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Associations of residential greenness exposure during early pregnancy with the risk of spontaneous abortion: the China Birth Cohort Study

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Abstract

Background Living in higher greenness level community has many benefits for pregnancy outcomes, however, few research have explored the relationship between greenness and spontaneous abortion (SAB). We aimed to analyze relationships between SAB and community greenness in Chinese pregnant women, and further assessed the modifying effects from air pollutants.

Methods We studied 90 890 pregnant women from the China Birth Cohort Study from February 2018 to December 2021. We diagnosed SAB by certified obstetricians and gynecologists. The level of exposure to greenness during the first trimester was measured using the normalized difference vegetation index (NDVI) and the enhanced vegetation index (EVI). Particulate matter $\leq 2.5 \mu\text{m}$ (PM_{2.5}), nitrogen dioxide (NO₂) and ozone (O₃) were used as proxies of ambient air pollution. Time-dependent multivariable adjusted Cox proportional hazards models, with gestational weeks as the time scale, were used to analyze the association between SAB and greenness. We additionally performed subgroup analyses stratified by age, urbanicity, research location, season of birth, temperature, humidity and air pollution levels.

Results Lower SAB prevalence was related to living in greener places. A 0.1 unit increase in NDVI_{500m} and EVI_{500m} was significantly associated with a 12.3% (95% CI 9.9%, 15.5%) and 16.2% (95% CI 11.4%, 20.6%) lower risks of SAB, respectively. In sensitivity analysis, these relationships remained consistent. The associations were stronger among older, participants lived in the north of China and lived in places with higher PM_{2.5} and lower NO₂ levels.

Conclusions Our findings indicate significantly inverse associations between community greenness and SAB in Chinese pregnant women, especially for older and participants who live in the north of China, the PM_{2.5} and NO₂ may modify the effects of greenness on SAB.

Keywords Spontaneous abortion, Greenness, Air pollutants, Birth cohort

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Introduction

Spontaneous abortion (SAB) (or miscarriage), defined as the loss of an intrauterine pregnancy before viability, is one of the most serious adverse pregnancy outcomes [1]. Globally, there occur about 73 million SAB occur every year [2]. In China, the incidence rate of spontaneous abortion ranges from 3 to 5% [3–5]. SAB is related to both physical and psychological illnesses, including anxiety, depression, post-traumatic stress disorder, and suicide [6]. Also, having a history of SAB might raise the possibility of adverse pregnancy outcomes in subsequent pregnancies including preterm birth [1].

Nearly half of the world's population now resides in cities, and by 2050, it is anticipated that this number will exceed 70% (approximately 6.4 billion people) [7]. Rapid urbanization has reduced greenness levels, which is quite concerning for public health because exposure to higher levels of greenness might result in several positive health effects [8]. Plenty of studies have shown that greenness is related to several adverse birth outcomes [9–11], such as preterm birth, low birth weight, and small for gestational age [12–14], and no study has explored potential effects of greenness on SAB. Mechanistically, greenness may bring a series of health benefits, including decreased negative environmental exposures (e.g., air pollution and noise), promoted health-related activities (e.g., physical activity), improved psychophysiological recovery (e.g., reducing stress), and reduced adiposity [15]. These proposed mechanisms resemble those implicated in the pathophysiologic pathways of SAB. Therefore, it is biologically plausible that higher levels of greenness exposure are related to lower risk of SAB, and we test the hypothesis based on a birth cohort study conducted throughout China.

Materials and methods

Study participants

The study population was derived from the China Birth Cohort Study (CBCS). Briefly, CBCS is a prospective, longitudinal mega-cohort study performed between February 2018 and December 2021 among 35 research sites across 17 provinces and autonomous regions in China [16]. Pregnant women those with 6–13⁺⁶ weeks of gestation, planned to attend regular prenatal examination, delivered at the research location, and continued to reside in the same place for more than a year, were recruited. They were assigned with a questionnaire to collect data on demographic characteristics, health status, reproductive history, lifestyles, and environment factors at baseline. After enrollment, follow-up interviews were performed by certified doctors or nurses at gestational weeks at 20–23⁺⁶, 28–33⁺⁶ and delivery, respectively,

to record information of pregnant outcomes. The study was approved by the Ethics Committee of Beijing Obstetrics and Gynecology Hospital, Capital Medical University (2018-KY-003–02). Written informed consent was obtained from all participants.

According to the current study, we included 106 087 potential study participants enrolled in CBCS. Of those, 90 890 (response rate=85.7%) were included in the current analysis (Additional file 1: Figure S1), based on the following six criteria: (1) had resided locally for more than one year; (2) planned to attend routine antenatal examinations and deliver in the study site; (3) had no hepatitis B, syphilis, AIDS and other notifiable infectious diseases prescribed by the State; (4) were willing and able to sign informed consent; (5) had complete records of required information; (6) not voluntary abortion.

Outcome assessments

SAB was defined as a fetal loss occurring before completed gestation of 28 weeks [1]. In our study, certified obstetricians and gynecologists who strictly adhered to the above criterion made the diagnosis of SAB, which was then noted in medical records. Timing of concept is assessed by obstetricians based on the last menstrual period, while time to event is calculated based on the weeks of the outcome and the weeks of the last menstrual period, using the following formula: the weeks of the outcome—the weeks of the last menstrual period.

Exposure assessments

As measures of greenness, we utilized the normalized difference vegetation index (NDVI) and the enhanced vegetation index (EVI). The following formula was used for estimating NDVI as a ratio difference between measured canopy reflectance in the red (RED) and near infrared (NIR) bands, respectively: $NDVI = (NIR - RED) / (NIR + RED)$. Similarly, EVI was determined using the formula: $EVI = 2.5 \times (NIR - RED) / (NIR + RED - 7.5 \times BLUE + 1)$, where BLUE stands for the reflectance of blue-region light. Higher values refer to more greenness for both indices, which have a range from -1 to 1. We used satellite images from Landsat8 OLI and TIRS at a 30 m × 30 m spatial resolution to calculate the NDVI and EVI around the centroid of each study participant through the latitude and longitude of the residential address. The USGS EarthExplorer (<https://earthexplorer.usgs.gov/>) provided remote sensing data for the year 2016 [17]. We assessed the NDVI and EVI every 16 days and then averaged them during the first trimester (0–13⁺⁶ weeks). For the initial analysis, we used the NDVI and EVI values with the 500 m buffer. Other metrics and buffers were presented in sensitivity analyses as well.

The China High Air Pollutants (CHAP) dataset was used to get full-coverage ground-level PM_{2.5}, NO₂, and O₃ concentrations with 0.1°×0.1° spatial resolution. Details of the air pollutants exposure assessments have been described elsewhere [18–20]. In short, to estimate the ambient PM_{2.5}, NO₂, and O₃ concentrations, an extensive collection of data from ground-based measurements, satellite remote sensing products, model simulations, and atmospheric reanalysis was fitted using artificial intelligence algorithms. The assessments were then validated using the tenfold cross-validation approach by measuring the adjusted coefficient of determination (R²) and root mean squared error (RMSE). Air pollutants concentrations were assigned to each participant according to their residential addresses, and the measurement period of air pollutants concentrations is in the first trimester.

We collected daily average temperature and humidity from the China Meteorological Data Service Center (CMDC, <http://data.cma.cn/en>). Then, we calculated the average ambient temperature and humidity of first trimester for every participants.

Potential confounders and mediators

We used self-filled questionnaires to collect the following information: (a) characteristics of pregnant women, including age (years), ethnicity (Han vs. others), education (high school or lower versus college vs. master or higher), annual family income (<100 000 CNY vs. 100 000–200 000 CNY vs. >200 000 CNY), residential region (South vs. North) and residential address; (b) habits of life, such as alcohol intake (yes vs. no) and maternal smoke exposure (yes vs. no); and (c) present clinical information, including parity (0 vs. ≥1), pre-pregnancy BMI (kg/m²) and season of pregnancy outcome (spring vs. summer vs. fall vs. winter).

Pre-pregnancy BMI was calculated as follows: weight in kilos divided by square of height in meters. The height and weight for three month before pregnancy were reported by pregnant women. The Chinese Statistical Yearbooks (<http://www.stats.gov.cn>) were used to identify urbanicity (urban vs. rural). The 35 member centers were distinguished as north and south based on the Qinling Mountain-Huaihe River Line (near latitude 33°N), a natural boundary for regional demarcation between North and South China [21].

Statistical analysis

Continuous variables were expressed as mean ± standard deviation (SD) and categorical variables as frequency with percentage, respectively. We used the Chi-square test or t-test to test the differences of characteristics between SAB and non-SAB. Time-dependent multivariable adjusted Cox proportional hazards

models, with gestational weeks as the time scale, were constructed to estimate hazard ratios (HRs) and 95% confidence intervals (CIs) of explore the associations between residential greenness (NDVI_{500m} and EVI_{500m}) and SAB after adjusting for potential confounding variables, including age, pre-pregnancy BMI, education, annual family income, ethnicity, parity, season of birth, region and PM_{2.5}. From the Cox model fit we have: $Y(t) = \beta_1 \cdot \text{age}(t) + \beta_2 \cdot \text{pre-pregnancy BMI} + \beta_3 \cdot \text{education}(t) + \beta_4 \cdot \text{annual family income}(t) + \beta_5 \cdot \text{ethnicity} + \beta_6 \cdot \text{parity} + \beta_7 \cdot \text{season of birth}(t) + \beta_8 \cdot \text{region} + \beta_9 \cdot \text{PM}_{2.5} + \beta_{10} \cdot \text{NDVI}_{500m}$, β is a vector of regression coefficients [22].

We used the restricted cubic spline (RCS) function to test the potential nonlinear associations between greenness exposure during the first trimester and risk of SAB, with three knots set at the 10th, 50th and 90th percentiles.

Subgroups analyses were also performed according to maternal age, pre-pregnancy BMI, annual family income, air pollutants levels, temperature and humidity to identify whether they were potential modifiers of associations between greenness and SAB. Maternal age was categorized as high risk group (≥35 years) and low risk group (<35 years). Pre-pregnancy BMI was categorized as normal group (<24 kg/m²) and overweight/obesity group (≥24 kg/m²) [23], and annual family income as low income group (<100 000 Yuan), middle income group (100 000–200 000 Yuan) and high income group (>200 000 Yuan). A lower exposure group and a higher exposure group were designed for PM_{2.5}, NO₂, and O₃. Lower exposure represented less than the first interquartile range of air pollution, while higher exposure represented more than the first interquartile range of air pollution; the first interquartile range in PM₁: 23.535 µg/m³; in PM_{2.5}: 29.732 µg/m³; in PM₁₀: 43.458 µg/m³; in NO₂: 25.548 µg/m³; and in O₃: 62.089 µg/m³. Temperature and humidity were categorized as lower group and higher group by median (18.1 °C and 65.3%, respectively). We repeated the analysis for each subgroup and P-values for interactions were reported.

Sensitivity analyses

We performed two sensitivity analyses to assess the robustness of our findings. First of all, we used the other two buffers (namely 250 m and 1 000 m buffers for NDVI) in the model. Then, we investigated the relationship between residential greenness and SAB after excluding multipara and participants who smoke or drink alcohol.

All analyses were conducted using R (version 4.0.3, R Foundation for Statistical Computing). A two-tailed P-value <0.05 was considered as statistically significant.

Results

Population description

Table 1 shows the descriptive statistical characteristics of the entire cohort ($n = 90\,890$), with a total of 2 817 (3.1%) were detected as SAB. Compared with the non-SAB participants, the patients with SAB were older and

had a higher proportion of education level and annual family income.

Greenness and air pollutants exposure

In terms of environmental factors, pregnant women with SAB lived in areas with lower greenness levels and higher air pollution levels during the first trimester, except for

Table 1 Characteristics of participants in the study

Variable*	Total ($n = 90\,890$)	Non-SAB ($n = 88\,073$)	SAB ($n = 2\,817$)	P-value
Mothers				
Age, year; mean \pm SD	29.58 \pm 4.27	29.53 \pm 4.25	31.05 \pm 4.82	< 0.0001
Pre-pregnancy BMI, kg/m ² ; mean \pm SD	21.68 \pm 3.26	21.67 \pm 3.26	22.07 \pm 3.38	0.012
Education (%)				< 0.0001
High school or lower	19 434 (21.4)	18 834 (21.4)	600 (21.3)	
College	61 859 (68.1)	60 014 (68.1)	1 845 (65.5)	
Master or higher	9 597 (10.5)	9 225 (10.5)	372 (13.2)	
Annual family income, CNY (%)				< 0.0001
< 100 000	31 249 (34.4)	30 328 (34.4)	921 (32.7)	
100 000–200 000	30 897 (34.0)	30 062 (34.2)	835 (29.6)	
> 200 000	28 744 (31.6)	27 683 (31.4)	1 061 (37.7)	
Ethnicity (%)				0.019
Han	85 199 (93.7)	82 588 (93.8)	2 611 (92.7)	
Others	5 691 (6.3)	5 485 (6.2)	206 (7.3)	
Smoke (%)				0.919
Yes	2 123 (2.3)	2 058 (2.3)	65 (2.3)	
No	88 767 (97.7)	86 015 (97.7)	2 752 (97.7)	
Drink (%)				0.032
Yes	2 999 (3.3)	2 886 (3.3)	113 (4.0)	
No	87 891 (96.7)	85 187 (96.7)	2 704 (96.0)	
Parity (%)				< 0.0001
0	44 090 (48.5)	42 943 (48.8)	1 147 (40.7)	
≥ 1	46 800 (51.5)	45 130 (51.2)	1 670 (59.3)	
Urban (%)				0.110
Yes	71 601 (78.8)	69 416 (78.8)	2 185 (77.6)	
No	19 289 (21.2)	18 657 (21.2)	632 (22.4)	
Environmental factors				
NDVI _{500m} ; mean \pm SD	0.296 \pm 0.128	0.297 \pm 0.128	0.283 \pm 0.122	0.027
EVI _{500m} ; mean \pm SD	0.181 \pm 0.088	0.181 \pm 0.088	0.172 \pm 0.083	0.009
NDVI _{250m} ; mean \pm SD	0.274 \pm 0.107	0.275 \pm 0.107	0.264 \pm 0.097	< 0.0001
NDVI _{1000m} ; mean \pm SD	0.302 \pm 0.109	0.302 \pm 0.109	0.294 \pm 0.103	0.008
PM ₁ , $\mu\text{g}/\text{m}^3$; mean \pm SD	29.981 \pm 9.670	29.973 \pm 9.674	30.255 \pm 9.528	0.076
PM _{2.5} , $\mu\text{g}/\text{m}^3$; mean \pm SD	42.325 \pm 18.412	42.333 \pm 18.477	42.054 \pm 16.241	< 0.0001
PM ₁₀ , $\mu\text{g}/\text{m}^3$; mean \pm SD	63.185 \pm 22.778	63.134 \pm 22.806	64.793 \pm 21.848	< 0.0001
NO ₂ , $\mu\text{g}/\text{m}^3$; mean \pm SD	33.856 \pm 10.697	33.827 \pm 10.728	34.780 \pm 9.641	< 0.0001
O ₃ , $\mu\text{g}/\text{m}^3$; mean \pm SD	91.221 \pm 35.265	91.186 \pm 35.206	92.324 \pm 37.062	< 0.0001
Temperature, °C; mean \pm SD	16.459 \pm 8.023	16.464 \pm 8.014	16.286 \pm 8.315	< 0.0001
Humidity, %; mean \pm SD	63.835 \pm 14.990	63.887 \pm 14.971	62.196 \pm 15.483	< 0.0001

SD, standard deviation; SAB, spontaneous abortion; BMI, body mass index; CNY, China Yuan; PM₁, particulate with aerodynamic diameter $\leq 1\ \mu\text{m}$; PM_{2.5}, particulate with aerodynamic diameter $\leq 2.5\ \mu\text{m}$; PM₁₀, particulate with aerodynamic diameter $\leq 10\ \mu\text{m}$; NO₂, nitrogen dioxide; O₃, ozone

* Continuous variables are presented as mean \pm standard deviation and categorical variables are presented as numbers (percentage)

PM_{2.5}. Pregnant women with SAB live in environments with lower PM_{2.5} levels. The mean NDVI_{500m} and EVI_{500m} in non-SAB participants was 0.296 and 0.181, respectively, and in the SAB cases was 0.283 and 0.172, respectively. PM_{2.5}, NO₂ and O₃ in non-SAB participants was 42.333 µg/m³, 33.827 µg/m³ and 91.186 µg/m³, respectively, and in the SAB cases was 42.054 µg/m³, 34.780 µg/m³ and 92.324 µg/m³, respectively. The median of PM_{2.5}, NO₂ and O₃ was 37.778 µg/m³, 32.556 µg/m³ and 85.444 µg/m³, respectively (Additional file 1: Table S1).

Greenness and spontaneous abortion

As shown in Additional file 1: Figure S2, NDVI_{500m} had no significant nonlinear associations with SAB ($P > 0.05$). Our research showed a straight line.

The associations between residential greenness and SAB are shown in Table 2. In the unadjusted model, for 0.1 unit increase in NDVI_{500m}, the HR for SAB was 0.916 (0.889, 0.944). After fully multivariate adjustment, for every 0.1 unit increase in the NDVI_{500m}, the risk of SAB (HR = 0.877, 95% CI 0.845–0.911 in model1; HR = 0.925, 95% CI 0.852–0.959 in model2; HR = 0.912, 95% CI 0.877–0.948 in model3) significantly decreased. In model 1, compared with Q1, the protection effect of the greenness measured by NDVI_{500m} was strongest in Q4 (HR = 0.686, 95% CI 0.604–0.778). In model 2 and model 3, the protection effect of the greenness measured by NDVI_{500m} was strongest in Q3 (HR = 0.815, 95% CI 0.725–0.916 and HR = 0.766, 95% CI 0.673–0.871, respectively). Among all three models, there is no statistical significance in Q2, and the protection

effect is very closed in Q3 and Q4. The same trend can also be observed in EVI_{500m}.

The Kaplan–Meier survival curves for NDVI_{500m} and EVI_{500m} with different interquartile range groups are shown in Additional file 1: Fig. S3–S4.

Sensitivity analyses

NDVI_{250m} and NDVI_{1000m} were used in sensitivity analysis, which indicated that the correlations were mainly consistent (Additional file 1: Table S2). Additionally, estimates remained consistent after excluding individuals who smoked, drank alcohol, or had multipara (Additional file 1: Tables S3–S5).

Effect modification

Figure 1 shows associations for greenness exposures and SAB according to potential effect modifiers. The associations between greenness and subsequent SAB risk were more pronounced among participants with older age than those younger than 35 years at the baseline. In addition, the relationship between residential greenness and SAB was stronger among participants lived in north of China and those whose birth outcomes occur in spring and winter. We also found that the relationship between residential greenness and SAB was stronger in participants with higher PM_{2.5} and lower NO₂. The results of stratified analysis by urbanicity, temperature, humidity and O₃ were not statistically significant.

Table 2 Associations of residential greenness with SAB

SAB	Unadjusted HR (95% CI)	Model1 HR (95% CI)	Model2 HR (95% CI)	Model3 HR (95% CI)
NDVI _{500m}				
Per 0.1 unit	0.916 (0.889, 0.944)	0.877 (0.845, 0.911)	0.925 (0.852, 0.959)	0.912 (0.877, 0.948)
Q1 (<0.203)	1	1	1	1
Q2 (0.203–0.291)	0.934 (0.845, 1.031)	0.909 (0.816, 1.013)	1.014 (0.912, 1.127)	0.971 (0.869, 1.086)
Q3 (0.292–0.373)	0.779 (0.702, 0.865)	0.692 (0.613, 0.782)	0.815 (0.725, 0.916)	0.766 (0.673, 0.871)
Q4 (≥0.374)	0.792 (0.714, 0.879)	0.686 (0.604, 0.778)	0.820 (0.724, 0.928)	0.773 (0.675, 0.884)
EVI _{500m}				
Per 0.1 unit	0.882 (0.844, 0.922)	0.838 (0.794, 0.886)	0.901 (0.854, 0.950)	0.886 (0.837, 0.938)
Q1 (<0.116)	1	1	1	1
Q2 (0.117–0.173)	0.936 (0.846, 1.035)	0.909 (0.816, 1.013)	1.004 (0.903, 1.116)	0.970 (0.868, 1.084)
Q3 (0.174–0.231)	0.820 (0.738, 0.910)	0.729 (0.646, 0.823)	0.854 (0.759, 0.960)	0.811 (0.713, 0.922)
Q4 (≥0.232)	0.790 (0.711, 0.878)	0.691 (0.609, 0.785)	0.823 (0.726, 0.933)	0.783 (0.683, 0.897)

Model 1: Adjusted for age, pre-pregnancy BMI, education, annual family income, ethnicity, parity, season of birth, region and particle with aerodynamic diameter less than 2.5 µm (PM_{2.5})

Model 2: Adjusted for age, pre-pregnancy BMI, education, annual family income, ethnicity, parity, season of birth, region and nitrogen dioxide (NO₂)

Model 3: Adjusted for age, pre-pregnancy BMI, education, annual family income, ethnicity, parity, season of birth, region and ozone (O₃)

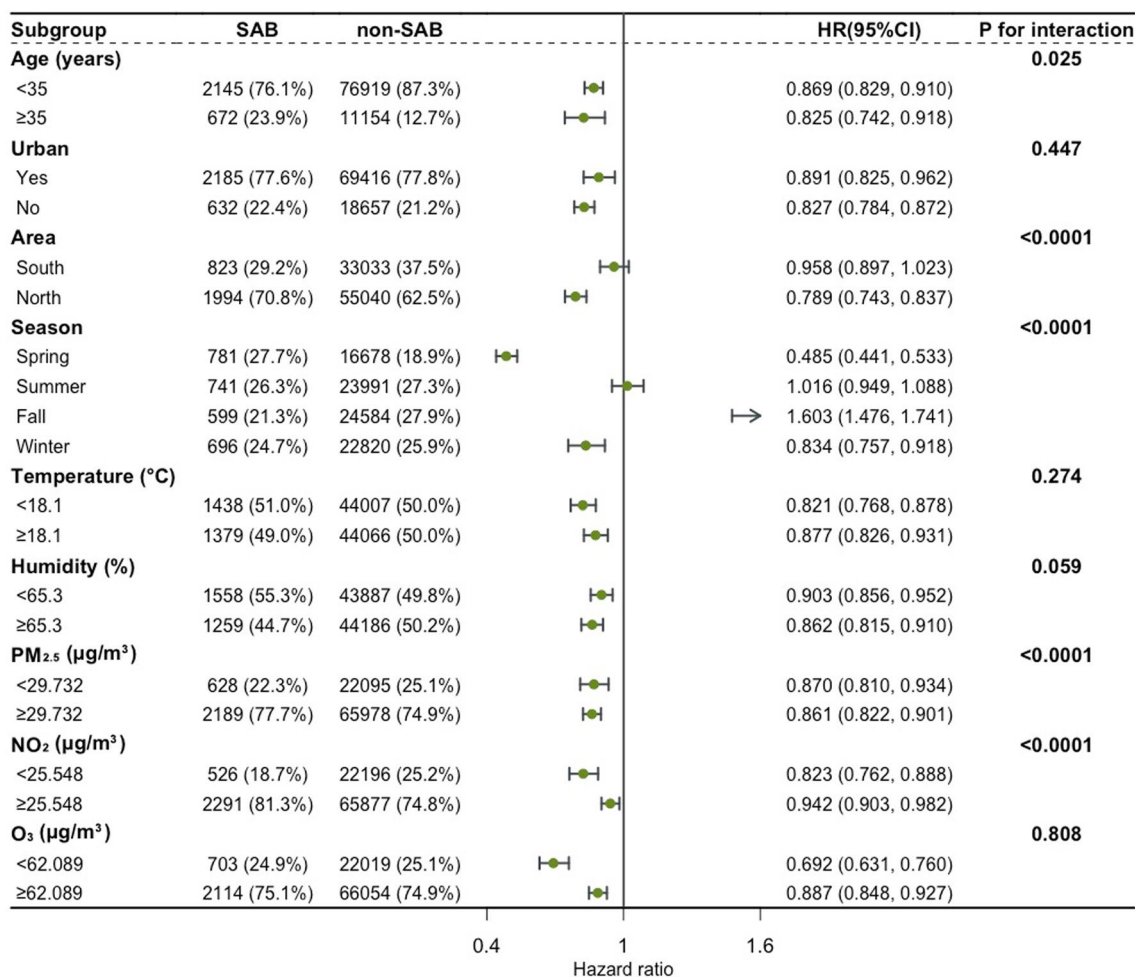


Fig. 1 Associations between per 0.1 unit increase in NDVI_{500m} and SAB by age, urbanicity, research location, season of birth, temperature, humidity and air pollutant level (n = 90 890)*. *The model was adjusted for maternal age, education, pre-pregnancy BMI, ethnicity, annual family income, parity, season of birth, region, particle with aerodynamic diameter less than 2.5 µm (PM_{2.5}), nitrogen dioxide (NO₂) and ozone (O₃).

Discussion

Key findings

In our large population-based cohort study, we found that increased greenness exposure during the first trimester was significantly associated with lower risk of SAB, especially in older and participants lived in the north of China, and this association showed a linear dose-response relationship. In addition, concentrations of PM_{2.5} and NO₂ may modify the effects of greenness on SAB.

Comparison with prior studies and interpretations

To our knowledge, this is the first epidemiological study that demonstrates a relationship between early prenatal exposure to community greenness and SAB. Only one study performed by Sun et al. [24] found greenness can attenuate the effect of temperature on SAB, which supported our findings of protective effects of gestational

greenness exposure on SAB. Besides SAB, many studies have estimated the effects of greenness exposure on other adverse pregnancy outcomes, including small for gestational age (SGA), low birth weight (LBW) and preterm birth (PTB) [13, 25–28], and most of indicated a beneficial effects of greenness on these outcomes. The prior studies combined with ours indicated that living greener areas may be beneficial for birth outcomes, especially our large and well-represented study firstly find a protective association for SAB.

Underlying mechanism

Notwithstanding that the biological mechanisms of the relationship between SAB and residential greenness are still unclear, several biopsychosocial pathways have been proposed. First of all, those who live near green space are more likely to exercise, which can lower the risk of obesity, which has been correlated to an increased

risk for SAB [29, 30]. Stratification analyses in our study confirmed this hypothesis by finding the higher the pre-pregnancy BMI, the less protective effect green space has on SAB. Second, green space may decrease the negative effects of air pollution on the environment, such as $PM_{2.5}$, which has been widely discussed as risk factors for SAB [31–33]. According to our findings, $PM_{2.5}$ can attenuate the negative relationship between increasing gestational greenness exposure and a reduced risk of SAB, which is in line with the proposed hypothesis. Third, according to studies, living in greener places may also help with reduced mental stress and concentration problems, improved social interaction, increased microbial diversity, and altered human microbiota composition [8, 15]. We were unable to explore these mechanisms as potential moderators of the relationship between greenness and SAB, however, given that our study's data were lacking. More mechanistic research is, therefore, required to confirm the underlying mechanisms.

Susceptible populations

We found that the association between greenness exposure during the first trimester and the risk of SAB was stronger in the north of China. To our knowledge, no studies have been done to examine the relationship between SAB and being exposed to greenness while pregnant. Nonetheless, our results were not surprising. Compared with southern China, northern China urbanizes more rapidly [34]. For example, areas with high urbanization have better access to healthcare and community involvement, which attenuate the prevalence of SAB [35]. The relationship may also be explained by socioeconomic status factors [36, 37], such as income and education. People with higher income level and higher education level are more likely to participate in physical exercise and maintain a healthy lifestyle, thus attenuating the risk of SAB. In addition, due to the more suitable temperature and humidity for vegetation growth, the greenness level in southern China is better than that in the north. Therefore, there is a slight change in the greenness level in the north, the result will be more significant changes. We also detected that older seems more vulnerable than younger in the association between greenness and SAB. Furthermore, the relationship between residential greenness and SAB was stronger among participants whose birth outcomes occur in spring and winter. Since the overall greenness level in spring and winter is lower than that in summer and fall, the change of greenness level in spring and winter will make the results more significant.

In addition, we noted the modifying effect of air pollution on the relationship between exposure to gestational greenness and the risk of SAB, which the effect of greenness exposure were stronger in higher levels of $PM_{2.5}$, and

lower levels of NO_2 . Although we were unable to search for any studies examining the impact of air pollution on residential greenness and SAB, the similar reason have been explained in studies of greenness and other adverse birth outcomes [13, 38]. The possible reason is that the risk of SAB is increased by air pollution [1], so higher levels of air pollutants may lead to higher prevalence of SAB. Given that limited evidence is available, additional research is required to confirm our findings.

Strengths and limitations

Our study has several strengths. First, this prospective cohort study eventually included a total of 90,890 participants, it includes 17 Chinese provinces and autonomous areas, to our best knowledge, this is the largest cohort study of greenness during pregnancy and SAB, which reduce potential selection bias. Additionally, clinically verified diagnoses were utilized to mitigate outcome misclassification, and health professionals delivered a face-to-face study questionnaire to minimize exposure and covariate misclassification. Second, we calculated NDVI and EVI by the latitude and longitude of personal address, and the average exposure during the first trimester was calculated accurately which has been proved to be more accurate compared with studies that used residential postal code [39]. Third, we conducted detailed sensitivity studies to assess the reliability of the results.

Our study also had several limitations to acknowledge. First, this study did not collect information on the work addresses of the participants, which could have led to a potential misclassification bias between participants who remained employed during pregnancy and those who did not. Second, we didn't have enough information about individual anxiety, stress and depression to test the mechanisms in previous studies. Third, we measured greenness levels using the vegetation indices NDVI and EVI, which do not provide information on the kinds of vegetation or the accessibility of green space. Fourth, even though we considered and adjusted for a variety of covariates, there remains the possibility of unmeasured confounding, such as area-level GDP and population density, which may lead to potential selection bias. Fifth, since the miscarriage rate is higher in earlier pregnancies, the wide range of gestation age at enrollment may poses a risk of selection bias. Sixth, as we are unable to recruit miscarriage cases from 6 gestational weeks ago, so the incidence rate will be slightly lower, and it will inevitably lead to selection bias.

Conclusions

In conclusion, lower SAB prevalence was related to higher levels of community greenness, especially among older and pregnant women who live in the

north of China, the PM_{2.5} and NO₂ may modify the effects of greenness on SAB. As global urbanization intensification, our findings have critical public health implications. However, to protect pregnant women from adverse birth outcomes, particularly in the north of China with rapid urbanization, it is important to further examine the positive benefits of greenness on SAB through well-designed longitudinal research.

Abbreviations

SAB	Spontaneous abortion
NDVI	The normalized difference vegetation index
EVI	The enhanced vegetation index
PM ₁	Particulate matter ≤ 2.5 μm
PM _{2.5}	Particulate matter ≤ 2.5 μm
PM ₁₀	Particulate matter ≤ 2.5 μm
NO ₂	Nitrogen dioxide
O ₃	Ozone
CBCS	The China Birth Cohort Study
NIR	Near infrared
CHAP	China High Air Pollutants
RMSE	Root mean squared error
SD	Standard deviation
BMI	Body mass index
CNY	China Yuan
HR	Hazard ratio
CI	Confidence interval
RSC	The restricted cubic spline
SGA	Small for gestational age
LBW	Low birth weight
PTB	Preterm birth

Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1186/s12302-024-00869-x>.

Additional file 1: Table S1. Distributions of environmental factors during first trimester (n=90 890). **Table S2.** Associations between NDVI in different buffers and SAB (n = 90 890). **Table S3.** Associations between greenness and SAB in sensitivity analyses. **Table S4.** Associations between greenness and SAB in sensitivity analyses. **Table S5.** Associations between greenness and SAB in sensitivity analyses. **Figure S1.** Flow chart of participant recruitment. **Figure S2.** Nonlinear associations between greenness and spontaneous abortion (SAB). **Figure S3.** Kaplan-Meier survival curves of NDVI_{500m} (log-rank test: P<0.001). **Figure S4.** Kaplan-Meier survival curves of EVI_{500m} (log-rank test: P<0.001).

Acknowledgements

We appreciate the cooperation of all participating subjects in this study who have been very generous with their time and assistance. Finally, we acknowledge the efforts of all who did the fieldwork.

Author contributions

YC: provided conception and design of research; acquisition, analysis, and interpretation of data; drafted the manuscript. SG: provided conception and design of research; acquisition, analysis, and interpretation of data; revised the manuscript. BY: provided conception and design of research; acquisition, analysis, and interpretation of data; revised the manuscript. WY: acquisition and analysis. SS: acquisition and interpretation of data. EZ: acquisition and analysis. JL: acquisition and interpretation of data. SX: acquisition and interpretation of data. YZ: revised the manuscript. ZZ: revised the manuscript. RL: provided conception and design of research; revised the manuscript. GD: provided conception and design of research; revised the manuscript. CY: provided conception and design of research; analysis, and interpretation of data.

Funding

This work was supported by the National Key Research and Development Program of China (2016YFC1000101), the National Natural Science Foundation of China (no. 81972992), the Guangzhou Science and Technology Project (no. 202201011545) and R&D Program of Beijing Municipal Education Commission (KM202310025006).

Availability of data and materials

The datasets generated and analyzed during the current study are not publicly available due the authors do not have access to the database.

Declarations

Ethics approval and consent to participate

The study was approved by the Ethics Committee of Beijing Obstetrics and Gynecology Hospital, Capital Medical University (2018-KY-003-02). Written informed consent was obtained from all participants.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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Received: 11 August 2023 Accepted: 15 February 2024

Published online: 20 February 2024

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