Greenness around schools associated with lower risk of hypertension among children: Findings from the Seven Northeastern Cities Study in China

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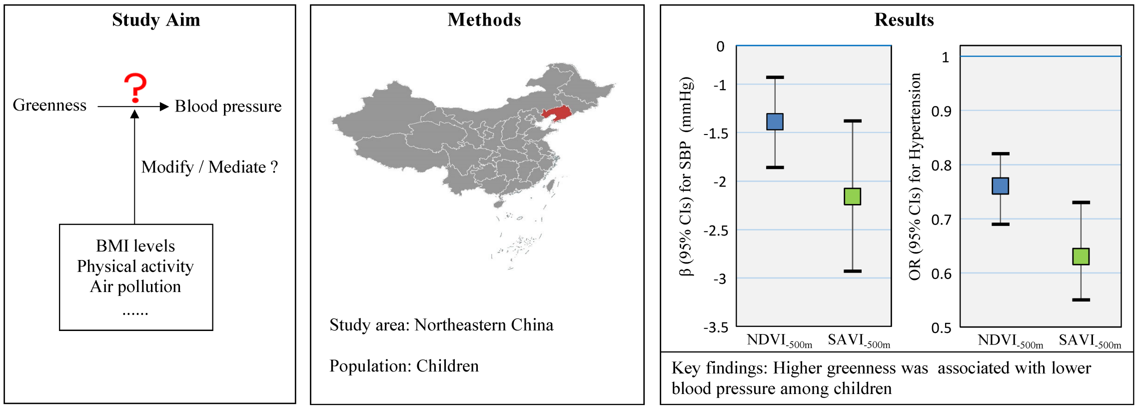
Study Aim
Greenness
?
Blood pressure
Modify / Mediate ?
BMI levels
Physical activity
Air pollution
......
Methods
Study area: Northeastern China
Population: Children
Results
β (95% CIs) for SBP (mmHg)
0
-1
-1.5
-2
-2.5
-3
-3.5
NDVI-500m
SAVI-500m
OR (95% CIs) for Hypertension
1
0.9
0.8
0.7
0.6
0.5
NDVI-500m
SAVI-500m
Key findings: Higher greenness was associated with lower blood pressure among children

Greenness around Schools Associated with Lower Risk of Hypertension among Children: Findings from the Seven Northeastern Cities Study in China

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Abstract

Evidence suggests that residential greenness may be protective of high blood pressure, but there is scarcity of evidence on the associations between greenness around schools and blood pressure among children. We aimed to investigate this association in China. Our study included 9,354 children from 62 schools in the Seven Northeastern Cities Study. Greenness around each child's school was measured by NDVI (Normalized Difference Vegetation Index) and SAVI (Soil-Adjusted Vegetation Index). Particulate matter ≤ 1μm (PM_1) concentrations were estimated by spatiotemporal models and nitrogen dioxide (NO_2) concentrations were collected from air monitoring stations. Associations between greenness and blood pressure were determined by generalized linear and logistic mixed-effect models. Mediation by air pollution was assessed using mediation analysis. Higher greenness was consistently associated with lower blood pressure. An increase of 0.1 in NDVI corresponded to a reduction in SBP of 1.39 mmHg (95% CI: -1.86, -0.93) and lower odds of hypertension (OR= 0.76, 95% CI: 0.69, 0.82). Stronger associations were observed in children with higher BMI. Ambient PM_1 and NO_2 mediated 33.0% and 10.9% of the association between greenness and SBP, respectively. In summary, greater greenness near schools had a beneficial effect on blood pressure, particularly in overweight or obese children in China. The associations might be partially mediated by air pollution. These results might have implications for policy makers to incorporate more green space for both aesthetic and health benefits.

Keywords**:** greenness; blood pressure; hypertension; modification; mediation

Capsule

Greater greenness near schools was associated with lower blood pressure among children, which might have implications for policy makers to incorporate more green space.

Abbreviations

BMI, body mass index; BP, blood pressure; CI, confidence interval; DBP, diastolic blood pressure; NDVI, normalized difference vegetation index; NO_2, nitrogen dioxide; OR, odds ratio, PM_1, particles with diameters ≤ 1.0 μm; SAVI, soil adjusted vegetation index; SBP, systolic blood pressure;

Introduction

The global urban population has increased dramatically, from approximately 751 million in 1950 to 4.2 billion in 2018, and now accounts for 55% of the world's population (United Nations 2018). As one of the global health challenges being confronted in the 21st century (Giles-Corti et al. 2016), rapid urbanization has resulted in alterations to the urban environment (Zhou et al. 2018), including changes in the amount of urban green space. More attention is drawn to green space due to recent findings about its public health impacts (Nieuwenhuijsen and Khreis 2017). A growing number of studies have demonstrated that proximity to green space, measured as "greenness", has many beneficial health effects (Nieuwenhuijsen et al. 2017), such as alleviating psychological stress (Gariepy et al. 2015; Pun et al. 2018; Van Aart et al. 2018), supporting normal body weight (Lachowycz and Jones 2011), reducing blood lipids levels (Yang et al. 2019) and lowering cardiovascular disease risk (Lane et al. 2017; Yitshak-Sade et al. 2017).

To date, few epidemiological studies have investigated the relationship between greenness and blood pressure. Raised blood pressure is the leading risk factor for cardiovascular diseases (Gillespie et al. 2013; WHO 2013), which has caused 9.4 million premature deaths and accounted for 7% of the global disease burden in 2010 (WHO 2014). Although thought to be less common in children, hypertension often originates in childhood (Feber and Ahmed 2010; Gupta-Malhotra et al. 2015) and may track into adolescence and adulthood (Chen and Wang 2008), possibly resulting in early vascular and heart damage (Gupta-Malhotra et al. 2015).

Only one study has investigated the impact of residential greenness on blood pressure in children (Markevych et al. 2014), which observed inverse association between residential greenness and blood pressure. To our knowledge, these findings have not been replicated in other childhood populations. Furthermore, the greenness around a child's school may be particularly important to children, given one of the mechanisms suggested for this link is increased physical activity (Jia et al. 2018), maintaining healthy body weight (Sander et al. 2017), stress relief and other recreational activities (Herrera et al. 2018; Van Aart et al. 2018). The other suggested mechanisms are reducing air pollution levels (Dadvand et al. 2012b; Thiering et al. 2016), which is itself a documented risk factor for hypertension (Yang et al. 2018b). However, the specific pathways linking greenness to blood pressure are not well understood.

Therefore, we aimed to contribute new information to help address this knowledge gap, and hypothesized that (1) higher greenness is associated with lower blood pressure among urban children; and (2) the associations between greenness and children's blood pressure occur via lower air pollution levels.

Methods

Design and study populations

From April 2012 to June 2013, the Seven Northeastern Cities (SNEC) study was conducted in Liaoning Province, China, to explore the health effects of exposure to environmental factors in children. The details of the study have been described previously (Dong et al. 2015; Zeng et al. 2017). Briefly, we randomly selected 24 study districts in seven cities: Shenyang, Dalian, Anshan, Fushun, Benxi, Liaoyang and Dandong. From each of the study districts we randomly selected one or two primary and one or two middle school (62 schools in total). From each grade of the schools we randomly selected one or two classes. All children in the selected classes, and their parents or guardians, were invited to participate in the study, provided that they had lived in the study district for at least two years. Participating children completed a physical examination, and participants' parents or guardians completed a study questionnaire to capture data about demographic information and environment exposure. A total of 10,428 children from the 62 random selected schools were invited and 9,567 participated in the study (response rate: 91.7%). After excluding 213 children who had not resided in their current district for more than two years, the final sample for our analysis comprised 9,354 children from 4.3 to 17.8 years of age (Figure 1). All children and their parents or guardians provided written informed consent. This study was approved by the Human Studies Committee of Sun Yat-sen University.

Blood pressure measurements

Blood pressure was measured according to the American Academy of Pediatrics guidelines (National High Blood Pressure Education Program Working Group on High Blood Pressure in and Adolescents 2004). All research personnel completed a training program to facilitate a standardized approach for blood pressure measurement. Study participants were asked not to drink coffee or tea, and to abstain from physical activity for at least 30 minutes prior to blood pressure measurements. After resting for five minutes in a quiet and temperate room, participants were seated with back support, feet on the floor, right arm supported and an appropriate cuff for children was placed around 2cm above the crease of the right arm elbow.

Trained nurses measured the brachial artery blood pressure at the upper right arm using a standardized mercury-column sphygmomanometer. Systolic blood pressure (SBP) was determined by the onset of the Korotkoff sounds (K1), and the fifth Korotkoff sound (K5) determined diastolic blood pressure (DBP). This was done three times at 2-minute intervals and we used the average of the three measurements in all analyses. Hypertension was defined as systolic (SBP) and/or diastolic blood pressure (DBP) ≥ 95th percentile for sex, age, and height (National High Blood Pressure Education Program Working Group on High Blood Pressure in and Adolescents 2004).

Greenness exposure assessment

Greenness was assessed using two indices of satellite-derived vegetation measures – Normalized Difference Vegetation Index (NDVI) and Soil-Adjusted Vegetation Index (SAVI). NDVI was calculated as the ratio of the difference between the reflectance of near-infrared region light and red region light by chlorophyll in plants, to the sum of these two measures (Tucker 1979). Compared with NDVI, SAVI includes a correction factor to suppress soil pixels (Huete 1988). Both indices range from -1 to +1, with -1 referring to water, values close to zero indicating barren soil and values close to +1 representing a high density of greenness. We used two cloud-free Landsat 5 Thematic Mapper satellite images from August 2010, at a spatial resolution of 30 m x 30 m (http://earthexplorer.usgs.gov), to derive NDVI and SAVI values at the school addresses. We calculated mean values of NDVI and SAVI values for circular buffers of 100m, 500m and 1000m around each school to assess exposure over differing proximities to the school. These calculations were performed using ArcGIS 10.4

(ESRI, Redlands, CA, USA). Similar methods have been used previously (Casey et al. 2016; Lane et al. 2017; Markevych et al. 2014).

Covariates and mediators

We selected the following covariates: age (years), gender (boy, girl), annual family income (RMB yuan), family history of hypertension (yes/no), premature birth (yes/no), environmental tobacco exposure (yes/no), home coal use (yes/no), parental education level (primary school or lower vs. middle school or higher), personal living area (m^2 /person) and the season when BP was measured. Additionally, we used concentrations of air pollutants as possible mediators in our mediation analyses. BMI was calculated as measured body weight divided by height squared (kg/m^2). BMI higher than the 85th percentile based on gender, age, and height was considered to be overweight.

Blood pressure is reported to be associated with both ambient air pollution and urban greenness (Dadvand et al. 2012a; Yang et al. 2018b). We chose particulate matter with an aerodynamic diameter $\leq 1 \mu m$ (PM_1) and nitrogen dioxide (NO_2) as two proxies of air pollution. Four-year (2009-2012) average PM_1 concentrations were predicted by using spatiotemporal models based on PM_1 concentrations from air monitoring stations, satellite-based aerosol optical depth (AOD), meteorology and land use information. In brief, two types of Moderate Resolution Imaging Spectroradiometer (MODIS) Collection six aerosol optical depth (AOD) data—Dark Target (DT) and Deep Blue (DB)—were combined to generate the spatiotemporal models. Four-year average ground-monitored NO_2 concentration was used. (Supplementary File). The details have been described in previous studies (Yang et al. 2018c).

Statistical analysis

As multiple levels (both individual and school) of data existed in our study, we applied generalized linear mixed-effects regression models (lmer and glmer function in R package) to investigate associations between greenness and blood pressure or childhood hypertension (Supplementary File). We used city and school as random effect in the models. Similar statistical models were used in our previous study (Zeng et al. 2017).

We implemented two sets of models for each endpoint: (1) crude mixed effect model, without adjustment for covariates; (2) adjusted mixed effect model, adjusted for age, gender, parental education, income, and season. In line with previous studies, we used the 500m buffer NDVI and SAVI values for the main analyses (Dzhambov et al. 2018a; Markevych et al. 2014; Yang et al. 2018a). Finally, we evaluated effects in the adjusted models for NDVI and SAVI averaged over 100m and 1000m buffers in a sensitivity analysis to assess the stability of our results. We also excluded participants with a family history of hypertension from the adjusted models in sensitivity analysis to assess the impact of a family history of hypertension. In another sensitivity analysis, in order to investigate if there is any study that were so heterogeneous that can bias the overall effect estimates, seven additional sensitivity analyses were also conducted in which we excluded one city at a time in each analysis.

We performed stratified and interaction analyses by using age, sex, BMI, family income and parental education levels as modifiers to investigate the potential difference of effect of residential greenness among different subgroups. For these analyses, age (≤ 11 vs > 11 years) and family income level (≤ 30000 vs > 30000 yuan per year) were split at the median. The interaction effect was estimated by significance of the corresponding interaction item (greenness×modifier) additionally added in the models.

We followed the Baron-Kenny's step for mediation analyses to examine whether air pollutants concentrations could be modes or mechanisms through which greenness affected blood pressure and hypertension (Baron and Kenny 1986). Briefly, we first constructed a full model that includes the exposure, mediator and all covariates. Then we constructed a mediate model that mediator was regressed on the exposure and all covariates. Last, the exposure effect in first model was compared with the counterpart in the second model. These results were generated by bootstrapping (500 simulations) using the function mediate implemented in the R package 'mediation' (Imai et al. 2010).

All statistical analyses were performed using R version 3.5.1. All statistical tests used two-tailed $P < 0.05$ to indicate statistical significance.

Results

Baseline characteristics

Study participants were 10.9 years of age on average (ranging from 4.3 to 17.8 years), just under half (49%) were girls, and 41.5% lived in a family with an annual income greater than 30000 yuan (Table 1). The average systolic and diastolic blood pressures were (111.0±14.1) mmHg and (64.5±9.8) mmHg, respectively, and 13.8% were hypertensive. Compared to normotensive children, participants with hypertension were older ($P<0.05$), had higher BMI ($P<0.05$), were more likely to be exposed to environmental tobacco smoke ($P<0.05$) and to have a family history of hypertension ($P<0.05$). Greenness levels varied markedly across different schools (Supplementary Materials, Figure S1, Table S1). For example, $NDVI_{-500m}$ levels ranged from -0.09 to 0.77, with a median value of 0.31, whereas $SAVI_{-500m}$ levels ranged from 0.00 to 0.47 with a median value of 0.18. The greenspace indices were also strongly positively inter-correlated (r_s: 0.63 to 0.99), while their inverse correlations with air pollutant concentrations were comparatively weaker (r_s: -0.15 to -0.33).

Associations between greenness and blood pressure

Associations of greenness with systolic and diastolic blood pressure and with hypertension, are presented in Table 2. In the adjusted model, a 0.1-unit increase in $NDVI_{-500m}$ exposure was significantly associated with a -1.39 (95% CI: -1.86, -0.93) mmHg reduction in SBP and a 24% (OR= 0.76, 95% CI: 0.69, 0.82) lower odds of hypertension, similarly, a 0.1-unit increase in $SAVI_{-500m}$ exposure was significantly associated with a -2.16 (95% CI: -2.93, -1.38) mmHg reduction in SBP and a 37% (OR= 0.63, 95% CI: 0.55, 0.73) lower odds of hypertension. We did not observe any significant association with DBP in adjusted model.

Sensitivity analyses

The direction and significance of our results were consistent when participants with a family history of hypertension were excluded (Supplementary file, Table S2), when participants exposed to environmental tobacco were excluded (Supplementary file, Table S3), when 100m and 1000m buffers were used to calculate NDVI and SAVI values (Supplementary file, Table S4) and when the participants from each one of the seven cities were excluded (Supplementary file, Table S5 and Table S6).

Effect modification

We also evaluated modification of the greenness-blood pressure associations according to the key factors shown in Table 3. We found statistically significant interactions for BMI, in which stronger associations for both NDVI ($P<0.0001$) and SAVI ($P<0.0001$) with SBP were observed among overweight/obese participants compared to those with normal weight (Table 4). The 3D response surface and the 2D contour plots are graphical representations of the regression equation (Figure 2). Each contour curve represents an infinite number of combinations of greenness and BMI. Greenness showed a negative association with SBP when the BMI level was fixed. There was a linear increase in SBP with an increase in BMI, but a decrease in greenness level. We also detected statistically significant interactions of NDVI ($P<0.0001$) and SAVI ($P<0.0001$) with sex, in which higher levels of greenness was associated with higher DBP in boys, but with lower DBP in girls. No interaction with SES factors (family income and parental education levels) was observed.

Mediation analyses

We found that 33.0% and 10.9% of the effects of greenness on SBP was mediated by lower ambient levels of PM_1 and NO_2, respectively ($P <0.0001$). It is important to note that road traffic is a source of both of these pollutants (PM_1 and NO_2), therefore there is usually an association between their concentrations in close proximity to a roadway. However, we did not detect significant mediation effects for exercise time (data not shown). The mediation analysis results were similar for the associations between greenness and hypertension (Table 5). We used BMI as potential moderators in the mediation models (Supplementary file, Table

S7). The mediation effect of air pollutants varied remarkably by BMI quantiles.

Discussion

Key findings

Higher exposure to greenness surrounding school, as measured by NDVI and SAVI, was significantly associated with lower SBP and lower odds of hypertension in children living in Northeast China. The relationship was stronger among overweight/obese children. Furthermore, ambient PM_1 and NO_2 concentrations might be mediating variables in the associations between greenness and SBP and greenness and hypertension.

Comparison with other studies and interpretations

To our knowledge, only one previous study has investigated the associations between greenness and blood pressure in children. In that study, Markevych et al. (2014) found beneficial associations between lower greenness levels (calculated as NDVI) and higher SBP and DBP in 10-year-old German children, which are in line with our results. However, a number of studies have reported associations on greenness and blood pressure in adults. Dzhambov et al. (2018a) conducted a study in residents of an Alpine valley in Austria and observed that an interquartile range (IQR = 0.16) increase in greenness was associated with lower odds (OR=0.64 95% CI: 0.52, 0.78) of hypertension and a 2.84 mmHg decrease in SBP. A twin cohort study carried out in Belgium reported that an interquartile increase (IQR = 46% change) in residential greenness in early life resulted in a decrease of 3.59 mmHg and 4.0 mmHg in night-time SBP and DBP respectively (Bijnens et al. 2017). Jendrossek et al. (2017), however, detected no effect of greenness on maternal hypertension assessed by questionnaire.

A recent meta-analysis pooling most previously published studies indicated that the current evidence generally supports a relationship between higher greenness levels and lower blood pressure levels (Twohig-Bennett and Jones 2018). Collectively, our results, combined with previous studies, support an inverse relationship between greenness and SBP levels and importantly, the overall observed associations in adults can also be detected at much younger ages. However, given the cross-sectional nature of the studies addressing the influence of greenness on children's blood pressure, future longitudinal studies in children are needed to confirm our findings.

Effects modification and mediation

In stratified analyses, we found a statistically significant interaction between greenness and sex. To the best of our knowledge, this study is the first reporting on the interaction between greenness and sex, so it is difficult for us to compare the results and discuss the possible explanations. And the interaction showed only on DBP, so this result should be interpreted cautiously. It is likely that psychological and endocrine factors may contribute to the differences of the effect. We also found a stronger association between $NDVI_{-500m}$ and SBP among children with higher BMI. As far as we are aware, only one previous study showed a similar result (Dzhambov et al. 2018a). In our data, under or normal weight children and overweight or obese children exercised for 7.5 hours/week and 7.8 hours/week on average (data not shown), respectively (P=0.17). Thus, children with higher BMI levels might benefit more from increasing greenness than those with lower BMI given the same physical activity level. Unfortunately, we did not collect information about individual greenspace use and so future studies that include such data may provide more definitive answers. Notably, our results indicated that family income and parental education level did not modify the relationship between greenness and blood pressure, while previous studies have shown that the relationship between greenness with health outcomes was stronger in lower income groups (Browning and Rigolon 2018; Dzhambov et al. 2018a). The inconsistency could be attributed in part to differences in the study populations – children in our study and adults in the previously reported studies, different greenness exposure – school-based versus residential, and differences in ethnic groups. Also, our study population resided in a region dominated by heavy industry, and so the industrial influence and economic development status may be quite different to those studies conducted in developed countries (Dzhambov et al. 2018a; Jendrossek et al. 2017). For example, participants with lower income were surrounded by higher greenness (average $NDVI_{500m}$ is 0.34 in the lower income versus 0.32 in the higher income group, $P < 0.05$), contrary to other studies in which lower income residents were surrounded by lower greenness (Astell-Burt et al. 2014; Bell et al. 2008).

We found that higher levels of greenness were significantly associated with lower air pollution, and mediation analyses showed that both airborne particles and gaseous pollutants might partially explain the associations between greenness and blood pressure. Previous studies have suggested that the concentration levels of urban ambient air pollutants can be reduced by vegetation (Hirabayashi and Nowak 2016; Nowak et al. 2013; Uni and Katra 2017). Green areas, which are barriers between the pollution source and receptors, can remove some particles and gaseous pollutants, although the efficacy is likely to be limited

(Gómez-Moreno et al. 2019; Markevych et al. 2017; Xing and Brimblecombe 2019). Regardless of the ability of greenness to act as a filter of air pollution, its presence may reflect a relative absence of pollutant sources and also can increase the distance between the source and the receptor (Richmond-Bryant et al. 2018), enabling greater dilution. In addition, some studies have also speculated that people were more likely to engage in physical activities when exposed to higher green space (Markevych et al. 2017), which in turn may be protective against hypertension (Huai et al. 2013; Lagisetty et al. 2016). Jia et al. (2018) found that physical activity accounted for a 55% reduced risk of hypertension in adults when exposed to higher greenness. However, based on our data, we did not find that the greenness association with blood pressure was mediated through physical activity levels (data not shown). One possible explanation for the discrepancy could be that children's exercise time in schools is usually scheduled and consequently would be independent of greenness levels around schools. Nevertheless, our results were consistent with previous study (Markevych et al. 2014) which also reported that the effect on children's blood pressure was independent of physical activity. It should be noticed that even though greenness around school may not affect the time of children's exercise but rather, greenness may affect the environmental quality of the place where they exercise or engage in other recreational activities, through lowering stress and increasing social engagement (Herrera et al. 2018; Markevych et al. 2017). More interestingly, BMI tended to moderate or modify the greenness-air pollution-blood pressure process instead of mediating the association directly. Among participants with higher BMI, less effect of greenness could be explained by air pollution.

Implications for policy makers

As children usually spend lots of time in school and most of their outdoor activities (taking exercise, reading a book outside, or doing other recreational activity) may happen in school, school-based greenness is important to children. This study suggests a beneficial effect for greenness surrounding schools on children's blood pressure. This finding may have important implications for policy makers to plan more greenspace around schools for not only the aesthetic benefits but also the health effect that may influence all children in the school.

Strengths and limitations

Our study is the largest to date to evaluate the association between greenness and childhood blood pressure and hypertension. It was based on a large sample size and we achieved a high participation rate (91.7%), minimizing the likelihood for selection bias and strengthening the external validity of our results. We leveraged two widely recognized, valid and reliable indices to assign greenness exposure, the NDVI and SAVI, and we captured a comprehensive profile of covariates to adjust for confounders. Several sensitivity analyses were also conducted to validate the robustness of the associations. We also examined interactions according to the most likely effect modifiers and conducted mediation analyses to determine the contribution of ambient PM_1 and NO_2, as well as physical activity and BMI to the greenness-BP associations. In addition, our study is the first to date to evaluate the health effect of school-based greenness on children given that children usually spend much time participating in a wide range of outdoor activities in school.

Our study also had some limitations and therefore the results should be interpreted cautiously.

First, we may not capture greenness exposure from other non-school places (such as home). However, due to a Chinese policy restricting children from attending trans-regional schools, our data showed that the average walk time from their homes to schools was about 12 minutes, and thus the school-based greenness exposures are very likely to represent residential greenness exposure to a large extent. The latter was also confirmed when we generated similar results using a larger buffer (1000m exposure buffer instead of the 500m exposure buffer) and found that the results were consistent. The major limitation of exposure assessment in our study was that we could not differentiate greenness within the premises of the schools form the buffered greenness so that we could not determine how much of the exposure was contributed by the greenness within schools as this could vary depending the area of each school. Some studies showed slight differences between the effect of greenness within and around school boundaries, which should be considered in further study. Second, although we adjusted for the most likely confounders in our analysis, we cannot rule out the possibility of unmeasured confounding due to other factors that co-vary with greenness and have been shown to impact blood pressure, including noise (Dzhambov et al. 2018b), walkability (James et al. 2017) and psychological status (Herrera et al. 2018; Van Aart et al. 2018). We were also unable to adjust our analyses for neighborhood socioeconomic status because we did not have such data, either. Third, although we tried to explore the mediation effect of air pollution by using model predicted PM_1 and NO_2 from air monitoring stations, the deviation of air pollution assessment brought by inherent limitation of model prediction was inevitable, thus the results of mediation analysis should be interpreted with caution. Forth, the cross-sectional design of our study prevented us from inferring temporality, in that we cannot be sure if greenness exposure preceded blood pressure values in time. Still, we believe it unlikely for children's blood pressure to have impacted the distribution of greenness around their homes and schools. However, for mediation analyses, we cannot rule out the possibility that greener schools were located in regions where air pollution levels were lower, thus temporality of the mediation process cannot be inferred, either.

Conclusion

Higher levels of greenness near schools was associated with lower systolic blood pressure and lower odds ratio of hypertension in school children from Northeastern China, especially in children with higher BMI. Air pollutants might partly mediate the associations. Further well-designed longitudinal studies with more specific assessment of individual greenness exposure are needed to confirm our results. If confirmed in future studies, this effect could have implications for policy makers and public health authorities to build more greenery, not only for its aesthetic benefits but also for better health.

Declaration of interests

None.

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Figure legends

Figure 1. Children recruitment flow chart of the Seven Northeastern Cities Study

Figure 2. The 3D response surface and 2D contour plots showing interactive effects of BMI and greenness (500m buffer) on blood pressure

Footnote: Panel A for SBP-NDVI-BMI, Panel B for DBP-NDVI-BMI, Panel C for SBP-SAVI-BMI, Panel D for DBP-SAVI-BMI.

Table 1 Characteristics of participants from the Seven Northeastern Chinese Cities Study

Characteristic	Mean ± SD, *n* (%)		
	Total (*n* = 9354)	**Non-hypertension (*n* = 8065)**	**Hypertension (*n* = 1289)**
Age (years) [a]	10.9 ± 2.6	10.8 ± 2.6	11.9 ± 2.5
Sex			
Boys	4771 (51.0%)	4112 (51.0%)	659 (51.1%)
Girls	4583 (49.0%)	3953 (49.0%)	630 (48.9%)
BMI (kg/m^2) [a]	19.6 ± 4.3	19.2 ± 4.1	21.7 ± 5.2
Family income per year			
≤ 5000 yuan	1032 (11.0%)	891 (11.0%)	141 (10.9%)
5000-10000 yuan	1211 (12.9%)	1023 (12.7%)	188 (14.6%)
10000-30000 yuan	3230 (34.5%)	2778 (34.4%)	452 (35.1%)
30000-100000 yuan	3441 (36.8%)	2994 (37.1%)	447 (34.7%)
> 100000 yuan	440 (4.7%)	379 (4.7%)	61 (4.7%)
Parental education level [a]			
Primary school or lower	3595 (38.4%)	3066 (37.9%)	529 (41.0%)
Middle school or higher	5759 (61.6%)	4999 (62.1%)	760 (59.0%)
Family history of hypertension [a]			
No	5755 (61.5%)	5024 (62.3%)	731 (56.7%)
Yes	3599 (38.5%)	3041 (37.7%)	558 (43.3%)
Environment tobacco exposure [a]			
No	4868 (52.0%)	4264 (52.9%)	604 (46.9%)
Yes	4486 (48.0%)	3801 (47.1%)	685 (53.1%)
Home coal use [a]			
No	8466 (90.5%)	7328 (90.9%)	1137 (88.2%)
Yes	888 (9.5%)	737 (9.1%)	151 (11.8%)
Season of measurements [a]			
Spring	3622 (38.7%)	3048 (37.8%)	574 (44.5%)
Summer	1055 (11.3%)	858 (10.6%)	197 (15.3%)
Fall	1135 (12.1%)	866 (10.7%)	269 (20.9%)
Winter	3542 (37.9%)	3293 (40.8%)	249 (19.3%)
Average exercise per week (hours)	7.6 ± 7.8	7.6 ± 7.0	7.7 ± 8.6
Person living area (m^2)	22.7 ± 10.2	22.7 ± 9.8	22.3 ± 12.5
Temperature (°C) [a]	14.7 ± 6.0	15.0 ± 5.8	12.8 ± 6.5
Systolic blood pressure (mmHg) [a]	111.0 ± 14.1	108.1 ± 12.1	129.1 ± 11.5
Diastolic blood pressure (mmHg) [a]	64.5 ± 9.8	62.7 ± 8.3	75.6 ± 11.2

Abbreviations: BMI, body mass index

[a] $P < 0.05$ for difference between hypertension and non-hypertension groups.

Table 2 Associations of greenness indices[a] (per 0.1-unit increase) with blood pressure and hypertension (n = 9354)

	β / OR (95% CI) for NDVI			β / OR (95% CI) for SAVI		
Greenness	**SBP (β)**	**DBP (β)**	**Hypertension (OR)**	**SBP (β)**	**DBP (β)**	**Hypertension (OR)**
Buffer 500m						
Crude	-2.68 (-3.82, -1.53)	-0.84 (-1.28, -0.41)	0.70 (0.63, 0.77)	-4.12 (-5.98, -2.26)	-1.34 (-2.05, -0.62)	0.56 (0.47, 0.66)
Adjusted [b]	-1.39 (-1.86, -0.93)	-0.41 (-0.87, 0.05)	0.76 (0.69, 0.82)	-2.16 (-2.93, -1.38)	-0.64 (-1.39, 0.11)	0.63 (0.55, 0.73)

Abbreviations: BMI, body mass index. CI, confidence interval. DBP, diastolic blood pressure. NDVI, normalized difference vegetation index. OR, odds ratio, SAVI, soil adjusted vegetation index. SBP, systolic blood pressure.

[a] Greenness defined using a 500m buffer around each of the participating schools.

[b] Adjusted for age, sex, parental education, income and season.

Table 3 Associations of greenness indices (per 0.1-unit increase) and blood pressure, stratified by demographic factors (n = 9354) [a]

		β (95% CI) for $NDVI_{\text{-500m}}$				β (95% CI) for $SAVI_{\text{-500m}}$			
Subgroup	***n***	**SBP**	$P_{interaction}$	**DBP**	$P_{interaction}$	**SBP**	$P_{interaction}$	**DBP**	$P_{interaction}$
Sex									
Boys	4771	-1.20 (-1.81, -0.59)	0.846	-0.04 (-0.59, 0.50)	<0.0001	-1.89 (-2.88, -0.90)	0.692	-0.10 (-0.98, 0.79)	<0.0001
Girls	4583	-1.52 (-2.01, -1.04)		-0.78 (-1.23, -0.34)		-2.31 (-3.12, -1.49)		-1.19 (-1.91, -0.46)	
Age									
≤ 11 years	4545	-1.25 (-2.08, -0.43)	0.060	-0.63 (-1.29, 0.03)	0.229	-1.92 (-3.18, -0.65)	0.104	-0.94 (-1.95, 0.07)	0.202
> 11 years	4809	-2.12 (-2.85, -1.38)		-0.73 (-1.17, -0.29)		-3.23 (-4.49, -1.97)		-1.23 (-1.96, -0.50)	
BMI									
Normal	6323	-1.18 (-1.65, -0.72)	<0.0001	-0.50 (-0.95, -0.05)	<0.0001	-1.83 (-2.60, -1.06)	<0.0001	-0.79 (-1.51, -0.06)	<0.0001
Overweight/obese	3031	-1.45 (-2.15, -0.75)		-0.16 (-0.78, 0.46)		-2.27 (-3.40, -1.14)		-0.28 (-1.27, 0.72)	
Family Income									
≤ 30000 yuan	5473	-1.38 (-1.95, -0.81)	0.850	-0.40 (-0.91, 0.12)	0.951	-2.14 (-3.08, -1.19)	0.995	-0.61 (-1.44, 0.22)	0.982
> 30000 yuan	3881	-1.34 (-1.94, -0.74)		-0.42 (-0.89, 0.06)		-2.00 (-2.97, -1.04)		-0.66 (-1.41, 0.09)	
Parental education									
≤ Primary school	3595	-1.66 (-2.31, -1.02)	0.285	-0.63 (-1.16, -0.09)	0.065	-2.57 (-3.65, -1.49)	0.326	-0.99 (-1.86, -0.12)	0.082
> Middle school	5759	-1.19 (-1.67, -0.70)		-0.32 (-0.78, 0.15)		-1.84 (-2.61, -1.07)		-0.52 (-1.26, 0.22)	

Abbreviations: BMI, body mass index. CI, confidence interval. DBP, diastolic blood pressure. NDVI, normalized difference vegetation index. SAVI, soil adjusted vegetation index. SBP, systolic blood pressure.

[a] Adjusted for age, sex, parental education, income and season. (unless stratified by the respective factor).

Note: The P-values for interaction were calculated by adding a corresponding interaction item (greenness×modifier) in the model

Table 4 Associations between greenness indices (per 0.1-unit increase) and hypertension, stratified by demographic factors (n = 9354) [a]

		OR (95% CI) for NDVI$_{-500m}$		OR (95% CI) for SAVI$_{-500m}$	
Subgroup	***n***	**Hypertension**	$P_{interaction}$	**Hypertension**	$P_{interaction}$
Sex					
Boys	4771	0.81 (0.74, 0.89)	0.279	0.71 (0.61, 0.83)	0.259
Girls	4583	0.72 (0.65, 0.80)		0.59 (0.49, 0.70)	
Age					
≤ 11 years	4545	0.82 (0.72, 0.92)	0.200	0.73 (0.61, 0.87)	0.008
> 11 years	4809	0.73 (0.66, 0.80)		0.59 (0.49, 0.70)	
BMI					
Normal	6323	0.78 (0.69, 0.87)	< 0.0001	0.67 (0.55, 0.81)	< 0.0001
Overweight/obese	3031	0.74 (0.64, 0.85)		0.61 (0.48, 0.76)	
Family Income					
≤ 30000 yuan	5473	0.77 (0.70, 0.85)	0.912	0.65 (0.55, 0.77)	0.948
> 30000 yuan	3881	0.74 (0.67, 0.82)		0.62 (0.53, 0.73)	
Parental education					
≤ Primary school	3595	0.73 (0.64, 0.83)	0.197	0.59 (0.47, 0.74)	0.237
> Middle school	5759	0.78 (0.71, 0.86)		0.67 (0.57, 0.78)	

Abbreviations: BMI, body mass index. CI, confidence interval. DBP, diastolic blood pressure. NDVI, normalized difference vegetation index. OR, odds ratio. SAVI, soil adjusted vegetation index. SBP, systolic blood pressure.

[a] Adjusted for age, sex, parental education, income, exercise time and season. (unless stratified by the respective factor).

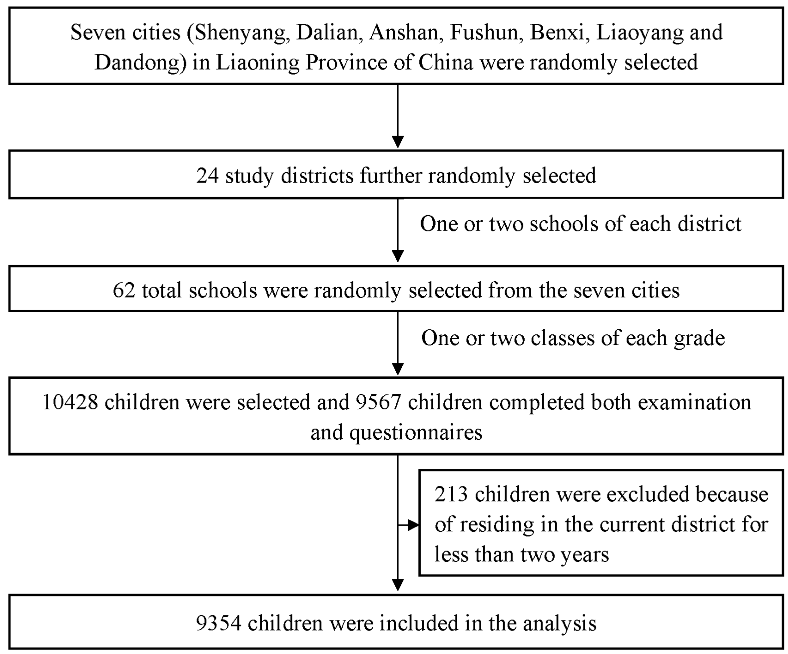
Note: The P-values for interaction were calculated by adding a corresponding interaction item (greenness×modifier) in the model.

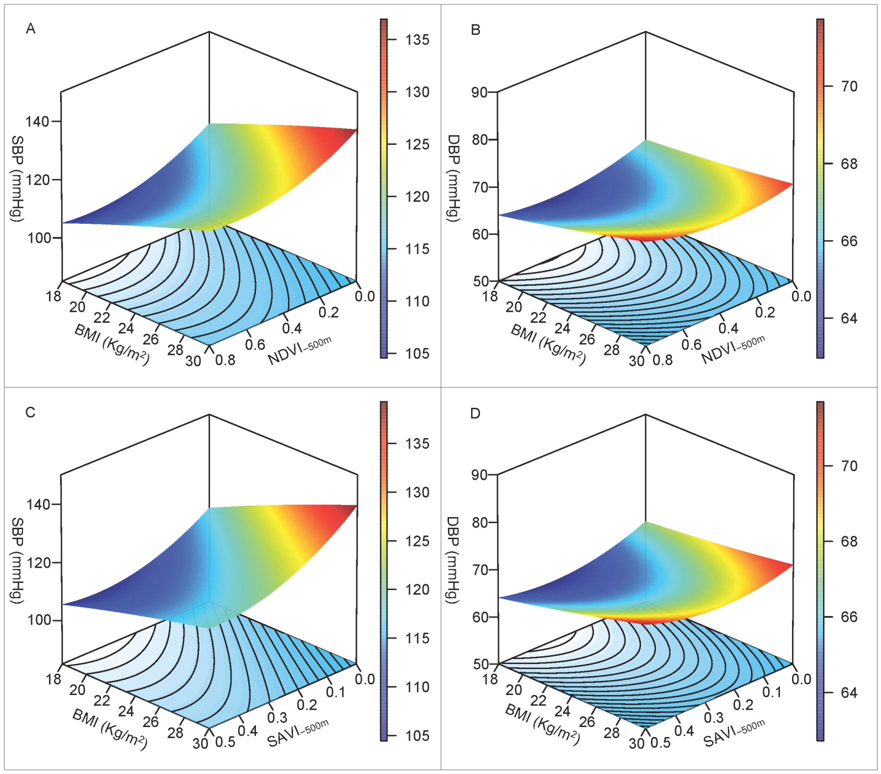
Table 5 Mediation of the association between greenness ($NDVI_{-500m}$) and SBP/hypertension explained by air pollutants, BMI, and exercise time [a]

Outcome	**Mediator**	**Proportion Mediated (95% CI) /%**	***P***
SBP			
	PM_1	33.0 (25.6, 44.0)	< 0.0001
	NO_2	10.9 (5.4, 18.0)	< 0.0001
Hypertension			
	PM_1	11.7 (8.0, 17.0)	< 0.0001
	NO_2	12.2 (5.5, 23.0)	< 0.0001

[a] Adjusted for age, sex, parental education, income, exercise time and season.

Abbreviations: BMI, body mass index. CI, confidence interval. NDVI, normalized difference vegetation index. SBP, systolic blood pressure.


Seven cities (Shenyang, Dalian, Anshan, Fushun, Benxi, Liaoyang and Dandong) in Liaoning Province of China were randomly selected
24 study districts further randomly selected
One or two schools of each district
62 total schools were randomly selected from the seven cities
One or two classes of each grade
10428 children were selected and 9567 children completed both examination and questionnaires
213 children were excluded because of residing in the current district for less than two years
9354 children were included in the analysis


A
SBP (mmHg)
BMI (Kg/m²)
NDVI-500m
B
DBP (mmHg)
BMI (Kg/m²)
NDVI-500m
C
SBP (mmHg)
BMI (Kg/m²)
SAVI-500m
D
DBP (mmHg)
BMI (Kg/m²)
SAVI-500m

Highlights

- Evidence on the association between greenness and blood pressure among children is scarce.
- We are the first to explore this topic based on school surrounding greenness exposure.
- Attending schools with higher greenness showed beneficial effects on blood pressure.
- The beneficial effects were stronger in children with higher BMI levels.
- Air pollution might partially mediate the effects of greenness on blood pressure.

Declaration of interests

☑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.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: