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Greenness surrounding schools is associated with lower risk of asthma in schoolchildren

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A R T I C L E I N F O

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A B S T R A C T

Background: There is increasing interest in the effect of residential greenness on respiratory health in children with inconsistent results. However, there are no studies investigating the association between greenness around schools, a representative environment for children and childhood asthma.
Objectives: To investigate the association between greenness surrounding schools and asthma in schoolchildren.
Methods: We recruited 59,754 schoolchildren from 94 schools in 2012–2013 from the Seven Northeast Cities Study, China. Greenness surrounding schools was measured using the normalized difference vegetation index (NDVI) and soil adjusted vegetation index (SAVI) at buffers from 30 to 1000 m. Asthma symptoms were collected from validated self-reported questionnaires. Logistic mixed-effects regression models were used to estimate the associations between greenness surrounding school and childhood asthma after adjustment for covariates.
Results: We found that greenness surrounding schools in all buffered sizes was negatively associated with the prevalence of asthmatic symptoms in schoolchildren. A 0.1-unit increase in $NDVI_{1000m}$ was associated with lower odds of current asthma (odds ratio: 0.81, 95% confidential interval: 0.75, 0.86) and current wheeze (OR: 0.89, 95% CI: 0.84, 0.94) in children after covariate adjustments. Higher greenness was associated with less asthma symptoms in a dose-response pattern (P for trend < 0.05). The estimated associations appeared to be stronger in children exposure to higher air pollution level. The observed associations varied across seven cities.
Conclusion: Our findings suggest beneficial associations of greenness surrounding schools with childhood asthma. Further studies are needed to confirm our results.

1. Introduction

Asthma is the most common chronic airway disease in childhood and environmental factors are thought to play a key role in its development (Gaffin et al., 2014). While air pollution is associated with exacerbation of asthma (Khreis et al., 2017), there is increasing interest in the potential health effects of urban greenness on childhood asthma (Ferrante et al., 2020). It has been reported that greenness may provide beneficial effects by reducing ambient air pollution levels (Dadvand et al., 2015; Franchini and Mannucci, 2018; Ozdemir 2019), and enriching microbial flora (Rook 2013). The available evidence, however, for an association between greenness and childhood asthma remains inconsistent and showed strong regional heterogeneity (Ferrante et al., 2020; Lambert et al., 2017).

Home and school are the two dominant places where children spend most of their time. While effects of residential greenness exposure on children's health have been investigated in a number of epidemiological studies, evidence for associations with green space around schools

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remains limited particularly in association with children's behavior and mental health (McCormick 2017). Children spend 6–10 h at school during daytime which probably exposes them to higher levels of air pollution and traffic noise due to the timing of peak vehicle traffic (Esty et al., 2019; McCormick 2017). A recent review suggests that the school environment, particularly the schoolyard is one of the greatest sources for moderate-to-vigorous intensity physical activity in children (Jiang et al., 2019). Therefore, school represents a unique and important environment which may have a substantial health effect in children (Esty et al., 2019). Dadvand and his colleagues (2015) found that higher levels of green space around school were associated with lower levels of air pollution in both school playgrounds and classrooms. However, much less is known about the effect of green space around schools in children aside from the residential greenness exposure.

To address this knowledge gap, we assessed the associations between greenness surrounding schools and childhood asthma using the data from the Seven Northeastern City Study (SNEC), a large population-based cross-sectional study in China.

2. Materials and methods

2.1. Study population

We identified our study population and obtained data on outcomes and covariates from the Seven Northeast Cities Study (SNEC). The SNEC was conducted to investigate air pollution exposure and health outcomes in schoolchildren and has been described previously (Dong et al., 2013; Yang et al., 2018). Briefly, all 27 urban districts in seven cities (Shenyang, Dalian, Fushun, Anshan, Benxi, Liaoyang, and Dandong) from Liaoning province, northeastern China were selected based on having air quality monitoring data available from 2009 to 2012. One or two kindergartens, elementary schools, and middle schools were randomly chosen in the location within a one-two km radius from local air monitoring station in each district. More detailed study design is described in the Supplementary Materials (eMethod 1).

From April 2012 to January 2013, a total of 68,647 children in 94 public schools were recruited. Guardians of participating children provided written informed consent and completed the study questionnaires with the response rate of 93.1% (63,910 children). The final sample included 59,754 eligible children after excluding 4156 children who had lived at their current address for less than two years. The study protocol was approved by the Human Studies Committee of Sun Yat-sen University.

2.2. Assessment of school surrounding greenness and air pollution

Our assessment of greenness exposure was based on the outdoor greenness surrounding schools. We applied the normalized difference vegetation index (NDVI) and the soil-adjusted vegetation index (SAVI) derived from Landsat 5 Thermatic Mapper satellite images (http://earthexplorer.usgs.gov) at 30 m × 30 m resolution. To achieve the maximum exposure contract of greenness, we acquired available cloud-free Landsat TM images and generated the NDVI and SAVI maps by using two cloud-free images obtained during August 2010. The reason we looked for cloud-free images taken during the summer months was because of the high amount of green vegetation during summer. Therefore, using this season, we could discern maximum exposure contrasts of greenness for different study regions (Thiering et al., 2016). However, cloud-free images in October (autumn) were also obtained and used in a sensitivity analysis. The values ranged from −1 to 1 with higher numbers indicating more greenness (*e.g*, −1 corresponding to water, 0 corresponding to barren rock, +1 corresponding to vegetated areas). Greenness surrounding schools was defined as the mean of NDVI or SAVI values in circular buffers of 100 m, 300 m, 500 m, and 1000 m around each school. In order to test the temporal stability of the NDVI or SAVI, we generated further NDVI and SAVI maps by using two cloud-free images obtained during August 2014. Exposure assessment of greenness was performed using ArcGIS 10.4 (ESRI, Redlands, CA, USA).

We applied a random forest model to estimate concentrations of air pollutants at a spatial resolution of 10 × 10 km (Yang et al., 2018), including particulate matter with an aerodynamic diameter < 1 μm (PM_1), 2.5 μm ($PM_{2.5}$) or 10 μm (PM_{10}) and nitrogen dioxide (NO_2) from 2009 to 2012 matched to address of 94 schools. Detailed information regarding the modeling is presented in Supplementary Materials (eMethods 2). In addition, the collection of PM_{10} and NO_2 concentration from local air monitoring station in each district were also described (eMethods 3). Annual daily averages air pollutants were used to compute the school-specific mean levels for the period from 2009 to 2012 and considered as surrogates for long-term air pollution exposures (Zhang et al., 2019).

2.3. Asthma outcomes

We collected information on asthma using the validated Chinese version of Epidemiologic Standardization Project Questionnaire of the American Thoracic Society (ATS-DLD-78-A) (Dong et al., 2013; Yang et al., 2018). The definitions of current asthma and current wheeze are described in the Supplementary Materials (eMethods 4).

2.4. Covariates and mediators

Potential confounding variables for the association between greenness and childhood asthma were identified *a priori* based on direct acylic graph (DAG, Fig. S1), with reference to previous literature. These included information from children, parents, and the household environment (Dadvand et al., 2014; Sbihi et al., 2017). A detailed description of these covariates is described in the Supplementary Materials (eMethods 5). Minimal sufficient adjustment set of variables for estimating the direct effect of greenness exposure on childhood asthma in the DAG includes: family socioeconomic status, adverse birth outcome of child, breastfeeding status in child, home coal usage, mould in home, household secondhand smoke (SHS), residential area, and family history of asthma. Furthermore, we identified that body mass index (BMI), physical activity, and allergy were potential mediators on the pathway between greenness exposure and asthma in the DAG. Therefore, we did not adjust for mediators in main models.

From the DAG, we considered the role of air pollution on the association between greenness exposure and childhood asthma under two situations: (1) air pollution was a confounder due to potential common cause (*e.g*, land use) influencing both air pollution and greenness; and (2) air pollution was a mediator due to the potential for greenness on less air pollution.

2.5. Statistical analysis

All analyses were conducted using the SAS software version 9.4 (SAS Institute Inc., Cary, NC, USA). The GLIMMIX procedure in SAS was used to fit the logistic mixed-effects regression models estimating children at the first-level units and study districts at the second-level units (Dong et al., 2013). The Spearman correlation coefficient was used to analyze the relationship between greenness indices and air pollution levels. Statistical significance was tested using two-tailed tests, and P values $<$ 0.05 or 0.1 were considered statistically significant for main effects or interactions, respectively. We did not adjust P values for multiple comparisons because our analyses were hypothesis driven.

2.5.1. Main analyses

Greenness indices were treated as independent continuous or categorical (in tertiles) predictors and asthmatic symptoms were treated as dependent variables. Odds ratio (OR) and 95% confidence intervals (95% CIs) are reported per 0.1 unit increase in NDVI or SAVI.

A recent systematic review has suggested that larger buffer sizes may predict physical health better than smaller ones (Browning and Lee, 2017). Therefore, we used 1000-m buffer in the main analysis. Results using other buffers are also reported as well in the Supplementary Materials. In addition, because the associations of NDVI with asthma was similar to that with SAVI (see Results), therefore, we chose $NDVI_{1000m}$ (NDVI in 1000 m buffer) as the primary predictor in the main analyses.

We applied four logistic regression models to estimate the odds of asthmatic symptoms predicted by $NDVI_{1000m}$: (1) crude model without adjustment (model 1); (2) model 1 adjusted for age, gender, parental education, family income, breastfeeding, adverse birth outcomes, residential area, SHS, mould in home, home coal usage, and family history of asthma (model 2, main model); and (3) model 2 additionally adjusted for PM_{10} concentration collected from the air monitoring station (model 3); (4) model 2 additionally adjusted for NO_2 concentration collected from air monitoring station (model 4).

2.5.2. Mediation analyses

Because we identified air pollution, physical activity, BMI, and allergy as mediators from the DAG (Fig. S1), we used mediation analysis to explore whether these mediators could be mechanisms underlying the associations between greenness exposure and asthma. The CAUSALMED procedure in SAS was used to calculate the proportions of the mediated effect based on the theoretical foundation provided by Valeri and Vanderweele (2013). We used bias-corrected confidence intervals at 1000 bootstraps. The covariates adjusted in the mediation models were as same as in the main models.

2.5.3. Sensitivity analyses

We conducted a number of sensitivity analyses to evaluate the robustness of our findings. (1) Previous studies showed that the association between greenness exposure and respiratory outcomes were regional heterogeneity (Fuertes et al., 2016). Therefore, we analyzed the associations between greenness and childhood asthma in each city to investigate if the association varied by geographical locations. (2) Previous study showed that neighborhood (urban area *vs* rural area) may modify the association between greenness exposure and asthma (Donovan et al., 2018). Therefore, we used the cutoff of the lowest quartile of air pollutant level to define lower (air pollutant level $\le 1^{st}$ quartile) or higher air pollution area (air pollutant level $> 1^{st}$ quartile), and stratified the associations between greenness and childhood asthma by air pollution levels. (3) We tested the robustness of the associations between greenness exposure and childhood asthma by using NDVI and SAVI data obtained from October 2010. (4) We examined the robustness of the associations between greenness exposure and asthma by adjusting for the concentrations of air pollutants (PM_1, $PM_{2.5}$, PM_{10}, and NO_2) estimated from the air pollutant prediction model. (5) The greenness around school may have overlaps with residential greenness in current study because most children lived closed to school. Therefore, we restricted participants who reported living in the area with walking distance > 15 min from school (presumably > 1000 m) to minimize the overlap of greenness exposure between school and home (n = 18,864). (6) Because previous study showed that younger children were more vulnerable to environmental exposure (Yang et al., 2018), therefore, we further evaluated the effect modification of age on the main associations. (7) Considering the genetic predisposition of asthma, we excluded participants with family history of asthma (n = 4113).

3. Results

3.1. Characterization of population and greenness exposure

In total, 59,754 children participated in this study. The average was 10.3 years old and 50.6% were boys (Table 1). Among all participants, 68.4% lived in areas with walking distance to school (≤15 min). The prevalence of asthma symptoms ranged from 2.8% for current asthma and 4.0% for current wheeze (Table 1).

Table 1
Prevalence of outcomes and characteristics among study participants (n = 59,754).[a]

Variables	Values
Outcomes	
Current asthma	1,643 (2.8%)
Current wheeze	2,369 (4.0%)
Covariates	
Age (year)	10.3 ± 3.6
BMI (kg/m^2)	18.6 ± 4.5
Physical activity (hour/week)	6.6 ± 8.0
Residential area (m^2/person)	23.6 ± 12.4
Gender	
Boys	30,260 (50.6%)
Girls	29,494 (49.4%)
Annual family income (Chinese Yuan)	
≤ 9999 CNY	12,459 (20.9%)
10,000–29,999 CNY	22,170 (37.1%)
30,000–100,000 CNY	20,998 (35.1%)
> 100,000 CNY	4,127 (6.9%)
Parental education (≥high school)	43,786 (73.3%)
Breastfeeding (≥3 months)	39,756 (66.5%)
Low birthweight (< 2,500 g)	2,187 (3.7%)
Preterm (gestation age < 37 week)	3,217 (5.4%)
Doctor-diagnosed allergy symptom	6,859 (11.5%)
Walking distance from home to school ≤ 15 min	40,890 (68.4%)
Household second-hand smoke (SHS)	27,822 (46.6%)
Mould in home	10,041 (16.8%)
Home coal usage	3,459 (5.8%)
Family asthma history	4,113 (6.9%)

[a] Values are represented as mean ± SD or as n (%).

The median (quartile 1, quartile 3) level of NDAVI and SAVI surrounding schools in buffer of 1000 m was 0.28 (0.23, 0.36) and 0.16 (0.13, 0.20), respectively (Table 2). The levels of NDVI and SAVI were higher in August than in October ($P < 0.001$, Table S1). The greenness indices in August 2010 were similar and highly correlated to those from August 2014, and those from October 2010 as well ($P < 0.05$, Table S1).

3.2. Main analyses

Greenness surrounding schools in all buffer sizes were consistently associated with lower prevalence of childhood asthma symptoms (Table S2). We also observed stronger associations for school greenness in larger buffers (Table S2). The observed association was consistent in both crude models and multi-adjusted models (Table 3). A 0.1-unit increase in $NDVI_{1000m}$ was associated with 19% (95% CI: 14, 25%) lower odds for current asthma and 11% (95% CI: 6, 16%) lower odds for current wheeze in the main model (model 2). And the effect

Table 2
Greenness indexes around schools with different buffers in 2010.

Greenness index	Mean ± S.D	Medium (Q1, Q3)	Minimum	Maximum
$NDVI_{30m}$	0.30 ± 0.18	0.24 (0.17, 0.37)	−0.07	0.79
$NDVI_{100m}$	0.32 ± 0.15	0.27 (0.21, 0.38)	0.02	0.81
$NDVI_{300m}$	0.32 ± 0.15	0.29 (0.21, 0.38)	0.11	0.81
$NDVI_{500m}$	0.32 ± 0.14	0.29 (0.23, 0.38)	0.06	0.77
$NDVI_{1000m}$	0.31 ± 0.12	0.28 (0.23, 0.36)	0.06	0.68
$SAVI_{30m}$	0.17 ± 0.11	0.13 (0.09, 0.20)	−0.03	0.53
$SAVI_{100m}$	0.18 ± 0.10	0.15 (0.11, 0.22)	0.02	0.50
$SAVI_{300m}$	0.18 ± 0.09	0.17 (0.12, 0.21)	0.06	0.49
$SAVI_{500m}$	0.18 ± 0.09	0.16 (0.12, 0.21)	0.05	0.47
$SAVI_{1000m}$	0.18 ± 0.08	0.16 (0.13, 0.20)	0.05	0.42

S.D: standard deviation; Q1: quartile 1; Q3: quartile 3; IQR: interquartile range. NDVI: normalized difference vegetation index; SAVI: soil adjusted vegetation index; 30 m-1000 m: the green buffer ranged from 30 md to 1000 m.

Table 3
The adjusted ORs and 95% CIs of asthma with per 0.1-unit increase of NDVI in 1000 m buffer around schools in children.

	Model 1	*P*	Model 2	*P*	Model 3	*P*	Model 4	*P*
Current asthma	0.63 (0.59, 0.67)	< 0.001	0.81 (0.75, 0.86)	< 0.001	0.81 (0.75, 0.86)	< 0.001	0.81 (0.76, 0.87)	< 0.001
Current wheeze	0.67 (0.63, 0.70)	< 0.001	0.89 (0.84, 0.94)	< 0.001	0.89 (0.84, 0.94)	< 0.001	0.89 (0.84, 0.94)	< 0.001

Model 1: crude model.
Model 2: main model. Model 1 additionally adjusted for age, gender, parental education, family income, breastfeeding, low birthweight, preterm, residential area, SHS, mould in home, home coal usage, and family history of asthma.
Model 3: model 2 additionally adjusted for PM_{10} concentration collected from the air monitoring station.
Model 4: model 2 additionally adjusted for NO_2 concentration collected from the air monitoring station.

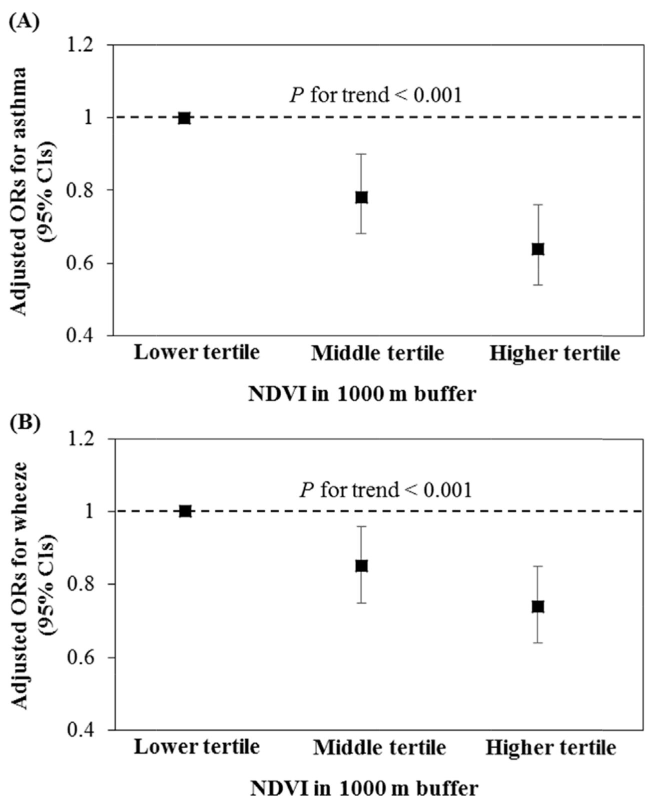

Fig. 1. The adjusted ORs and 95% CIs of current asthma symptoms in (A) asthma and (B) wheeze, with NDVI in 1000 m buffer in children, by NDVI tertile. Models adjusted for age, gender, parental education, family income, breastfeeding, low birthweight, preterm, residential areas per person, environmental tobacco smoke, mould in home, home coal usage, family history of asthma, and district. NDVI: normalized difference vegetation index. Lower tertile (1^{st} tertile): $NDVI_{1000m} < 0.24$. Middle tertile (2^{nd} tertile): $0.24 \leq NDVI_{1000m} < 0.31$. Higher tertile ($3^{rd}$ tertile): $NDVI_{1000m} \geq 0.31$.

estimates were not influenced by additional adjustments for PM_{10} and NO_2 concentrations collected from air monitoring station (model 3 and model 4, Table 3). Similar results were also observed in models additionally adjusting for PM_1, $PM_{2.5}$, PM_{10} and NO_2 concentrations derived from prediction models (model 2- model 5, Table S3).

When we used greenness levels in the lower tertile (1^{st} tertile) as reference, we found that higher greenness surrounding schools was related to lower prevalence of asthma and wheeze in schoolchildren in a dose-response manner (P for trend < 0.001, Fig. 1). A similar trend was also observed for the SAVI index in both 300 m and 1000 m buffers (Table S4).

3.3. Mediation analyses

Mediation analysis models showed that air pollution exposure and doctor-diagnosed allergy symptoms may mediate the association between greenness exposure and asthma, particularly for air pollution, while physical activity, and BMI did not play a mediation role after being adjusted for the same covariates as in the main models (Table S5).

3.4. Sensitivity analyses

We analyzed the heterogeneity in the observed associations across different cities. We found statistical significant negative associations in three cities (Dalian, Fushun, and Benxi) which accounted for 54.5% of the whole population ($P < 0.05$, Fig. S2).

We found that air pollution levels modified the association between greenness with asthma symptoms (Table 4). For example, the adjusted ORs for current asthma in association with a 0.1-unit increase in $NDVI_{1000}$ ranged from 0.72 to 0.76 in children exposed to higher air pollution, while ranged from 1.00 to 1.08 in children living in lower polluted areas (all interaction for P values < 0.05, Table 4). Similar results were also observed for current wheeze (Table 4).

We analyzed the associations between greenness exposure and asthma using NDVI and SAVI estimated in October 2010 to test if the associations varied seasonally (Table S6). Result shows that the effect estimates remained stable across seasons (Table S6).

In addition, the observed beneficial associations between greenness and asthma were more marked in younger children ≤ 12 years old compared to the older ones ($P_{-int} < 0.05$, Table S7).

To minimize the overlap of greenness exposure between school and residence, we restricted the participants living in areas with walking distance > 15 min to school (n = 18,864), the result was similar to the main results for current asthma (Table S8).

Table 4
The adjusted ORs and 95% CIs of asthma with per 0.1-unit increase of NDVI in 1000 m buffer around schools in children, stratified by air pollution exposure levels.[a]

		ORs (95% CIs)		P_{-int}
		Lower exposure[b]	Higher exposure[b]	
Current asthma	PM_1	1.01 (0.84, 1.21)	0.74 (0.67, 0.82)	0.003
	$PM_{2.5}$	1.08 (0.91, 1.29)	0.76 (0.69, 0.84)	< 0.001
	PM_{10}	1.08 (0.91, 1.29)	0.76 (0.69, 0.84)	< 0.001
	NO_2	1.00 (0.88, 1.14)	0.72 (0.65, 0.80)	< 0.001
Current wheeze	PM_1	1.07 (0.92, 1.25)	0.86 (0.79, 0.94)	0.011
	$PM_{2.5}$	1.06 (0.92, 1.23)	0.87 (0.80, 0.94)	0.017
	PM_{10}	1.06 (0.92, 1.23)	0.87 (0.80, 0.94)	0.017
	NO_2	1.02 (0.92, 1.14)	0.84 (0.77, 0.91)	0.003

NDVI: normalized difference vegetation index; PM_1, particle with aerodynamic diameter ≤ 1 μm; $PM_{2.5}$, particle with aerodynamic diameter ≤ 2.5 μm; PM_{10}, particle with aerodynamic diameter ≤ 10 μm; NO_2, nitrogen dioxide.

[a] Models adjusted for age, gender, parental education, family income, breastfeeding, low birthweight, preterm, residential area, SHS, mould in home, home coal usage, family history of asthma, and district.

[b] Lower exposure indicated the air pollution level ≤ 1^{st} quartile, higher exposure indicated the air pollution level > 1^{st} quartile; the 1^{st} quartile in PM_1: 41.1 μg/m^3; in $PM_{2.5}$: 48.8 μg/m^3; in PM_{10}: 89.3 μg/m^3; and in NO_2: 31.1 μg/m^3.

We further evaluated the robustness of our results by excluding children with family history of asthma who may have a genetic predisposition for asthma (Table S9). The results were consistent with the main findings.

4. Discussion

Our findings suggest a beneficial association of greenness surrounding schools with childhood asthma, particularly in higher air pollution areas. To our knowledge, our study is the first to link the greenness surrounding schools with asthma symptoms in schoolchildren and adds evidence to the limited literatures on the associations of children health with green spaces.

In recent years, the association between urban green spaces and respiratory conditions in children has been investigated with inconsistent findings (Ferranteet al., 2020; Hartley et al., 2020; Lambertet al., 2017; Lovasi et al., 2013). These inconsistencies are likely due to differences in types of study design (*e.g.*, birth cohort *vs*. cross-sectional study), greenness assessment, exposure timing (*e.g.*, exposure in early life *vs*. exposure in later life), and the region-specific confounding factors (Dadvandet al., 2014; Ferranteet al., 2020; Fuerteset al., 2016; Tischer et al., 2017). Our findings, however, were in line with several previous observations which reported beneficial associations of residential greenness exposure and respiratory outcomes. A 10-year follow-up of a Canadian birth cohort suggested that residential greenness exposure was associated with reduced incidence of asthma in children living in metropolitan areas (Sbihi et al., 2015). A similar result was reported by Tischer et al. (2017) who found a protective association between residential green spaces and childhood wheezing in Spanish children. A large New Zealand birth cohort indicated that higher residential greenness and proximity to green spaces were inversely related to wheezing in children at 4 years old (Donovanet al., 2018). In addition, these authors reported that greenness may provide greater protection for asthma in children living in urban areas (exposed to higher air pollution levels) compared with those living in rural areas (Donovanet al., 2018). Alcock et al (2017) also reported that higher tree density was associated with lower asthma hospitalisation in highly polluted areas while no significant association was observed in low polluted areas. Consistent with these findings, we observed stronger beneficial associations of greenness surrounding schools and asthma in children living in areas that had higher levels of air pollution compared to low air pollution.

School is an important location for moderate-to-vigorous intensity physical activity which is associated with higher inhalation rates than during rest or sleep at home (Ma et al., 2019). Therefore, a favorable environment, such as lower air pollution and less traffic noise within and around schools may be beneficial to the well-being in children. In this study, we found higher school greenness exposure was associated with lower current asthma among schoolchildren with a clear dose-response pattern. However, the observed associations were heterogeneous across seven cities, in which significant associations were observed in three cities accounting for 54.5% of the study population. A similar finding was observed by Fuertes et al (2016), who reported that the direction of associations between residential greenness and childhood allergic rhinitis in seven birth cohorts varied by region. In a birth cohort located in Euro-Siberian and Mediterranean, Tischer et al. (2017) also reported that associations between residential greenness and respiratory outcomes differed by region. These authors suggested that the observed effects may be driven by chance or unknown region-specific confounding factors. Further research considering region-specific characteristics and a range of relevant pathways will help to explore the remaining uncertainties.

The mechanism for the effects of greenness exposure remains unclear. However, it has been reported that the beneficial effects linked with childhood asthma symptoms may be partially explained by the reduced air pollution (Franchini and Mannucci, 2018). There is evidence that planting roadside trees decreases ambient particulate matter concentrations, including ultrafine particles (Hagler et al., 2012) and reduces the heavy metal concentrations in $PM_{2.5}$ (Ozdemir, 2019). In a study investigating the association between greenness within and surrounding school boundaries and levels of TRAPs, Dadvand et al. (2015) found that higher NDVI around schools was associated with reduced TRAP levels both in school playgrounds and in the classrooms. In this study, mediation analysis suggested that mitigation in air pollutants by vegetation may partly explain our observed beneficial associations with greenness. However, we need to interpret this result with caution because we cannot provide the temporal patterns of the negative associations between greenness exposure and air pollution.

Another potential reason for the associations between greenness and health effects is that greenness protects against inflammatory responses through more diverse microbial exposure (Rook, 2013). Increasing evidence indicates that exposure to a more diverse microbial environment might lead to an enhanced immune tolerance and protect against asthma development (von Mutius, 2016). By using an Australian national-wide dataset, Liddicoat et al. (2018) suggested the possibility of a protective immunomodulatory effect from microbial diversity associated with natural green environments. Specifically, schoolchildren living in a more environmentally biodiverse areas were found to have higher genetic diversity in the bacteria on their skins, which was inversely related to atopic sensitization (Hanski et al., 2012). A similar phenomenon was found for children who lived on farms, exposed to a wider range of environmental microbials, and explained a protective effect on the development of asthma, which also supported the hypothesis of “environmental microbiome” (Ege et al., 2011). However, other unknown biological mechanisms related to greenness exposure may also contribute to the observed beneficial associations.

This is the first study to investigate the association between greenness surrounding schools and asthma symptoms in a general paediatric population. The major strength of our study includes the large number of study subjects from 94 schools in seven cities which allowed sufficient power to detect these associations. Second, a wide range of covariates ensured comprehensive adjustment for potential confounders and modifiers and the ability to test for the robustness of our findings in various sensitivity analyses. Third, we used two greenness indices at different buffers as objective greenness exposure measurements and they both found similar results.

Our study also has some limitations. First, the cross-sectional design limited the causal inference of the observed associations. One-point-in-time greenness measure may also result in systematic measurement error (Donovan et al., 2018). However, the NDVI in 2014 remained highly correlated with that in 2010 which suggested the relatively high stability of greenness exposure over years in this study region. Second, outcome information and covariates were based on the self-reported questionnaires, which may induce recall error. In addition, the questionnaires did not consider all aspects of real situation in life. For example, we did not measure other important covariates, such as regional socioeconomic levels, traffic noise, and walkability to school which may induce residual confounding as well. Third, although NDVI is able to capture greenness cover, it does not allow the identification of particular types of vegetation or qualities of greenness that may influence human-environment interactions (Gernes et al., 2019). Fourth, we did not have the greenness data at residential level which make it impossible to distinguish the greenness boundaries around schools, commuting routes to school and around residential address. Therefore, we cannot rule out the possibility that the observed associations may also be related to residential greenness exposure or the joint effects. Fifth, we only had 94 exposure data of greenness indices and air pollution levels in this study which may introduce exposure misclassification in individuals among this large population.

5. Conclusion

In conclusion, our findings suggest beneficial associations between greenness surrounding schools and asthma in schoolchildren, providing new evidence to the limited investigations on health effect of green space around schools. However, we need to interpret the findings with caution due to the study limitations. Further studies are needed to confirm our results in different regions and underlay the mechanism. This finding is relevant for school decision-makers and local governments to set up a more favorable environment around schools and build asthma-friendly schools.

CRediT authorship contribution statement

Xiao-Wen Zeng: Data curation, Funding acquisition, Writing - original draft. **Adrian J. Lowe:** Methodology, Writing - review & editing. **Caroline J. Lodge:** Writing - review & editing. **Joachim Heinrich:** Writing - review & editing. **Marjut Roponen:** Writing - review & editing. **Pasi Jalava:** Writing - review & editing. **Yuming Guo:** Methodology, Writing - review & editing. **Li-Wen Hu:** Writing - review & editing. **Bo-Yi Yang:** Writing - review & editing. **Shyamali C. Dharmage:** Supervision, Writing - original draft. **Guang-Hui Dong:** Funding acquisition, Supervision.

Declaration of Competing Interest

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

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2020.105967.

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