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Identifying the critical windows and joint effects of greenness and particulate matter exposures for preterm birth: a retrospective study across Guangdong Province in China from 2014 to 2018

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Abstract

Background Green space may have a wide range of beneficial health effects, but its association with preterm birth (PTB) remains inconclusive. Therefore, our study aims to investigate the effect of green space and its joint effect with particulate matter (PM) on PTB. Additionally, we seek to identify its critical susceptibility window.

Methods This retrospective study included 5,240,828 pregnant women in Guangdong Province from 2014 to 2018. Due to clustering among pregnant women, generalized estimating equations were used to examine the effects of green space and its joint effect with PM pollution on PTB, by using the normalized difference vegetation index (NDVI) and the fraction vegetation coverage (FVC) within 500 m and 1,000 m.

Results Green space can effectively reduce PTB risk, particularly in the first trimester. The odds ratio for PTB associated with NDVI throughout the pregnancy was 0.80 (95% CI: 0.70, 0.92) within 500 m and 0.81 (95% CI: 0.70, 0.93) within 1,000 m. When accounting for joint effects, high green space combined with low PM levels had the strongest protective effect, especially in the third trimester. On the other hand, the association between the FVC and PTB was similar to that between the NDVI and PTB. Additionally, green space helped mitigate PTB risk even in the areas with higher PM concentrations.

Conclusions Our finding enables us to create targeted approaches to increase exposure to green space during pregnancy. Furthermore, green spaces should be considered a beneficial factor in the decision-making process.

Keywords Preterm birth, Green space, Particulate matter, Joint effect, Critical window

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Introduction

Green space plays a significant role in the outdoor environment. Recent studies have shown that the presence of greenery can have an impact on various health issues. For instance, exposure to green space has been found to act as a protective factor against cardiovascular diseases. Additionally, an increase in residential green space has been associated with a reduced risk of mortality [1, 2]. Furthermore, a higher normalized difference vegetation index (NDVI)-500 m has been found to be strongly correlated with lower systolic blood pressure [3]. Moreover, increased exposure to green space has been shown to effectively decrease the probability of obesity [4]. The presence of greenery also has the potential to partially mitigate these adverse effects by providing the room for social and physical activities, and thus promoting a positive mood.

The condition of the fetus at birth, particularly whether it is preterm, significantly impacts its future growth. Preterm birth (PTB) is defined as the delivery of a live baby before the completion of 37 weeks of gestation. The World Health Organization estimates that approximately 15 million premature babies (born between 20 and 36 weeks) are delivered globally each year [5]. PTB is the leading cause of neonatal death [6]. Pregnancy is a sensitive period during which intrauterine exposures can influence fetal development and have long-term effects on offspring [7]. Previous studies have found that both extreme temperatures and high levels of pollutants can increase the incidence of PTB. Pregnant women are susceptible to environmental toxicants, and the fetuses are easily affected by toxicants due to their limited ability to detoxify exogenous compounds. The levels of air pollution exposure during pregnancy are associated with PTB and intrauterine stunting. At the same time, the level of air pollution could be affected by residential greening, as green space can reduce exposure to air pollution by filtering pollutants or toxic chemicals from the air, or by improving urban ventilation to increase the diffusion of pollutants [8]. Joint interventions for green space and air pollution during pregnancy may have more significant benefits than individual effect alone. Furthermore, the impact of exposure levels on PTB may vary during different stages of pregnancy [9]. Exploring the susceptibility window of exposure to PTB can help investigate potential mechanisms and guide for developing timely interventions. Therefore, it is necessary to identify the susceptibility window for green space exposure associated with PTB.

A population-based retrospective study was conducted, encompassing approximately 5.24 million singleton live births in 21 cities across Guangdong Province in China. Through the aforementioned information, this study aimed to explore how green space affected PTB, and identify the corresponding susceptibility windows to green space exposure and the potential joint effects of green space and particulate matter (PM) pollution during pregnancy.

Methods

Study population

We collected the data on births from all the 21 cities of Guangdong Province in China, from January 1, 2014 to December 31, 2018, using the database of the Guangdong Provincial Birth Registry System. In this registry system, birth information is acquired from all midwifery clinics and hospitals in GuangdongProvince. Dataset included birth date, maternal age, mode of delivery, birth weight, fetal outcome, neonate's sex, gestational age, number of pregnancies, number of deliveries, number of maternal births, and mother's residential address. We restricted our analyses to the births whose mothers were permanent residents living in Guangdong Province and vaginal delivery. The mother's home address was geocoded and ArcMap 10.8 software was used to check whether their address was in Guangdong Province. Our study population was selected based on the following eligibility criteria: singleton live births to mothers aged 16–50 years, with a gestational age between 22 and 40 weeks. To avoid "fixed cohort bias" [10], all pregnant women included in the study must have completed their pregnancy and given birth between 2014 and 2018. The flowchart of the study population is shown in Fig. S1. Approval to conduct the study was obtained from the institutional ethical committee of Guangdong Women and Children Hospital (Approval no 202401093).

Outcome and covariates

The outcome of our study was PTB, which was defined that the gestational age was less than 37 weeks. Our study considered the following covariates, maternal age: the mother's age was under 35 years old or at least 35 years old; neonate's sex: male or female; gravidity: Whether the mother has been pregnant before, yes or no; parity: whether the mother had given birth before, yes or no; birthing season: the season when the baby was born (spring: March-May; summer: June-August; autumn: September-November; winter: December-February) [11], we worked it out from the neonate's birth date.

Assessments of exposure

We utilized the NDVI and the fraction vegetation coverage (FVC) indicator as overall green space indicators. NDVI and FVC data were acquired from the Moderate Resolution Imaging Spectroradiometer (MODIS) vegetation indices, which have a spatial resolution of 250 m (https://data.tpdc.ac.cn/home). The name of the data set of NDVI is China Regional 250 m Normalized Difference

Vegetation Index Data Set (2000–2023); the name of the data set of FVC is China Regional 250 m Fractional Vegetation Cover Data Set (2000–2023). NDVI values range from − 1 to 1, with negative values meaning water bodies, close to zero meaning barren areas, and positive values meaning green vegetation. We restricted our data to the values bigger than 0 to disentangle the effects of green space from the potential effects of living near water. FVC data were calculated based on the NDVI, so there is a strong correlation between the NDVI and FVC. Our findings were primarily derived from NDVI analysis, and the FVC index can be utilized to validate the accuracy of the NDVI analysis results. Due to the small value range of NDVI and FVC, our study considered the impact on PTB for every 0.1 change in green space indices.

Exposure to PM is more evenly distributed in space compared to exposure to other pollutants, making it a useful proxy for an individual's overall exposure to various air pollutants [12]. In our study, we primarily focused on two types of air pollutants: $PM_{2.5}$ and PM_{10}, which were obtained from the ChinaHighAirPollutants (CHAP) datasets with a spatial resolution of 1 km (https://weijing-rs.github.io/product.html). Previous researches showed that the datasets have good predictability for $PM_{2.5}$ and PM_{10} with 10-fold cross-validation R^2's of 0.90 and 0.90, respectively [13–15]. The temperature data were derived from National Tibetan Plateau Scientific Data Center (https://zenodo.org/records/5502275), with R^2 range being 0.99 ~ 1.00. Then, we calculated the average near surface body temperature of pregnant women.

For all the exposures, we calculated an average for each woman throughout her pregnancy, and we also calculated the mean concentrations during each window period of pregnancy (the first trimester: 0–13 weeks, the second trimester: 14–27 weeks, and the third trimester: after 27 weeks) [16]. In this study, the research scope of environmental exposure is within 500 m and 1,000 m buffers around the pregnant women, which represent the areas within a 10 to 15-minute walking distance from the participants' homes [17, 18]. This is considered a practical and realistic range for daily exposure to environmental factors.

Statistical analysis

Spearman's rank correlation coefficient was used to test the correlation between NDVI and FVC to ensure that the results based on FVC could be utilized to verify the robustness of those based on NDVI. Compared to the traditional methods, the generalized estimating equations (GEE) model does not require the outcome variables to be independent. It can be suitable for discrete outcomes in regression and allows for the presence of clustering among individuals. Furthermore, GEE models the within-group correlations using a working correlation matrix, allowing for population-averaged effect estimates that reflect the overall association at the population level, not at the individual level. Note that our primary aim was to examine the overall relationship between green space exposure and preterm birth rather than to explore individual-level heterogeneity. At the same time, we found that previous studies have suggested using GEE models to examine the impact of outdoor air pollution on adverse pregnancy outcomes [16]. This approach accounts for multiple clustering levels of the data and minimizes the effect of spatial heterogeneity. To assess heterogeneity among preterm newborns across different districts or towns in Guangdong Province, Cochran's Q test was conducted, with statistical significance defined as $P < 0.05$. Additionally, the I^2 statistic was used to preliminarily quantify heterogeneity. The results indicated significant spatial heterogeneity in PTB across all study regions ($P < 0.05$, $I^2 > 90\%$). Therefore, the GEE model was selected for the analysis [19]. We employed the GEE logistic regression to compute odds ratios (ORs) and their corresponding 95% confidence intervals (CIs) to assess the effect estimates of PTB in relation to exposures. Continuous variables were dichotomized based on their median values in each study stage, for example, high NDVI: NDVI ≥ $P_{50_{NDVI}}$, and low NDVI: NDVI < $P_{50_{NDVI}}$. Therefore, green space variables and air pollutants variables were also converted into the combined categorical variables, such as low NDVI & high $PM_{2.5}$, low NDVI & low $PM_{2.5}$, high NDVI & high $PM_{2.5}$ and high NDVI & low $PM_{2.5}$, which produce a new variable, named NDVI & $PM_{2.5}$. These four-category variables were incorporated into the models to explore the joint effects of green space and PM pollutants. Besides, the models adjusted the influences of maternal age, neonate's sex, gravidity, parity, birthing season and temperature. We built the GEE model using the "GENMOD" procedure in SAS software (version 9.4). We determined the NDVI threshold based on the association between NDVI and PTB. Specifically, we identified the NDVI value corresponding to the average PTB rate in Guangdong Province from 2014 to 2018. When NDVI is higher than this threshold, the probability of PTB is lower than the provincial average, indicating a potential protective effect. Conversely, when NDVI is lower than this threshold, the risk of PTB increases.

In addition to the primary analyses, we conducted the following sensitivity analyses. In the first sensitivity analysis, a basic model including only green space, PM pollutants, and temperature was constructed to compare its results with those of the primary analysis. Further, to test the robustness of the impact of pollutants and the impact of other hybrid pollutants, two-pollutant models were established. Ozone (O_3) and nitrogen dioxide (NO_2) were added to the models in turn, with $PM_{2.5}$ as the representative of PM pollutants. In the third sensitivity analysis, stratified analyses were conducted based on maternal age (< 35 years or ≥ 35 years), neonate's sex (male or female), gravidity (yes or no), and parity (yes or no) to evaluate the potential modifying effects of these factors on the relationship between green space and PTB. Note that green space distribution varies across regions, and PTB occurrence may change over time and location. Bayesian spatiotemporal models account for spatial heterogeneity using random effects, enabling a more precise estimation of green space's impact on PTB [20]. So, the last sensitivity analysis, we used a Poisson-based Bayesian spatiotemporal model to analyze this relationship while considering spatial and temporal influences. In these sensitivity analyses, the exposure was measured within 500 m around pregnant women. The green space index NDVI and the PM pollutant factor $PM_{2.5}$ were selected.

Table 1 Descriptive characteristics of participants

Characteristics	Total (n = 5240828)	Preterm (n = 209014)	Non-Preterm (n = 5031814)
Gestational age (weeks, mean (SD))	39.18 (1.41)	34.97 (2.06)	39.36 (1.06)
Maternal age, n (%)			
< 35 years	4796513 (91.52)	183856 (87.96)	4612657 (91.67)
≥ 35 years	444315 (8.48)	25158 (12.04)	419157 (8.33)
Neonate's sex, n (%)			
Male	2741340 (52.31)	123679 (59.17)	2617661 (52.02)
Female	2470859 (47.15)	84032 (40.20)	2386827 (47.43)
Missing	28629 (0.55)	1303 (0.62)	27326 (0.54)
Gravidity, n (%)			
Yes	3052010 (58.24)	121127 (57.95)	2930883 (58.25)
No	1682737 (32.11)	70738 (33.84)	1611999 (32.04)
Missing	506081 (9.66)	17149 (8.20)	488932 (9.72)
Parity, n (%)			
Yes	2649919 (50.56)	103347 (49.45)	2546572 (50.61)
No	2091446 (39.91)	89044 (42.60)	2002402 (39.79)
Missing	499463 (9.53)	16623 (8.04)	482840 (9.60)
Birthing season, n (%)			
Spring	1264967 (24.14)	50361 (24.09)	1214606 (24.14)
Summer	1398909 (26.69)	55540 (26.57)	1343369 (26.70)
Autumn	1538014 (29.35)	58773 (28.12)	1479241 (29.40)
Winter	1038938 (19.82)	44340 (21.21)	994598 (19.77)

Results

Characteristics of participants and exposures

A total of 5,240,828 pregnant women were included in our analysis, of which 209,014 had PTB (3.99%). Table 1 shows the basic characteristics of participants. Most of the mothers were under 35 years old, accounting for 91.52%. The proportion of preterm pregnant women under 35 years old was lower than that of non-preterm pregnant women, accounting for 87.96% and 91.67%, respectively. Among the infants in preterm pregnancies, 59.17% were male and 40.20% were female. Compared with the non-preterm pregnancies, there is a large difference. It can be seen from the table that most pregnant women had gravidity and parity. Babies born in winter have an increased rate of PTB compared to normal babies. Figure 1 depicts the PTB rate in all the 21 cities of Guangdong Province. The map highlights that the four cities with the highest PTB rates-Guangzhou, Zhaoqing, Jiangmen, and Zhuhai, with the rates ranging from 4.55 to 5.05%, significantly exceeding the overall PTB rate.

Within 500 m buffers of pregnant women, the median levels of NDVI and FVC throughout the entire pregnancy were 0.337 and 0.436, respectively. In the PTB group, the median NDVI and FVC were 0.327 and 0.422, both lower than those in the non-preterm group (0.338 and 0.436, respectively). Table 2 summarizes the medians and the interquartile ranges of green space (NDVI and FVC), PM pollutants ($PM_{2.5}$ and PM_{10}), and temperature (TEMP) within 500 m buffers around each pregnant woman per year. It can be seen from Table 2 that from 2014 to 2018, the green space level of pregnant women in the first trimester, represented by NDVI and FVC, increased annually, whereas no such trend was observed in the second and third trimester.

Associations between green space and PTB

Spearman's rank correlation coefficient between NDVI and FVC was 0.98 ($P < 0.001$), indicating a strong positive correlation. Table 3 presents the associations between NDVI or FVC and PTB within the 500 m and 1,000 m buffers throughout the entire pregnancy or each trimester, which were all statistically significant, and the most affected period was the first trimester. Irrespective of $PM_{2.5}$ or PM_{10}, green space was a protective factor for PTB, and the effect sizes were similar, with all the P values being less than 0.001. Within 500 m, when the pollutant was $PM_{2.5}$, a 0.1 increase in NDVI was associated with an OR of 0.80 (95% CI: 0.70, 0.92) throughout pregnancy and 0.75 (95% CI: 0.72, 0.78) in the first trimester. Similar results were observed for FVC, and findings remained stable at the 1,000 m buffer.

The joint effect of green space and PM pollution on PTB throughout the entire pregnancy and three window periods within 500 m of the pregnant woman is

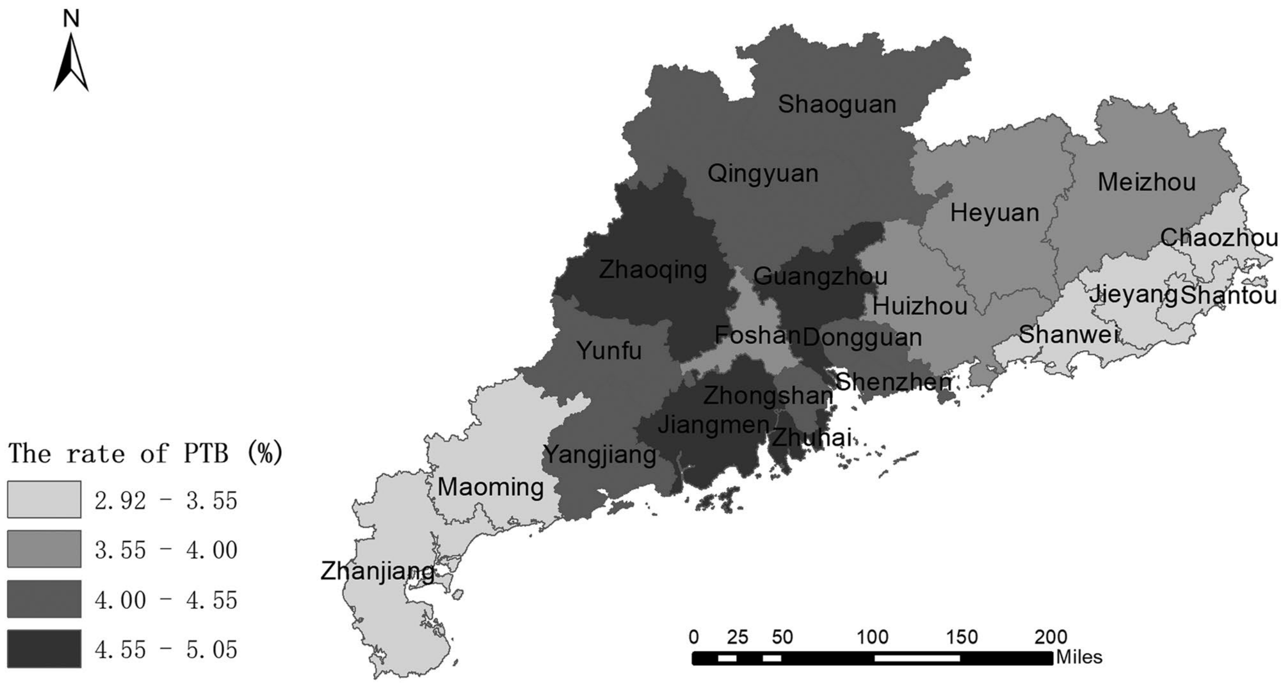

Fig. 1 PTB rate in all the 21 cities of Guangdong Province

illustrated in Fig. 2, while results for the 1,000 m buffer are shown in Fig. 3. In the joint effect analysis, the reference category was low green space combined with high PM levels. All the results were statistically significant ($P < 0.01$) throughout the entire pregnancy. Regardless of the pregnancy period, the joint exposure to high green space and low PM levels had lower OR values compared to other categories, indicating that it more effectively reduces the probability of PTB occurrence. When exploring the joint effect of NDVI and PM_{10} within 500 m, the ORs for low green space and low PM_{10} were 1.06 (95% CI: 1.01, 1.11) in the first trimester, 1.11 (95% CI: 1.05, 1.17) in the second trimester, and 0.81 (95% CI: 0.76, 0.87) in the third trimester, suggesting the third trimester as a susceptibility window. Similar patterns were observed for FVC, with consistent results at the 1,000 m buffer.

To identify a potential protective threshold for NDVI, we estimated the NDVI values corresponding to the average PTB rate (3.99%). Figs. S2 and S3 show the dose-response curves of NDVI and the predicted probability of PTB in the ranges of 500 m and 1,000 m around the residence of the pregnant woman, respectively. Within 500 m, the model-predicted PTB rate matched the provincial average when NDVI = 0.164. If NDVI was lower than 0.164, the predicted PTB risk was higher than the average, whereas NDVI above this threshold was associated with a lower risk. Similarly, within 1,000 m, the corresponding threshold was NDVI = 0.186, with lower values linked to increased risk and higher values associated with reduced risk. These results suggest that maintaining NDVI above 0.164–0.186 in residential areas may help lower the risk of PTB.

Sensitivity analyses

Four sensitivity analyses were conducted in this study. In the first sensitivity analysis, Table S1 displays the association between NDVI and PTB only adjusted by $PM_{2.5}$ and temperature within 500 m, and the corresponding joint effect results of NDVI and $PM_{2.5}$ on PTB are shown in Fig. S4. From Table S1, we found that for every 0.1 increase in the mean NDVI, the OR value was 0.75 (95% CI: 0.65, 0.86) during the entire pregnancy, with the first trimester being the most affected period. The joint exposure of high NDVI and low $PM_{2.5}$ levels can more effectively reduce the probability of PTB events. The model's robustness confirmed that green space consistently protected against PTB.

The results of adding O_3 and NO_2 sequentially in the second sensitivity analysis are shown in Table S2. We found that when O_3 and NO_2 were added in the model successively, the corresponding OR values were 0.80 (95% CI: 0.70, 0.92) and 0.81 (95% CI: 0.71, 0.93), and there was no significant change compared to our primary analysis (Table 3). Green space remained a protective factor for PTB. The susceptibility window of green space to PTB was still the first trimester.

The third sensitivity analysis stratified by maternal age, neonate's sex, gravidity, and parity (Table S3) showed that green space had a stronger protective effect against PTB in male infants and pregnant women with gravidity or

Table 2 Basic characteristics of exposures within 500 m buffers around each mother's residence each year

Year	Period	NDVI			FVC			$PM_{2.5}$ (μg/m³)			PM_{10} (μg/m³)			TEMP (∘C)		
		25th	50th	75th	25th	50th	75th	25th	50th	75th	25th	50th	75th	25th	50th	75th
2014	Trimester1	0.260	0.303	0.373	0.322	0.378	0.481	32.97	39.73	45.55	53.77	60.17	68.85	18.48	20.66	22.32
	Trimester2	0.286	0.347	0.476	0.363	0.443	0.639	20.75	24.10	28.13	41.43	46.37	49.93	28.05	28.65	29.09
	Trimester3	0.305	0.369	0.467	0.394	0.481	0.627	36.08	43.10	49.50	60.83	68.63	76.30	21.21	25.37	27.07
	Entire Pregnancy	0.284	0.345	0.434	0.364	0.437	0.584	32.27	34.84	39.04	54.40	58.45	62.56	23.78	24.37	24.85
2015	Trimester1	0.260	0.323	0.436	0.325	0.417	0.572	30.03	38.08	47.30	50.20	59.70	71.87	18.87	22.38	27.42
	Trimester2	0.269	0.341	0.448	0.335	0.441	0.585	25.27	36.83	46.20	42.83	58.03	70.07	18.98	25.04	27.94
	Trimester3	0.278	0.352	0.460	0.349	0.457	0.605	26.30	33.23	42.03	43.93	52.43	64.58	19.52	25.01	27.75
	Entire Pregnancy	0.278	0.333	0.460	0.351	0.428	0.582	33.32	36.85	40.66	53.42	58.55	63.12	22.22	23.03	24.12
2016	Trimester1	0.269	0.337	0.442	0.336	0.437	0.576	28.30	33.03	36.93	45.23	51.00	56.38	18.19	22.17	27.31
	Trimester2	0.275	0.337	0.439	0.356	0.451	0.596	25.25	31.40	35.55	42.53	48.95	54.55	18.68	25.81	28.11
	Trimester3	0.279	0.344	0.445	0.365	0.459	0.600	25.93	31.23	35.37	42.90	48.67	54.35	18.88	24.73	27.81
	Entire Pregnancy	0.283	0.336	0.436	0.369	0.442	0.581	28.48	31.22	34.09	45.60	49.35	53.28	21.86	22.75	23.92
2017	Trimester1	0.281	0.343	0.444	0.367	0.458	0.593	26.07	33.23	39.08	43.73	52.97	61.55	19.47	22.66	27.75
	Trimester2	0.288	0.350	0.456	0.364	0.455	0.594	24.15	32.05	38.58	41.70	51.33	59.95	19.46	24.24	27.43
	Trimester3	0.283	0.346	0.450	0.358	0.451	0.587	24.17	31.57	39.57	42.00	51.97	61.83	18.86	23.97	27.57
	Entire Pregnancy	0.290	0.341	0.451	0.374	0.440	0.594	29.38	32.20	35.73	47.78	51.92	56.92	22.27	23.21	24.10
2018	Trimester1	0.296	0.352	0.456	0.377	0.461	0.594	26.40	34.38	40.55	45.70	55.63	62.75	18.62	22.37	27.47
	Trimester2	0.279	0.331	0.437	0.352	0.425	0.567	22.93	36.20	43.15	41.23	56.95	64.70	17.09	19.70	26.97
	Trimester3	0.281	0.337	0.445	0.350	0.429	0.579	22.40	27.15	32.70	40.10	47.10	54.67	21.93	24.97	27.18
	Entire Pregnancy	0.289	0.338	0.449	0.366	0.434	0.583	29.41	32.36	35.87	48.90	52.70	56.99	21.83	22.45	23.35

Table 3 Associations between NDVI or FVC and PTB within 500 m and 1,000 m buffers in four periods. [a]

PM	Period	NDVI		FVC	
		OR (95% CI)	P	OR (95% CI)	P
Buffer-500 m					
$PM_{2.5}$	Trimester 1	0.75 (0.72, 0.78)	< 0.001	0.81 (0.78, 0.83)	< 0.001
	Trimester 2	0.87 (0.84, 0.90)	< 0.001	0.90 (0.88, 0.92)	< 0.001
	Trimester 3	0.86 (0.83, 0.89)	< 0.001	0.89 (0.87, 0.92)	< 0.001
	Entire pregnancy	0.80 (0.70, 0.92)	0.002	0.86 (0.77, 0.95)	0.005
PM_{10}	Trimester 1	0.72 (0.68, 0.76)	< 0.001	0.78 (0.75, 0.81)	< 0.001
	Trimester 2	0.85 (0.82, 0.88)	< 0.001	0.88 (0.86, 0.91)	< 0.001
	Trimester 3	0.84 (0.80, 0.88)	< 0.001	0.88 (0.85, 0.91)	< 0.001
	Entire pregnancy	0.74 (0.63, 0.87)	< 0.001	0.81 (0.71, 0.91)	< 0.001
Buffer-1,000 m					
$PM_{2.5}$	Trimester 1	0.72 (0.69, 0.76)	< 0.001	0.79 (0.76, 0.82)	< 0.001
	Trimester 2	0.86 (0.83, 0.89)	< 0.001	0.89 (0.87, 0.91)	< 0.001
	Trimester 3	0.86 (0.82, 0.89)	< 0.001	0.89 (0.86, 0.91)	< 0.001
	Entire pregnancy	0.81 (0.70, 0.93)	0.003	0.85 (0.77, 0.95)	0.004
PM_{10}	Trimester 1	0.69 (0.65, 0.73)	< 0.001	0.77 (0.73, 0.80)	< 0.001
	Trimester 2	0.84 (0.81, 0.88)	< 0.001	0.88 (0.85, 0.90)	< 0.001
	Trimester 3	0.84 (0.80, 0.87)	< 0.001	0.87 (0.85, 0.90)	< 0.001
	Entire pregnancy	0.76 (0.64, 0.89)	< 0.001	0.81 (0.72, 0.92)	0.001

[a] The models were adjusted by maternal age, neonate's sex, gravidity, parity, birthing season and temperature

parity. Across all strata, the first trimester remained the most sensitive period.

The results of the sensitivity analysis based on the Bayesian spatiotemporal model are shown in Fig. S5. The figure presents the posterior probability density of the effect of NDVI on PTB. We found that when the effect size of NDVI was −0.05, the posterior probability density reached its peak, with a corresponding relative risk of 0.95 (95% CI: 0.92, 0.98) ($P < 0.05$). This sensitivity analysis further confirms that green space is a protective factor against PTB, supporting the reliability of our results.

Discussion

In this study, we investigated how green space affected PTB, and explored the susceptibility window period of green space for PTB to determine the best time for pregnant women to engage in outdoor activities. We analyzed the data from 5,240,828 singleton live births in Guangdong Province, and we found that an increase in residential green space within 500 m and 1,000 m around pregnant women, measured by NDVI and FVC, is associated with a reduced incidence rate of PTB. All the three periods of pregnancy are susceptible windows for PTB events when exposing to green space, and the most affected period is the first trimester. On the other hand, taking the category of low green space and high PM levels as reference, the joint effect of high green space (NDVI and FVC) and low PM ($PM_{2.5}$ and PM_{10}) levels could decrease the probability of PTB throughout the entire pregnancy. This protective impact of the joint exposure was most influential in the third trimester. These association analyses were conducted by adjusting the factors, maternal age, neonate's sex, the mother's gravidity, the mother's parity, the birthing season, and temperature.

Current conclusions regarding the relationship between green space and PTB are inconsistent. Some studies found no correlation between green space and PTB [21–23], but there was heterogeneity among the studies in the meta-analysis. However, most research supports a negative correlation between green space and PTB [18, 24–26]. In 2014, Hystad et al. [24] utilized newborn data in Vancouver and found that a 0.1 increase in NDVI was associated with an OR of 0.91 (95% CI: 0.77, 1.07) for severe PTB and 0.95 (95% CI: 0.91, 0.99) for moderate PTB after adjusting for environmental exposures. In 2021, Lee et al. [25] conducted a study on the association between NDVI affected by pollutants and pregnancy outcomes. The results demonstrated that during the first and third trimesters, an increase in NDVI is associated with a reduced risk of PTB. The OR values are 0.93 (95% CI: 0.89, 0.97) and 0.94 (95% CI: 0.90, 0.98) for the first and third periods, respectively. Their findings are similar to ours.

The relationship between green space and air pollution is intricate. Studies that did not take their joint exposures into account may overestimate the impact of a single exposure [27]. Our study suggests that the joint effect of high green space and low PM levels more effectively reduces PTB risk. In 2020, Sun et al. [28] explored the correlation between the green space index NDVI and pregnancy outcomes in the presence of air pollutants (O_3, NO_2, and $PM_{2.5}$). They discovered that an increase in NDVI could decrease the probability of PTB, and the joint effect of high NDVI and low air pollutants levels were beneficial for PTB during pregnancy. These are similar to our findings, even though the pollutants differ in our study, because the PM pollutants can serve as a representative measure for all the pollutant levels.

Some periods during pregnancy may be more critical than others to prevent adverse pregnancy outcomes. Identifying these critical windows will help us better

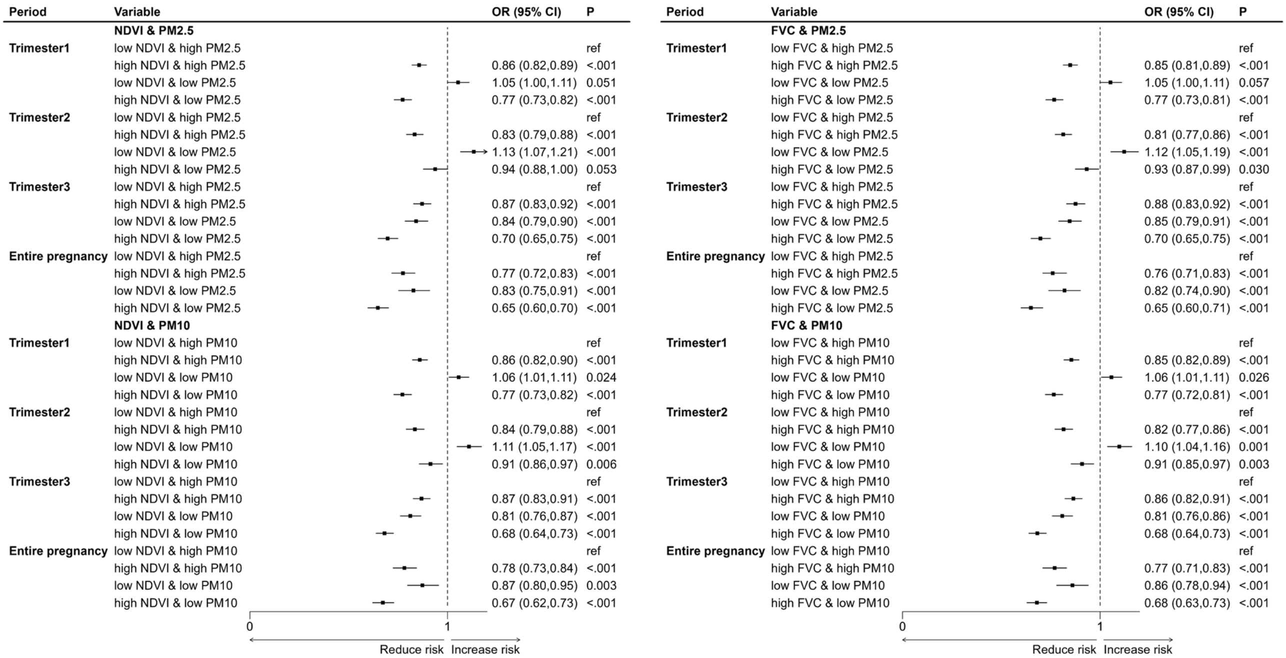

Fig. 2 The joint effects of the new variables on PTB within 5,00 m in four periods. Models were constructed by green index (NDVI or FVC), PM pollutants ($PM_{2.5}$ or PM_{10}), and adjusted the influences of maternal age, neonate's sex, gravidity, parity, birthing season and temperature. high NDVI: NDVI ≥ $P_{50_{NDVI}}$, and low NDVI: NDVI < $P_{50_{NDVI}}$; high FVC: FVC ≥ $P_{50_{FVC}}$, and low FVC: FVC < $P_{50_{FVC}}$; high PM2.5: $PM_{2.5}$ ≥ $P_{50_{PM_{2.5}}}$, and low PM2.5: $PM_{2.5}$ < $P_{50_{PM_{2.5}}}$; high PM10: PM_{10} ≥ $P_{50_{PM_{10}}}$, and low PM10: PM_{10}< $P_{50_{PM_{10}}}$

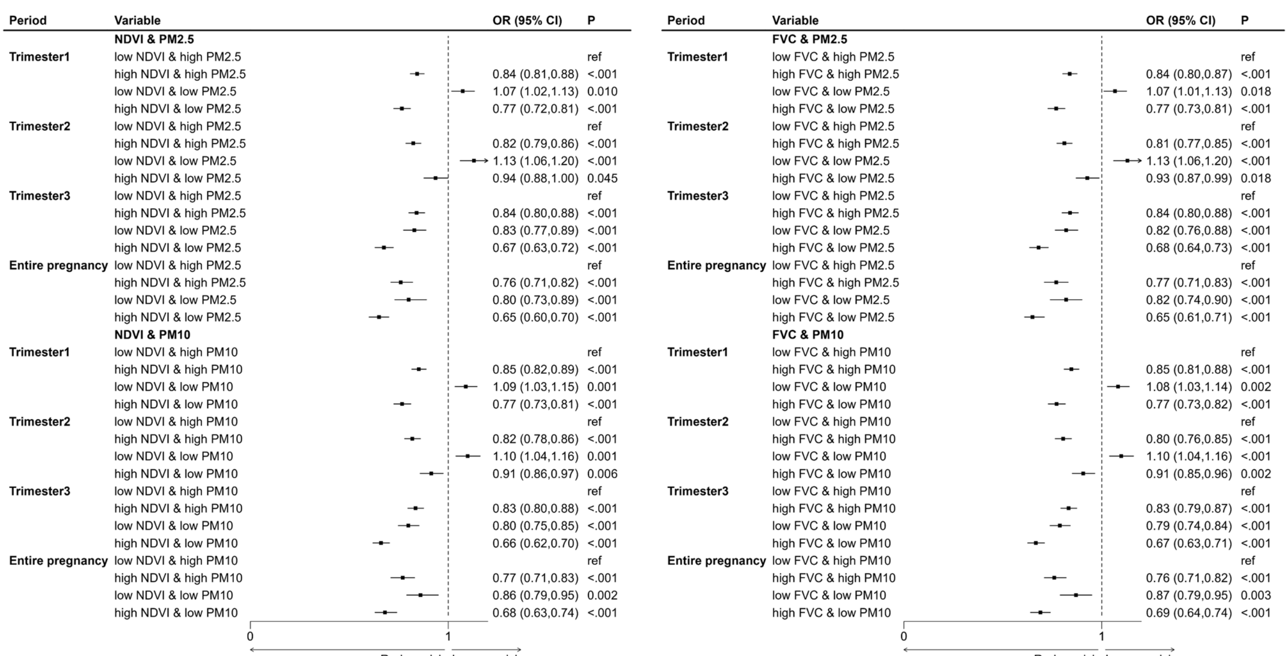

Fig. 3 The joint effects of the new variables on PTB within 1,000 m in four periods. Models were constructed by green index (NDVI or FVC), PM pollutants ($PM_{2.5}$ or PM_{10}), and adjusted the influences of maternal age, neonate's sex, gravidity, parity, birthing season and temperature. high NDVI: NDVI ≥ $P_{50_{NDVI}}$, and low NDVI: NDVI < $P_{50_{NDVI}}$; high FVC: FVC ≥ $P_{50_{FVC}}$, and low FVC: FVC < $P_{50_{FVC}}$; high PM2.5: $PM_{2.5}$ ≥ $P_{50_{PM_{2.5}}}$, and low PM2.5: $PM_{2.5}$ < $P_{50_{PM_{2.5}}}$; high PM10: PM_{10} ≥ $P_{50_{PM_{10}}}$, and low PM10: PM_{10}< $P_{50_{PM_{10}}}$

understand the underlying biological mechanisms and develop targeted preventive interventions [29]. In our study, we found that higher level of green space was negatively correlated with PTB throughout the pregnancy. Although the green space was a susceptible factor for PTB events in all the three trimesters, its impact was the greatest in the first trimester. The first trimester is a crucial period for embryonic and fetal development, and access to green space may have a protective effect on fetal growth by alleviating maternal stress and inflammatory responses [30, 31].

The environment we live in is complex, and it is impossible to be exposed to any single environmental factor alone. Therefore, it is important to simultaneously study the effects of multiple factors on health outcomes. Previous studies have found that the joint effect of pollutants and extreme temperatures increases the probability of PTB occurrence [32, 33]. As the PM can be indicative of pollutant levels [12], we conducted a study on the impact of the combination of green space and PM pollutants on the probability of PTB events. Our findings displayed that the joint exposure of high green space and low PM levels is effective in reducing PTB events throughout the pregnancy, with the effect being the most pronounced in the third trimester. This is not contradictory to the earlier finding that the first trimester is the sensitive window for the effect of green space on PTB. This precisely demonstrates that the complexity of environmental influences on maternal health, offering important evidence for further research into the mechanisms of complex environmental factors.

Several mechanisms have been proposed to explain the correlation between green space and birth outcomes, including reducing harmful environmental exposure, facilitating social interaction, providing space for physical activity, alleviating psychological stress, and creating an environment with psychological benefits, such as enhanced social connections and a sense of community [34–38]. All of these may provide better intrauterine environment for fetal growth by improving fetal oxygenation. Green space can improve the functioning of the immune system, promote moderate physical activity, and alleviate anxiety and stress, thereby avoiding frequent and sustained activation of the hypothalamic-pituitary-adrenal axis, and further reducing the levels of reactive oxygen species or oxidative stress byproducts in the blood of the mother and the fetus [26, 28].

Our study covered 5,240,828 single live births in all the 21 cities of Guangdong Province during 5 years, and the sample size was large enough to increase the reliability and the applicability of our analysis results. The single impact of green space is most significant during the first trimester. However, due to the complexity of the environment, the joint effects of green space and pollutants indicate that the third trimester is a critical period of susceptibility. This finding is not contradictory; rather, it highlights the importance of studying how complex environmental factors affect the health of pregnant women. At the same time, it also provides evidence for the mechanism study of the influence of complex environment on the health of pregnant women. Based on the results of this study, it is advisable to increase outdoor activities during pregnancy, especially in the third trimester. We also suggested that the government should expand the coverage of green spaces while ensuring economic development, and more sport equipment can also be built near residents to attract people to do more outdoor activities.

In this study, we found a statistically significant association between green space exposure and the risk of preterm birth, although the effect size was relatively small (e.g., OR close to 0.80). It is important to note that preterm birth is primarily influenced by maternal health conditions, such as gestational hypertension and gestational diabetes, which are internal factors. In contrast, environmental exposures, such as green space coverage, act as external factors that may contribute to the risk of preterm birth but are not the primary determinants. Therefore, observing an OR of approximately 0.80 is reasonable and aligns with the effect sizes commonly reported in environmental health studies. From a clinical perspective, even a small reduction in risk can lead to meaningful improvements at the population level. From an environmental and public health perspective, the benefits of green space exposure are especially significant because they offer a low-cost, long-term, and sustainable intervention. Unlike medical treatments, which may be costly and have potential side effects, increasing urban green space requires minimal individual effort and provides continuous benefits over time.

There are some limitations to this study. Firstly, we evaluated the environmental level among participants by considering their residential addresses. However, it is important to note that this measure may not accurately represent their exposure to environmentally friendly practices in their workplace or other frequently visited locations. Secondly, we assumed that the mother did not relocate during pregnancy. Thirdly, the mother's economic status is also a possible influencing factor, but we did not collect socioeconomic data, so we did not adjust economic effects at the individual level in this study. Finally, the psychological status of pregnant women may also affect PTB, but the examination of psychological impacts was not undertaken in our study. More researches are needed to validate our findings and to further explore the mechanisms behind the association between green space and pregnancy outcomes in future.

Conclusions

This study provided the evidence for the associations of the joint exposure to green space and PM pollutants ($PM_{2.5}$ or PM_{10}) with PTB based on a large population sample. We found that green space exposure during pregnancy was a protective factor for PTB events. We also found that the joint exposure of high green space and low PM levels was more effective in reducing the probability of PTB events during pregnancy when taking the category of low green space and high PM levels as reference, with the most effective in the third trimester. These findings may have public health reference that, pregnant women should take more beneficial outdoor exercises when there are more green space and less air pollution.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12889-025-22890-2.

Supplementary Material 1

Author contributions

Zhijiang Liang: Resources, Investigation, Project administration, Methodology. Fan-Shuo Meng: Formal analysis, Software, Writing - original draft, Methodology. Yi Zhang: Methodology, Validation, Software. Jialing Qiu: Writing - review & editing, Validation. Lulu Xie: Investigation, Data curation, Visualization. Qian Yao: Validation, Visualization. Xianqiong Luo: Conceptualization, Resources, Supervision, Project administration. Ji-Yuan Zhou: Writing - review & editing, Funding acquisition, Supervision, Data curation, Validation, Project administration. All authors read and approved the final manuscript.

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Data availability

Some of the datasets analyzed during the current study are available in this website (https://data.tpdc.ac.cn/home), but the authors do not have permission to share data about pregnant.

Declarations

Ethical approval

Approval to conduct the study was obtained from the institutional ethical committee of Guangdong Women and Children Hospital (Approval no 202401093).

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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