_2, Q_3, and Q_4 compared with Q_1, respectively.

Next, we tested whether age, sex, and household income levels were potential modifiers of associations between $NDVI_{500\text{-m}}$ and blood pressure metrics. In these tests, age was categorized as older group (≥65 years) and younger group (< 65 years), and household income levels as high income group (≥10,000 Yuan) and low income group (< 10,000 Yuan). Effect modification was tested in subgroup analyses and considered present if a regression cross-product term (i.e., greenness ∗ age or greenness ∗ sex or greenness ∗ income) was statistically significant.

As prior evidence (Markevych et al., 2017) and our DAG suggested that air pollution, physical activity, and adiposity were potential mediators of the effects of greenness on human health, we used these factors in mediation analyses (Schisterman et al., 2009). We used the PROCESS v. 2.16.3 macro for SAS (pre-specified Model 4 in the SAS procedure) to assess the mediating effects of air pollutants and BMI, by calculating bias-corrected 95% CIs of indirect paths (Hayes, 2013). In this analysis, we applied 5000 bootstraps. The proportion of the mediated effect was calculated as: $(\beta_{\text{indirect effects}} / \beta_{\text{total effects}}) \times 100\%$. The two mediators were tested one-at-a-time. We did not account for the multi-level nature of the data. However, we adjusted for community as fixed effects to partially offset the issue of clustering. As our physical activity variable was dichotomous, it could not be assessed in mediating modelling and therefore, we assessed its mediation effects by comparing the effect estimates before and after additional adjustment for physical activity.

All statistical analyses were performed in SAS 9.4 (SAS Institute, Inc. Cary, NC, USA). A two-tailed p value < 0.05 was considered as statistically significant.

3. Results

3.1. Population characteristics

The average age of the study participants was 45.6 years and with similar proportions of women (49%) and men (51%) (Table 1). Most participants had a household income level of ≥10,000 Yuan per year (76.8%). Thirty percent of the participants were smokers, 23% consumed alcohol, and 31% exercised regularly. Mean SBP and DBP values were 127.28 mm Hg and 81.42 mm Hg, respectively. The prevalence of hypertension was 34.8%, which is similar to the 37.7% reported in a recent national survey (Li et al., 2018). Compared to non-hypertensive participants, hypertensive patients were more likely to be men, older, Han nationality, and to have lower levels of household income (Table S2).

3.2. Greenness exposure

Table S3 describes the distribution of greenness indicators in the 33 study communities. Greenness levels varied markedly among the different communities. For example, the median $NDVI_{500\text{-m}}$ value was 0.29, but with a wide range of 0.18 to 0.80. NDVI and SAVI were strongly and positively inter-correlated (r_s ranged from 0.67 to 0.98); however, their correlations with air pollutants ($PM_{2.5}$ and NO_2) were relatively weak and negative, with r_s ranging from −0.29 to −0.14 (Table S4).

3.3. Greenness and blood pressure and hypertension

Table 2 shows the associations for $NDVI_{500\text{-m}}$ with blood pressure and hypertension prevalence. In the unadjusted model, higher levels of $NDVI_{500\text{-m}}$ were consistently and significantly associated with lower SBP and DBP levels, as well as with lower hypertension prevalence. After adjustment for age, sex, ethnicity, income, and area-level GDP (Table 2, adjusted model), the associations were attenuated but remained statistically significant for SBP and hypertension prevalence. Specifically, an IQR (0.17 unit) increase in $NDVI_{500\text{-m}}$ was significantly associated with lower SBP of 0.82 mm Hg (95% CI: −1.13 to −0.51) and 5% (95% CI: 1–8%) lower odds for having hypertension.

3.4. Sensitivity analyses

The associations were generally consistent in sensitivity analyses using 1000-m NDVI and 500-m and 1000-m SAVI buffers (Tables 2 and S5). In addition, estimates did not differ substantially after excluding participants taking anti-hypertensive medicines, participants who reported cardiovascular diseases, or those who had hypotension (Table S6). Further, when treating $NDVI_{500\text{-m}}$ as quartiles of exposure, we also documented significant trends, in which the effect estimates decreased with increasing $NDVI_{500\text{-m}}$ levels (Fig. 2).

3.5. Effect modification

Table 3 shows associations for greenness exposures, blood pressure measures, and hypertension prevalence according to potential effect modifiers. We detected evidence of modification of effect by sex and age. More specifically, associations of $NDVI_{500\text{-m}}$ with SBP, DBP, and hypertension prevalence were statistically significant in women, but not in men. The effect modification of age was not consistent; while the association between $NDVI_{500\text{-m}}$ and SBP was stronger in older participants than in younger participants, an opposite pattern was observed for $NDVI_{500\text{-m}}$ and DBP (i.e., stronger association in the younger group). There was no evidence of effect modification by household income level.

Table 1
Participant characteristics.

Characteristics	(n = 24,845)
Sociodemographic factors (covariates)	
Age (n, %)	
< 65 years	22,611 (91.0)
≥65 years	2234 (9.0)
Sex (n, %)	
Men	12,661 (51.0)
Women	12,184 (49.0)
Ethnicity (n, %)	
Han	23,470 (94.5)
Others	1375 (5.5)
Household income level per year, Yuan (n, %)	
< 10,000	5761 (23.2)
≥10,000	19,084 (76.8)
District-level per capita GDP, Yuan (median, IQR)[a,b]	70,352 (52,784)
Exposure	
$NDVI_{500\text{-m}}$ (median, IQR)[c]	0.29 (0.17)
$NDVI_{1000\text{-m}}$ (median, IQR)[c]	0.31 (0.15)
$SAVI_{500\text{-m}}$ (median, IQR)[c]	0.16 (0.11)
$SAVI_{1000\text{-m}}$ (median, IQR)[c]	0.17 (0.10)
Candidate mediators	
Regular exercise (n, %)	
No	17,198 (69.2)
Yes	7647 (30.8)
BMI, kg/m^2 (mean ± SD)	24.40 ± 3.70
$PM_{2.5}$, $\mu g/m^3$ (median, IQR)[c]	73 (26)
NO_2, $\mu g/m^3$ (median, IQR)[b]	33 (9)
Outcomes	
SBP, mm Hg (mean ± SD)	127.28 ± 20.81
DBP, mm Hg (mean ± SD)	81.42 ± 11.99
Hypertension (n, %)	8657 (34.8)

Abbreviations: BMI, body mass index; DBP, diastolic blood pressure; GDP, gross domestic product; IQR, interquartile range; SBP, systolic blood pressure; SD, standard deviation.

[a] 1 US Dollar = 6.84 Yuan in 2009.
[b] Based on values from 11 study districts.
[c] Based on values from 33 study communities.

Table 2
Associations between per IQR[a] increase in NDVI and blood pressure metrics (n = 24,845).

Model	β (95% CI)		OR (95% CI)
	SBP	DBP	Hypertension
$NDVI_{500\text{-m}}$			
Crude	−2.20 (−2.53, −1.87)	−0.94 (−1.13, −0.75)	0.84 (0.81, 0.87)
Adjusted[b]	−0.82 (−1.13, −0.51)	−0.12 (−0.31, 0.07)	0.95 (0.92, 0.99)
$NDVI_{1000\text{-m}}$			
Crude	−2.07 (−2.39, −1.75)	−0.94 (−1.12, −0.75)	0.83 (0.80, 0.86)
Adjusted[b]	−0.78 (−1.08, −0.48)	−0.20 (−0.38, −0.02)	0.94 (0.91, 0.98)

Abbreviations: β, unstandardized regression coefficient; CI, confidence interval; DBP, diastolic blood pressure; IQR, interquartile range; NDVI, normalized difference vegetation index; OR, odds ratio; SAVI, soil adjusted vegetation index; SBP, systolic blood pressure.

[a] IQR was 0.17 unit for $NDVI_{500\text{-m}}$ and 0.15 unit for $NDVI_{1000\text{-m}}$.

[b] Adjusted for age, sex, ethnicity, household income level, and district gross domestic product level.

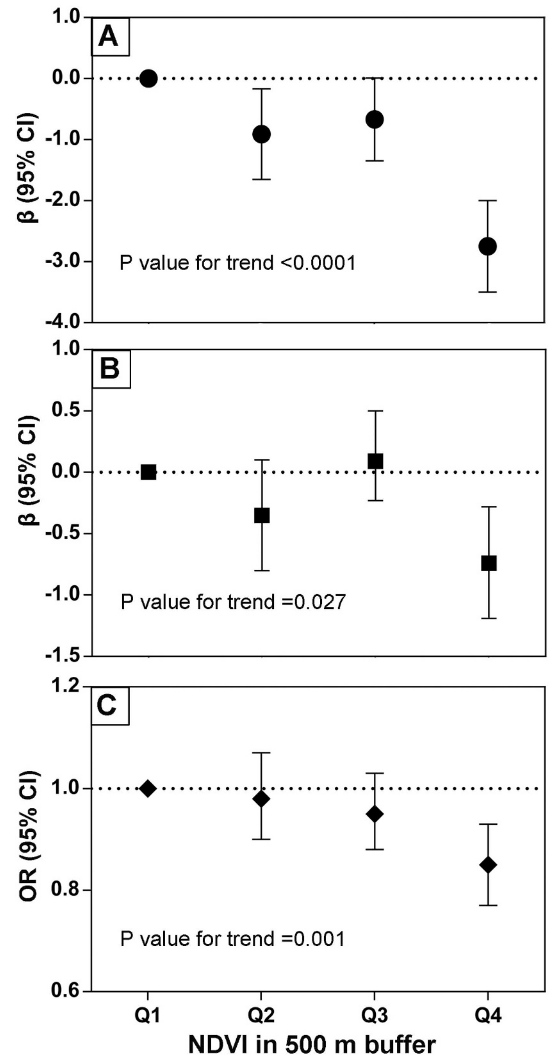

Fig. 2. Associations between $NDVI_{500\text{-m}}$ and blood pressure metrics. A, for systolic blood pressure; B, for diastolic blood pressure; C, for hypertension. The associations were adjusted by age, sex, ethnicity, household income level, and district GDP level. (Q1: quartile 1-reference category; Q2: quartile 2; Q3: quartile 3; Q4: quartile 4 with boxes representing the effect estimate of each quartile and whiskers representing the 95% confidence interval).

3.6. Mediation analyses

Since DBP was not associated with greenness in the main model, we only explored the mediating roles of air pollution, physical activity, and BMI on associations for greenness and SBP (Table 4). We observed that $PM_{2.5}$, NO_2, and BMI significantly mediated 13.9%, 16.0%, and 39.9% of the estimated associations between greenness and SBP, respectively. Additional adjustment by physical activity did not change effect estimates (Table S7).

4. Discussion

4.1. Key findings

The results of our large population-based study suggest that higher community greenness levels were significantly associated with lower SBP levels and decreased hypertension prevalence. These associations were robust to a series of sensitivity analyses. In addition, we observed that sex modified the association between greenness and blood pressure. While BMI mediated 39.9% of the association, air pollutants only mediated up to 16% of the associations and no mediation effect was observed for physical activity. To our knowledge, this is one of the few epidemiological studies to report the association of exposure to community greenness with blood pressure, especially in a developing country.

4.2. Comparison with prior studies and interpretations

In a systematic PubMed literature search, we found 12 previously published cross-sectional or cohort studies concerning associations between greenness exposures and blood pressure or hypertension (Bijnens et al., 2017; Brown et al., 2016; Dzhambov et al., 2018; Grazuleviciene et al., 2014; Groenewegen et al., 2018; Jia et al., 2018; Jendrossek et al., 2017; Lane et al., 2017; Markevych et al., 2014a; Morita et al., 2011; Tamosiunas et al., 2014; Vienneau et al., 2017). Our significant findings for SBP and hypertension concurred with nine (Bijnens et al., 2017; Brown et al., 2016; Dzhambov et al., 2018; Grazuleviciene et al., 2014; Groenewegen et al., 2018; Jia et al., 2018; Lane et al., 2017; Markevych et al., 2014a; Vienneau et al., 2017) of the 12 previously published studies; the remaining three reported no association for greenness exposure and hypertension (Jendrossek et al., 2017; Tamosiunas et al., 2014; Morita et al., 2011). Five previous studies looked at greenness exposures and DBP levels (Dzhambov et al., 2018; Bijnens et al., 2017; Lane et al., 2017; Markevych et al., 2014a; Morita et al., 2011). In line with our current findings, two of them did not detect any association between greenness and DBP (Dzhambov et al., 2018; Morita et al., 2011). However, the remaining three prior studies detected significant and reverse associations (Bijnens et al., 2017; Lane et al., 2017; Markevych et al., 2014a). The reasons for the inconsistent results between our study and the previous studies are unclear, but they may be related to differences in the study populations (e.g., age, sex proportion, lifestyles, and genetic background), exposure assessment strategies (e.g., NDVI, percentage of green space, and greenspaces use), and other co-exposures.

We also identified 13 previously published experimental studies of greenness and blood pressure, that were conducted in laboratory or natural settings (Calogiuri et al., 2016; Grazuleviciene et al., 2015; Hartig et al., 2003; Lee et al., 2014; Lee and Lee, 2014; Li et al., 2011; Ochiai et al., 2015; Park et al., 2010; Parsons et al., 1998; Sung et al., 2012; Toda et al., 2013; Tsunetsugu et al., 2013; Tsunetsugu et al., 2007). These studies typically had small sample sizes (9 to 280 participants) and explored the short-term effects of exercise in forested

Table 3
Associations between per IQR increase in $NDVI_{500\text{-}m}$ (0.17 unit) and blood pressure metrics by age, sex, and household income (n = 24,845).

Group	β (95% CI)[a]		OR (95% CI)[a]
	SBP	DBP	Hypertension
Age			
< 65 years	−0.91 (−1.25, −0.58)[b]	−0.24 (−0.43, −0.04)[b]	0.92 (0.88, 0.96)
≥65 years	−1.66 (−3.13, −0.18)[b]	−0.27 (−1.04, 0.50)[b]	1.02 (0.89, 1.16)
Sex			
Men	−0.03 (−0.49, 0.43)[b]	0.46 (0.17, 0.75)[b]	1.06 (0.99, 1.11)[b]
Women	−1.01 (−1.43, −0.60)[b]	−0.37 (−0.61, −0.13)[b]	0.87 (0.82, 0.92)[b]
Household income			
< 10,000 Yuan	−0.93 (−1.79, −0.06)	−0.31 (−0.82, 0.19)	0.99 (0.93, 1.05)
≥10,000 Yuan	−0.65 (−0.98, −0.33)	−0.01 (−0.21, 0.19)	0.95 (0.91, 0.98)

Abbreviations: β, unstandardized regression coefficient; CI, confidence interval; DBP, diastolic blood pressure; NO_2, nitrogen dioxide; NDVI, normalized difference vegetation index; OR, odds ratio; $PM_{2.5}$, particle with aerodynamic diameter ≤ 2.5 μm; SAVI, soil adjusted vegetation index; SBP, systolic blood pressure.
[a] Adjusted for age, sex, ethnicity, household income level, and district gross domestic product level.
[b] Statistically significant interaction ($p < 0.05$).

environments or of viewing natural environments on blood pressure levels. The majority (n = 11) of these studies detected a beneficial effect of greenness exposures on SBP and/or DBP (Calogiuri et al., 2016; Grazuleviciene et al., 2015; Hartig et al., 2011; Lee and Lee, 2014; Li et al., 2011; Ochiai et al., 2015; Park et al., 2010; Parsons et al., 1998; Toda et al., 2013; Tsunetsugu et al., 2013; Tsunetsugu et al., 2007), and only two of them reported no association (Lee et al., 2014; Sung et al., 2012). Although it is difficult to directly compare our results to the experimental studies due to the different study designs, these prior findings are roughly in line with our current findings and provide important support for our hypothesis.

Collectively, although results from our current study and those previously published are not completely consistent, the overall evidence generally supports an association between higher greenness levels and lower blood pressure levels (specifically SBP) and hypertension prevalence. However, it is notable that most of these studies were either cross-sectional by design or had small sample sizes, and thus a well-designed and large longitudinal investigation is needed to validate our findings.

4.3. Underlying mechanism

Although the mechanisms by which greenness benefits health remain unclear, several biopsychosocial pathways have been proposed (Markevych et al., 2017). First, green spaces can reduce ambient air pollution levels (Hirabayashi and Nowak, 2016), which have been associated with an increased risk for hypertension (Yang et al., 2018a). We tested this mechanism in mediation analyses and found that beneficial effects of greenness on blood pressure were largely independent of air pollution, which is in line with some earlier studies (Dzhambov et al., 2018; Vienneau et al., 2017). Second, living close to green spaces, such as parks, was associated with a higher likelihood of engaging in conducting physical activity (Lachowycz and Jones, 2011), which is a strong protective factor for hypertension (Oparil et al., 2018). In the mediation analyses, we did not detect evidence of mediating effects of physical activity. Our findings were in agreement with Markevych et al.'s (2014a) results that the effect of greenness on children's blood pressure was independent of physical activity. However, Jia et al. (2018) reported that approximately 50% of the association between NDVI and hypertension was mediated by physical exercise. Third, evidence suggests that green environments can reduce adiposity (Sarkar, 2017), which is a well-documented risk factor for hypertension. Our results support this hypothesis in that BMI mediated a large proportion of the association linking greenness to blood pressure. Fourth, evidence has suggested that greenness was also associated with psychological and physiological stress alleviation, increased social cohesion, greater and more diverse microbial exposure, and reduced exposure to noise and heat (Markevych et al., 2017; Rook, 2013). However, the absence of these data in our study prevented us from investigating these mechanisms as potential mediators of the association between greenness and blood pressure. More mechanistic studies are therefore needed to validate the underlying mechanisms.

4.4. Susceptible populations

We found that the greenness-blood pressure associations were stronger in women than in men. The evidence concerning sex modification of greenness-blood pressure association is limited and the results have been mixed. Most prior studies were conducted in women or men only or reported sex-adjusted effects. Of four previous studies that performed sex-stratified analysis (Dzhambov et al., 2018; Jia et al., 2018; Morita et al., 2011; Vienneau et al., 2017), one study reported a stronger association in men than in women (Jia et al., 2018), and the remaining three did not detect modification by sex (Dzhambov et al., 2018; Morita et al., 2011; Vienneau et al., 2017). Nevertheless, our results were not unexpected. One possible explanation may be that Chinese women may have a higher likelihood of using green spaces than Chinese men. Square dancing, for instance, is one of the most popular exercises among Chinese adults, but is practiced mostly by women in surrounding green spaces (Gao et al., 2016). In addition, evidence has shown that women may also spend more time around the

Table 4
Indirect effects linking greenness ($NDVI_{500\text{-}m}$) to systolic blood pressure (n = 24,845).

Indirect path	β (95% CI)[a]	p-Value	Indirect/total effects (%)
$PM_{2.5}$	−0.114 (−0.187, −0.043)	0.0022	13.9
NO_2	−0.131 (−0.191, −0.068)	< 0.0001	16.0
BMI	−0.327 (−0.422, −0.235)	< 0.0001	39.9

Abbreviations: β, unstandardized regression coefficient; BMI, body mass index; NO_2, nitrogen dioxide; NDVI, normalized difference vegetation index; $PM_{2.5}$, particle with aerodynamic diameter ≤ 2.5 μm; SBP, systolic blood pressure.
[a] Adjusted for age, sex, ethnicity, household income level, and district gross domestic product level, and community.

home and in nearby parks in associations with child care obligations and part-time employment (Tamosiunas et al., 2014). Another plausible explanation for the sex-specific association may be a preponderance of hazardous occupational exposures among men, which dominated to such an extent that any beneficial effects of greenness were masked.

We also detected modification of greenness-blood pressure associations by age, but the patterns were different for different blood pressure metrics. While the association between greenness and SBP was stronger in the older group, its association with DBP and hypertension prevalence was only statistically significant in the younger group. In line with our findings, Jia et al. (2018) observed a stronger association between greenness and hypertension in middle aged adults than in older adults. However, the picture is not clear- Dzhambov et al. (2018) did not detect modification by age. Further investigations therefore remain needed to validate our age-specific results.

4.5. Strengths and limitations

Strengths of our study include a large and population-based sample of Chinese urban dwellers and a high response rate (86.2%), which allowed for sufficient statistical power to detect modest effects. Moreover, blood pressures were measured three times using standard methods suggested by the American Heart Association (Pickering et al., 2005) to reduce variability in the study outcomes. In addition, we adjusted for a parsimonious, yet comprehensive panel of covariates to preclude confounding in our results without introducing further bias. Finally, we adopted a conditional procedure to quantify the mediating effects of air pollution and adiposity on greenness-blood pressure associations. This method tends to be more valid and have higher statistical power, and thus provides more precise estimates for the mediation effects compared with traditional Baron and Kenny approach (Baron and Kenny, 1986).

Our study also has several limitations. First, this study adopted a cross-sectional design, which precludes us from inferring any causal relationship. Reverse causality, i.e., the possibility that participants with hypertension may be less likely to live close to areas with higher greenness levels, cannot be excluded but is very unlikely. Second, greenness exposure levels were assigned to community centroids but not to personal addresses, which means that we only had 33 unique data points for the 24,845 study participants. This may have introduced exposure measurement misclassification. However, the exposure misclassification is likely to have been non-differential with respect to blood pressure and thus bias the results towards the null (Hutcheon et al., 2010). Third, due to the clustering sampling scheme used in our study, the data were aggregated into communities (a type of administrative unit). Additionally, as mentioned above, greenness exposure was measured at community-level. Thus, the modifiable areal unit problem, in which the choice of community boundaries impacts the results, is very likely and may have biased our estimates (Openshaw and Taylor, 1979). Fourth, information on physical activity was collected by dichotomous question (exercise regularly: yes or no), whereas detailed information on exercising time, duration, and location (indoor or outdoor) was unavailable, which might have introduced misclassification and prevented us from including this variable into the standard mediation analysis. Fifth, we used the vegetation indexes NDVI and SAVI to estimate greenness levels, which are sensitive to season, and cannot distinguish between structured greenspaces and vegetation outside them. This prevents us from finding out what aspects of greenspace are most relevant for the associations with blood pressure and hypertension. This may also be a reason for physical activity not mediating the greenness-blood pressure associations in our study. Satellite-derived greenness may include green that is weakly correlated with physical activity. For example, high volume roadways lined with trees are captured by satellite-derived greenness, but people do not like to do exercise along them because of traffic noise and air pollution, especially in China. In addition, we did not exclude blue pixels from the NDVI layer, thus, our greenness estimates can be partially affected in presence of water (Markevych et al., 2017). Sixth, although we considered and adjusted for a number of cofounders, the potential for unmeasured confounding is possible. Finally, although we performed repeated blood pressure measurements to ensure reliable study outcomes, they were carried out by nurses at clinics, so the “white coat effect” cannot be ruled out. In addition, we measured blood pressures at a single point in time, which may not represent long-term patterns of blood pressure.

5. Conclusion

In summary, higher community greenness levels were associated with lower SBP levels and decreased hypertension prevalence, especially in women. BMI mediated a large proportion of the association between greenness and blood pressure, whereas air pollution only mediated a small proportion. Our findings might help policy makers initiate, maintain, and increase green public areas, which in turn may help in reducing the hypertension burden. However, the beneficial effects of greenness on blood pressure should be further investigated by well-designed longitudinal studies, especially taking greenness types into account, which will help to refine preventive health and urban design strategies.

Declaration of interests

None.

Acknowledgements

The research was funded by the National Natural Science Foundation of China (No.81703179; No.81872582; No.91543208; No.81673128); the National Key Research and Development Program of China (No.2016YFC0207000); the Fundamental Research Funds for the Central Universities (No.16ykzd02; No.17ykpy16); the Guangdong Provincial Natural Science Foundation (No.2016A030313342; 2017A050501062); and Science and Technology Program of Guangzhou (201807010032; 201803010054). YG was supported by the Career Development Fellowship of Australian National Health and Medical Research Council (No.APP1107107). The authors acknowledge the cooperation of participants in this study who have been very generous with their time and assistance.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2019.02.068.

References

Baron, R.M., Kenny, D.A., 1986. The moderator-mediator variable distinction in social psychological research: conceptual, strategic, and statistical considerations. J. Pers. Soc. Psychol. 51, 1173–1182.
Bijnens, E.M., Nawrot, T.S., Loos, R.J., Gielen, M., Vlietinck, R., Derom, C., et al., 2017. Blood pressure in young adulthood and residential greenness in the early-life environment of twins. Environ. Health 16, 53.
Brown, S.C., Lombard, J., Wang, K., Byrne, M.M., Toro, M., Plater-Zyberk, E., et al., 2016. Neighborhood greenness and chronic health conditions in Medicare beneficiaries. Am. J. Prev. Med. 51, 78–89.
Calogiuri, G., Evensen, K., Weydahl, A., Andersson, K., Patil, G., Ihlebæk, C., et al., 2016. Green exercise as a workplace intervention to reduce job stress. Results from a pilot study. Work 53, 99–111.
Chobanian, A.V., Bakris, G.L., Black, H.R., Cushman, W.C., Green, L.A., Izzo, J.L.J., et al., 2003. National Heart, Lung, and Blood Institute; National High Blood Pressure Education Program Coordinating Committee. Seventh report of the Joint National Committee on Prevention, Detection, Evaluation, and Treatment of High Blood Pressure. Hypertension. 42, 1206–1252.
Dadvand, P., Nieuwenhuijsen, M., 2019. Green space and health. In: Nieuwenhuijsen, M., Khries, H. (Eds.), Integrating Human Health into Urban and Transport Planning. Springer, Cham, pp. 409–423.
Dadvand, P., Villanueva, C.M., Font-Ribera, L., Martinez, D., Basagaña, X., Belmonte, J., et al., 2014. Risks and benefits of green spaces for children: a cross-sectional study of associations with sedentary behavior, obesity, asthma, and allergy. Environ. Health

Perspect. 122 (12) (1329-133).
Dong, G.H., Qian, Z.M., Xaverius, P.K., Trevathan, E., Maalouf, S., Parker, J., et al., 2013. Association between long-term air pollution and increased blood pressure and hypertension in China. Hypertension 61, 578–584.
Dzhambov, A.M., Dimitrova, D.D., 2018. Residential road traffic noise as a risk factor for hypertension in adults: systematic review and meta-analysis of analytic studies published in the period 2011–2017. Environ. Pollut. 240, 306–318.
Dzhambov, A.M., Markevych, I., Lercher, P., 2018. Greenspace seems protective of both high and low blood pressure among residents of an Alpine Valley. Environ. Int. 121, 443–452.
Forouzanfar, M.H., Afshin, A., Alexander, L.T., Anderson, H.R., Bhutta, Z.A., Biryukov, S., et al., 2016. Global, regional, and national comparative risk assessment of 79 behavioural, environmental and occupational, and metabolic risks or clusters of risks, 1990–2015: a systematic analysis for the Global Burden of Diseases Study 2015. Lancet 388 (10053), 1659–1724.
Gao, L., Zhang, L., Qi, H., Petridis, L., 2016. Middle-aged female depression in perimenopausal period and square dance intervention. Psychiatr. Danub. 28 (4) (372-37).
Grazuleviciene, R., Dedele, A., Danileviciute, A., Vencloviene, J., Grazulevicius, T., Andrusaityte, S., et al., 2014. The influence of proximity to city parks on blood pressure in early pregnancy. Int. J. Environ. Res. Public Health 11, 2958–2972.
Grazuleviciene, R., Vencloviene, J., Kubilius, R., Grizas, V., Dedele, A., Grazulevicius, T., et al., 2015. The effect of park and urban environments on coronary artery disease patients: a randomized trial. Biomed. Res. Int. 2015, 403012.
Greenland, S., Pearl, J., Robins, J.M., 1999. Causal diagrams for epidemiologic research. Epidemiology 10, 37–48.
Groenewegen, P.P., Zock, J.P., Spreeuwenberg, P., Helbich, M., Hoek, G., Ruijsbroek, A., et al., 2018. Neighbourhood social and physical environment and general practitioner assessed morbidity. Health Place 49, 68–84.
Guan, W.J., Zheng, X.Y., Chung, K.F., Zhong, N.S., 2016. Impact of air pollution on the burden of chronic respiratory diseases in China: time for urgent action. Lancet 388, 1939–1951.
Guan, X., Wei, H., Lu, S., Dai, Q., Su, H., 2018. Assessment on the urbanization strategy in China: achievements, challenges and reflections. Habit. Int. 71, 97–109.
Hartig, T., Evans, G.W., Jamner, L.D., Davis, D.S., Garling, T., 2003. Tracking restoration in natural and urban field settings. J. Environ. Psychol. 23, 109–123.
Hayes, A., 2013. Introduction to Mediation, Moderation, and Conditional Process Analysis: A Regression-based Approach. Guilford Press, New York.
Hirabayashi, S., Nowak, D.J., 2016. Comprehensive national database of tree effects on air quality and human health in the United States. Environ. Pollut. 215, 48–57.
Huete, A., 1988. A soil-adjusted vegetation index (SAVI). Remote Sens. Environ. 25, 295–309.
Hutcheon, J.A., Chiolero, A., Hanley, J.A., 2010. Random measurement error and regression dilution bias. BMJ 340, c2289.
Jager, K.J., Zoccali, C., MacLeod, A., Dekker, F.W., 2008. Confounding: what it is and how to deal with it. Kidney Int. 73 (3), 256–260.
Jendrossek, M., Standl, M., Koletzko, S., Lehmann, I., Bauer, C.P., Schikowski, T., et al., 2017. Residential air pollution, road traffic, greenness and maternal hypertension: results from GINIplus and LISAplus. Int. J. Occup. Environ. Med. 8 (3), 131–142.
Jia, X., Yu, Y., Xia, W., Masri, S., Sami, M., Hu, Z., et al., 2018. Cardiovascular diseases in middle aged and older adults in China: the joint effects and mediation of different types of physical exercise and neighborhood greenness and walkability. Environ. Res. 167, 175–183.
Kohl III, H.W., Craig, C.L., Lambert, E.V., Inoue, S., Alkandari, J.R., Leetongin, G., et al., 2012. The pandemic of physical inactivity: global action for public health. Lancet 380, 294–305.
Lachowycz, K., Jones, A.P., 2011. Greenspace and obesity: a systematic review of the evidence. Obes. Rev. 12 (5), e183–e189.
Lane, K.J., Stokes, E.C., Seto, K.C., Thanikachalam, S., Thanikachalam, M., Bell, M.L., 2017. Associations between greenness, impervious surface area, and nighttime lights on biomarkers of vascular aging in Chennai, India. Environ. Health Perspect. 125, 087003.
Lee, J.Y., Lee, D.C., 2014. Cardiac and pulmonary benefits of forest walking versus city walking in elderly women: a randomised, controlled, open-label trial. Eur. J. Integr. Med. 6, 5–11.
Lee, J., Tsunetsugu, Y., Takayama, N., Park, B.J., Li, Q., Song, C., et al., 2014. Influence of forest therapy on cardiovascular relaxation in young adults. Evid. Based Complement. Alternat. Med. 2014, 834360.
Li, Q., Otsuka, T., Kobayashi, M., Wakayama, Y., Inagaki, K., Katsumata, M., et al., 2011. Acute effects of walking in forest environments on cardiovascular and metabolic parameters. Eur. J. Appl. Physiol. 111 (11), 2845–2853.
Li, Y., Wang, L., Feng, X., Zhang, M., Huang, Z., Deng, Q., et al., 2018. Geographical variations in hypertension prevalence, awareness, treatment and control in China: findings from a nationwide and provincially representative survey. J. Hypertens. 36 (1), 178–187.
Lim, W.S., van der Eerden, M.M., Laing, R., Boersma, W.G., Karalus, N., Town, G.I., et al., 2003. Defining community acquired pneumonia severity on presentation to hospital: an international derivation and validation study. Thorax 58, 377–382.
Markevych, I., Thiering, E., Fuertes, E., Suqiri, D., Berdel, D., Koletzko, S., et al., 2014a. A cross-sectional analysis of the effects of residential greenness on blood pressure in 10-year old children: results from the GINIplus and LISAplus studies. BMC Public Health 14, 477.
Markevych, I., Tiesler, C.M., Fuertes, E., Romanos, M., Dadvand, P., Nieuwenhuijsen, M.J., et al., 2014b. Access to urban green spaces and behavioural problems in children: results from the GINIplus and LISAplus studies. Environ. Int. 71, 29–35.
Markevych, I., Schoierer, J., Hartig, T., Chudnovsky, A., Hystad, P., Dzhambov, A.M., et al., 2017. Exploring pathways linking greenspace to health: theoretical and methodological guidance. Environ. Res. 158, 301–317.
Morita, E., Naito, M., Hishida, A., Wakai, K., Mori, A., Asai, Y., et al., 2011. No association between the frequency of forest walking and blood pressure levels or the prevalence of hypertension in a cross-sectional study of a Japanese population. Environ. Health Prev. Med. 16, 299–306.
Nieuwenhuijsen, M.J., Khreis, H., Triguero-Mas, M., Gascon, M., Dadvand, P., 2017. Fifty shades of green: pathway to healthy urban living. Epidemiology 28 (1), 63–71.
Ochiai, H., Ikei, H., Song, C., Kobayashi, M., Takamatsu, A., Miura, T., et al., 2015. Physiological and psychological effects of forest therapy on middle-aged males with high-normal blood pressure. Int. J. Environ. Res. Public Health 12, 2532–2542.
Oparil, S., Acelajado, M.C., Bakris, G.L., Berlowitz, D.R., Cifkova, R., Dominiczak, A.F., et al., 2018. Hypertension. Nat. Rev. Dis. Primers. 4, 18014.
Openshaw, S., Taylor, P., 1979. A million or so correlated coefficient: three experiments on the modifiable area unit problem. In: Wrigley, N. (Ed.), Statistical Applications the Spatial Sciences. Pion, London, pp. 127–144.
Park, B.J., Tsunetsugu, Y., Kasetani, T., Kagawa, T., Miyazaki, Y., 2010. The physiological effects of Shinrin-yoku (taking in the forest atmosphere or forest bathing): evidence from field experiments in 24 forests across Japan. Environ. Health Prev. Med. 15 (1), 18–26.
Parsons, R., Tassinary, L.G., Ulrich, R.S., Hebl, M.R., Grossman-Alexander, M., 1998. The view from the road: implications for stress recovery and immunization. J. Environ. Psychol. 18, 113–139.
Pickering, T.G., Hall, J.E., Appel, L.J., Falkner, B.E., Graves, J., Hill, M.N., et al., 2005. Recommendations for blood pressure measurement in humans and experimental animals: part 1: blood pressure measurement in humans: a statement for professionals from the Subcommittee of Professional and Public Education of the American Heart Association Council on High Blood Pressure Research. Circulation. 111 (5), 697–716.
Poulter, N.R., Prabhakaran, D., Caulfield, M., 2015. Hypertension. Lancet 386 (9995), 801–812.
Rook, G.A., 2013. Regulation of the immune system by biodiversity from the natural environment: an ecosystem service essential to health. Proc. Natl. Acad. Sci. U. S. A. 110 (46), 18360–18367.
Sarkar, C., 2017. Residential greenness and adiposity: findings from the UK Biobank. Environ. Int. 106, 1–10.
Schisterman, E.F., Cole, S.R., Platt, R.W., 2009. Overadjustment bias and unnecessary adjustment in epidemiologic studies. Epidemiology 20, 488–495.
Staessen, J.A., Wang, J., Bianchi, G., Birkenhäger, W.H., 2003. Essential hypertension. Lancet 361 (9369), 1629–1641.
Sung, J., Woo, J.M., Kim, W., Lim, S.K., Chung, E.J., 2012. The effect of cognitive behavior therapy-based “forest therapy” program on blood pressure, salivary cortisol level, and quality of life in elderly hypertensive patients. Clin. Exp. Hypertens. 34, 1–7.
Tamosiunas, A., Grazulevicience, R., Luksiene, D., Dedele, A., Reklaitiene, R., Baceviciene, M., et al., 2014. Accessibility and use of urban green spaces, and cardiovascular health: findings from a Kaunas cohort study. Environ. Health 13 (1), 20.
Toda, M., Den, R., Hasegawa-Ohira, M., Morimoto, K., 2013. Effects of woodland walking on salivary stress markers cortisol and chromogranin A. Complement Ther. Med. 21, 29–34.
Tsunetsugu, Y., Park, B.J., Ishii, H., Hirano, H., Kagawa, T., Miyazaki, Y., 2007. Physiological effects of Shinrin-yoku (taking in the atmosphere of the forest) in an old-growth broadleaf forest in Yamagata prefecture, Japan. J. Physiol. Anthropol. 26, 135–142.
Tsunetsugu, Y., Lee, J., Park, B.J., Tyrväinen, L., Kagawa, T., Miyazaki, Y., 2013. Physiological and psychological effects of viewing urban forest landscapes assessed by multiple measurements. Landsc. Urban Plan. 113, 90–93.
Tucker, C.J., 1979. Red and photographic infrared linear combinations for monitoring vegetation. Remote Sens. Environ. 8, 127–150.
Twohig-Bennett, C., Jones, A., 2018. The health benefits of the great outdoors: a systematic review and meta-analysis of greenspace exposure and health outcomes. Environ. Res. 166, 628–637.
Ulrich, R.S., Simons, R.F., Losito, B.D., Fiorito, E., Miles, M.A., Zelson, M., 1991. Stress recovery during exposure to natural and urban environments. J. Environ. Psychol. 11, 201–230.
United Nations, 2015. Department of Economic and Social Affairs, Population Division (UNDESAPD). World Urbanization Prospects: The 2014 Revision, (ST/ESA/SER.A/366). http://esa.un.org/unpd/wup/Publications/Files/WUP2014-Report.pdf, Accessed date: 20 May 2018.
Vienneau, D., de Hoogh, K., Faeh, D., Kaufmann, M., Wunderli, J.M., Röösli, M., et al., 2017. More than clean air and tranquillity: residential green is independently associated with decreasing mortality. Environ. Int. 108, 176–184.
Wang, Z., Chen, Z., Zhang, L., Wang, X., Hao, G., Zhang, Z., et al., 2018. Status of hypertension in China: results from the China Hypertension Survey, 2012–2015. Circulation 137 (22), 2344–2356.
World Bank, 2011. Toward a Health and Harmonious Life in China: Stemming the Risking Tide of Non-communicable Diseases. The World Bank, Washington, DC Available at: http://www.worldbank.org/en/news/feature/2011/07/26/toward-health-harmonious-life-china-stemming-rising-tide-of-non-communicable-diseases.
Yang, B.Y., Qian, Z.M., Vaughn, M.G., Nelson, E.J., Dharmage, S.C., Heinrich, J., et al., 2017. Is prehypertension more strongly associated with long-term ambient air pollution exposure than hypertension? Findings from the 33 Communities Chinese Health Study. Environ. Pollut. 229, 696–704.
Yang, B.Y., Qian, Z., Howard, S.W., Vaughn, M.G., Fan, S.J., Liu, K.K., et al., 2018a. Global association between ambient air pollution and blood pressure: a systematic review and meta-analysis. Environ. Pollut. 235, 576–588.
Yang, B.Y., Bloom, M.S., Markevych, I., Qian, Z.M., Vaughn, M.G., Cummings-Vaughn, L.A., et al., 2018b. Exposure to ambient air pollution and blood lipids in adults: the 33 Communities Chinese Health Study. Environ. Int. 119, 485–492.
Yang, B.Y., Qian, Z.M., Li, S., Chen, G., Bloom, M.S., Elliott, M., et al., 2018c. Ambient air pollution in relation to diabetes and glucose-homoeostasis markers in China: a cross-sectional study with findings from the 33 Communities Chinese Health Study. Lancet Planet. Health 2 (2), e64–e73.