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Urban green space landscape patterns and preterm birth: a multicenter cohort study of over one million births in Chengdu, China

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ABSTRACT

While the health benefits of urban green spaces for perinatal outcomes are established, evidence on how landscape configuration relates to preterm birth (PTB) and its subtypes remains limited. We estimated associations between landscape metrics of urban green space and PTB risk, and quantified potential mediating effects of ambient temperature and fine particulate matter ($PM_{2.5}$). We conducted a retrospective cohort study of 1,058,772 singleton live births in Chengdu, China (2014-2022). For each participant, we characterized green space within a 2-km residential buffer using three metrics: total area (TA), patch density (PD; fragmentation), and landscape shape index (LSI; morphological complexity). Multilevel logistic regression models were used to estimate associations with overall, early, and late PTB. We also performed stratified and mediation analyses to assess effect modification and indirect effects. Increases in TA and LSI were associated with reduced overall PTB risk (TA: odds ratios [OR] = 0.98, 95% confidence interval [CI]: 0.96-0.99 per 133.75-ha increase; LSI: OR = 0.98, 95% CI: 0.97-0.99 per 17.46-unit increase). These associations were primarily observed for late PTB. Mediation analyses revealed that $PM_{2.5}$ mediated 8.08% of the total effect of TA, 1.51% of PD, and 12.15% of LSI. The protective effects of TA and LSI were more pronounced in areas characterized by higher temperatures, lower $PM_{2.5}$, and higher ozone levels. Our results suggest that large and more morphologically complex green spaces may reduce PTB risk, partly through alleviating of air pollution and temperature, and highlight the importance of considering spatial configuration in urban planning for maternal health.

1. Introduction

Preterm birth (PTB), defined as delivery before 37 completed weeks of gestation, is a major global public health challenge (World Health Organization, 2023). It remains the leading cause of neonatal mortality, accounting for approximately 35% of neonatal deaths worldwide, and is a major contributor to long-term childhood morbidity (Chawanpaiboon et al., 2019; Liu et al., 2016). Children born preterm face an elevated risk of lifelong complications, including neurocognitive developmental disorders, visual or auditory impairments, and chronic diseases, such as hypertension and type 2 diabetes (Saigal and Doyle, 2008). Globally, PTB affects approximately 11% of live births (Chawanpaiboon et al., 2019). In China, the incidence has risen from 5.9% in 1998 to nearly 10% in recent years, imposing a significant strain on both medical resources and families (Liang et al., 2024). As progress toward the United Nations Sustainable Development Goal 3.2 has

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slowed, identifying modifiable risk factors for PTB is of increasing urgency (Lincetto and Banerjee, 2020).

PTB has multifactorial origins involving genetic, sociodemographic, and behavioral factors. Maternal environmental exposures during pregnancy have attracted growing attention as potentially modifiable determinants of perinatal health. Exposure to fine particulate matter ($PM_{2.5}$) has been linked to increased risk of PTB risk, plausibly through mechanisms of oxidative stress and vascular endothelial injury in the placenta (Guo et al., 2018). Similarly, exposure to high ambient temperatures during pregnancy may increase the risk of PTB by inducing maternal dehydration and hormonal changes (Bekkar et al., 2020).

Urban green space has emerged as a promising upstream determinant of maternal and child health in rapidly urbanizing setting. Green spaces can improve air quality, mitigate urban heat island effects, and foster physical activity and mental well-being (Markevych et al., 2017; Yang et al., 2024; Jiang et al., 2025). Consistent with these mechanisms, a growing body of epidemiological evidence suggests that greater residential greenness during pregnancy is associated with lower risks of adverse birth outcomes, including PTB, low birth weight, and small for gestational age infants (Ye et al., 2024a; Luo et al., 2023; Ebisu et al., 2016).

Despite these advances, two important gaps remain. First, most existing studies have treated green space as a uniform exposure, typically measured with normalized difference vegetation index (NDVI) or overall green coverage, without considering how green spaces are distributed, connected, or shaped within the urban fabric (Holland et al., 2021). Second, findings for greenness and PTB have been inconsistent. Some studies reported lower PTB risk associated with greater green space (Ye et al., 2024a, 2024b; Sun et al., 2020; Wang et al., 2024a), whereas others found no association (Glazer et al., 2018; Abelt and McLafferty, 2017; Agay-Shay et al., 2014). These inconsistencies may partly reflect differences in exposure characterization, the failure to consider PTB subtypes, and the possibility that the health relevance of green space depends on its spatial configuration rather than quantity alone.

Landscape ecology theory provides a framework for addressing these limitations by emphasizing that the effects of green space depend not only on the amount of green space but also on its spatial arrangement, connectivity, and complexity (Nguyen et al., 2021). These spatial characteristics may influence maternal environmental exposures by modifying air pollutant dispersion (Lei et al., 2021), local thermal conditions (Yin et al., 2019), and accessibility for physical activity and stress reduction (Wang et al., 2024b), which are biologically relevant to PTB through pathways such as inflammation, oxidative stress, and endocrine disruption (Goldenberg et al., 2008). Therefore, the health effects of green space may depend not only on its quantity but also on how it is spatially organized within the urban environment.

From a public health perspective, it remains unclear whether a single large park provides similar health benefits as several smaller, well-distributed “pocket parks” of equivalent total area or whether irregularly shaped green spaces that increase edge interfaces may better facilitate cooling and air exchange. Although evidence from the United States suggests that greater connectivity and morphological complexity of green space are associated with lower risks of PTB (Wang et al., 2024a), empirical studies that explicitly evaluate multiple landscape configuration of green space on perinatal health outcomes and potential mediating pathways remains limited, particularly in rapidly developing Chinese cities.

Given that China's urbanization rate expected to reach 80% by 2050, ongoing urban expansion continues to threaten the integrity of urban green spaces. Understanding which green space landscape patterns are most beneficial for pregnancy outcomes is therefore critical for evidence-informed urban planning. To address these gaps, we conducted a large-scale, population-based cohort study of over one million births in Chengdu, China from 2014 to 2022. We estimated the associations between urban green space landscape metrics, including total area, patch density, and landscape shape complexity, and the risk of PTB and its subtypes, and we examined whether $PM_{2.5}$ and ambient air temperature mediated these associations. Our findings aim to clarify how green space configuration may influence PTB risk and to inform effective urban planning strategies to promote maternal and child health.

2. Methods

2.1. Study design and population

We conducted a multicenter birth cohort study using electronic medical records from 568 hospitals in Chengdu, Sichuan Province, China, from 2014 to 2022. Eligible participants were singleton live births with complete delivery records during the study period. To ensure clinical comparability, valid gestational classification, and accurate spatial exposure assessment, we applied the following exclusion criteria: (1) multiple gestations, due to their distinct etiology and substantially elevated baseline risk of PTB; (2) stillbirths or missing pregnancy outcomes; (3) gestational age <24 or >42 completed weeks, consistent with conventional definitions of viability and post-term birth in obstetric practice; (4) maternal age <15 years, to restrict the cohort to biologically plausible reproductive ages and avoid potential data anomalies; (5) invalid residential address or residence outside Chengdu's administrative boundaries, to ensure accurate linkage with high-resolution urban green space metrics; (6) rural residency; and (7) incomplete records for key variables, including education level ($n = 4$), folic acid supplementation ($n = 28$), and parity ($n = 121$). Given the negligible proportion of missingness (totaling less than 0.02% of the cohort), a complete-case analysis was employed, resulting in a final analytical sample of 1,058,772 singleton live births (Fig. S1a).

2.2. Environmental exposure assessment

Environmental exposures were assigned for each pregnancy within a 2-km circular buffer centered on the geocoded maternal residential address. This buffer was selected to represent the neighborhood environment relevant to daily maternal activities (McGinn et al., 2007; Zare Sakhvidi et al., 2025).

2.2.1. Urban green space landscape patterns

We quantified green space configuration using the fine-grained Urban Green Space product (UGS-1m) (Fig. S1b) (Shi et al., 2023a, 2023b). This dataset, generated from Google Earth imagery (2020) and supplementary cloud-free scenes, provides a 1.1 m resolution green space map for 31 Chinese cities. The UGS-1m product was developed using a deep learning framework (UGSNet) that integrates attention mechanisms and adversarial domain adaptation, enabling robust extraction of urban vegetation across diverse imaging conditions. The reported overall accuracy (87.56%) and an F1-score (74.86%) represent pixel-level classification performance compared with reference land-cover data, indicating high reliability in distinguishing green space from non-green space areas (Shi et al., 2023b). These metrics support the validity of the derived landscape metrics used in our exposure assessment.

Within each participant's 2-km buffer, we calculated three landscape metrics quantifying green space scale, fragmentation, and morphological complexity. Total area (TA), expressed in hectares (ha), quantifies the total area of green space within the buffer and represents the overall scale of green resources. Patch density (PD) is defined as the number of discrete green patches per 100 ha (patches/100 ha), reflecting the degree of fragmentation and dispersion. Landscape shape index (LSI) is a measure of the geometric complexity of green space boundaries, calculated as the ratio of patch perimeter to area, and is dimensionless. All metrics were calculated using Python-based geospatial processing workflows and linked to individual pregnancy records via residential geocodes.

2.2.2. Vegetation greenness

Since the UGS-1m dataset provides a static representation of landscape patterns in 2020 and does not reflect seasonal or interannual variability during 2014-2022, we additionally characterized vegetation greenness using the normalized difference vegetation index (NDVI) (range -1 to 1). NDVI were obtained from the Moderate Resolution Imaging Spectroradiometer Terra MOD13Q1 Version 6 product (250-m spatial, 16-day temporal resolution). For each participant, we calculated the mean NDVI value within the 2-km buffer across the entire pregnancy. This measure was used to partially account for temporal variability in vegetation greenness not captured by the static UGS-1m dataset.

2.2.3. Meteorological and air pollution data

Daily meteorological data were obtained from the ERA5-Land Daily Aggregated dataset (1-km resolution), including ambient temperature and relative humidity. Relative humidity was derived from 2-m air temperature and dew point temperature. Daily $PM_{2.5}$, ozone (O_3), and nitrogen dioxide (NO_2) concentrations were obtained from the ChinaHighAirPollution (CHAP) datasets (Wei and Li, 2024; Wei and Li, 2024a; Wei and Li, 2024b). These datasets are based on the integration of ground-based monitoring, satellite remote sensing products, and machine-learning algorithms, as described in the corresponding methodological studies (Wei et al., 2020, 2021, 2022a, 2022b, 2023). For each participant, we calculated average ambient temperature, relative humidity, $PM_{2.5}$, O_3, and NO_2 across the pregnancy within the residential 2-km buffer.

The UGS landscape metrics were derived from a 2020 high-resolution map and treated as time-invariant exposures, reflecting relatively stable neighborhood structural characteristics over the study period. In contrast, air pollution and meteorological variables were assigned using time-resolved datasets and averaged over each participant's pregnancy period. This ensured temporal alignment between environmental exposures and pregnancy-specific exposure windows, while preserving the high spatial resolution required for characterizing green space configuration.

2.3. Ascertain of health outcomes

The primary health outcome was PTB, defined as live birth occurring before 37 completed weeks of gestation. Gestational age was calculated based on the date of the last menstrual period and the confirmed date of delivery recorded in the medical record. We further categorized PTB into early (<34 weeks) and late PTB (34-36 weeks).

2.4. Covariates

Covariates were selected priori based on previous literature (Ma et al., 2025). The selected covariates included maternal age, paternal age, education level, ethnicity, pre-pregnancy Body Mass Index (BMI), folic acid supplementation, parity, infant sex, birth year, COVID period, and season of delivery. To account for potential direct or indirect impacts of the COVID-19 pandemic, we included a binary indicator for the COVID period (covering 2020-2022, with 2014-2019 as the reference period). Season of delivery was categorized as spring (March-May), summer (June-August), autumn (September-November), and winter (December-February).

2.5. Statistical analysis

We summarized demographic and environmental characteristics for the overall cohort and by outcome group (term birth, overall PTB, early PTB, and late PTB). Categorical variables were reported as n (%) and including maternal age (< 25, 25-29, 30-34, ≥ 35 years), education level (less than bachelor, bachelor or above), ethnicity (Han, others), pre-pregnancy BMI (< 18.5, 18.5-23.9, 24.0-27.9, ≥ 28 kg/m^2), folic acid supplementation (initiated before pregnancy, initiated during pregnancy, none), parity (nulliparous, primiparous, multiparous), infant sex (male, female), season of delivery (spring, summer, autumn, winter), and paternal age (<25, 25-34, ≥ 35 years). Continuous variables were summarized as mean with standard deviations (SD), including landscape metrics (TA, PD, LSI), pregnancy-average NDVI, temperature, relative humidity, and $PM_{2.5}$ concentrations.

We used multilevel mixed-effects logistic regression models to estimate associations between each urban green space landscape metric and the risk of PTB outcomes. Because participants were nested within administrative districts, we included a district-level random intercept to account for potential geographic clustering and unmeasured contextual heterogeneity. Each participant was assigned to a district based on residential geocoded coordinates using spatial overlay techniques. Each metric was modelled as a continuous exposure in separate models to avoid multicollinearity and to allow clear interpretation of their independent associations. Results were expressed as odds ratio (OR) with 95% confidence interval (CI) per interquartile range (IQR) increase.

In the crude model, only the landscape metric variable was included along with the district-level random intercept. In the fully adjusted model, we additionally adjusted for maternal characteristics (maternal age, education level, ethnicity, pre-pregnancy BMI, folic acid supplementation, and parity), infant sex, paternal age, season of delivery, birth year, COVID period, and average pregnancy exposures to NDVI, temperature, relative humidity, $PM_{2.5}$, O_3, and NO_2. NDVI was included to disentangle the effects of landscape configuration from overall greenness quantity. Multicollinearity was assessed using variance inflation factors, and all values were below 2, indicating no evidence of substantial multicollinearity. To examine the exposure-response relationship for the association between urban green space and the risk of PTB outcomes, we used restricted cubic spline models with three knots placed at the 10th, 50th and 90th percentiles of each landscape metric. Nonlinearity was assessed using Wald tests for the spline terms.

To evaluate potential effect modification, we examined whether the associations varied by maternal characteristics, folic acid, parity, season of delivery, infant sex, ambient temperature, $PM_{2.5}$, O_3, and NO_2 exposure. Temperature, $PM_{2.5}$, O_3, and NO_2 were dichotomized into "low" and "high" groups using the population median. Effect modification was formally assessed by including multiplicative interaction terms between each exposure and the subgroup variable in the fully adjusted models. Wald tests were used to evaluate the statistical significance of interaction terms. To account for multiple comparisons across all exposure-subgroup combinations, false discovery rate (FDR) correction was applied using the Benjamini-Hochberg procedure. Adjusted q-values <0.05 were considered statistically significant. For descriptive purposes, stratum-specific effect estimates were also calculated from the interaction models. Strata with fewer than 50 PTB cases were excluded to ensure estimate stability.

Considering the relevance of mediators to both green space exposure and PTB risk, as well as the stability and interpretability of the exposure-mediator relationship, we selected ambient temperature and $PM_{2.5}$ as mediators a priori. Pollutants primarily driven by local emission sources (e.g., NO_2) or characterized by secondary formation (e.g., O_3) were not considered suitable for mediation analysis.

We conducted causal mediation analyses using the "mediation" R package to quantify the potential indirect effects of temperature and $PM_{2.5}$. To reduce potential temporal mismatch between green space exposure and environmental mediators, the mediation analyses were restricted to births occurring between 2018 and 2022. Land-use patterns are commonly updated every five years, therefore restricting the analysis to this period. For each mediator, we fitted a linear regression model for the mediator (temperature or $PM_{2.5}$) and a logistic regression model for PTB outcomes that included the exposure (landscape metrics), the mediator, and covariates. The mediation analysis estimated the average causal mediation effect (ACME; indirect effect), average direct effect (ADE), total effect, and the proportion mediated, with 95% CIs obtained using nonparametric bootstrapping (n = 1000). All mediation models were adjusted for the same covariates as in the fully adjusted models, including co-adjustment for other environmental exposures to isolate the independent mediating effects of each pathway. Exposure-mediator interaction terms were not included in the mediation models; therefore, the estimated mediation effects represent population-average mediation effects across the study population.

2.6. Sensitivity analyses

We conducted several sensitivity analyses to assess the robustness of our findings. First, to reduce potential exposure misclassification arising from the use of a static green space map, we restricted the analysis to pregnancies occurring between 2019 and 2020, which most closely aligns with the UGS-1m reference year. Second, to assess the potential impact of this exposure misclassification, we performed a probabilistic bias analysis using Monte Carlo simulations: each landscape metric was randomly perturbed within ±10% to reflect plausible interannual variation, and logistic regression models were re-estimated 1000 times to generate distributions of effect estimates. Third, to identify potential critical windows of susceptibility, we replaced full-pregnancy average NDVI, temperature, relative humidity, $PM_{2.5}$, NO_2, and O_3 with trimester-specific averages (first, second, and third trimesters). Fourth, we examined possible heterogeneity by mode of delivery, classified as vaginal delivery or cesarean delivery.

3. Results

A total of 1,058,772 births in Chengdu between 2014 and 2022 were included in the final analysis, with an overall PTB prevalence of 4.90% (n = 51,837) (Table 1). Early PTB constituted 0.76% (n = 8013) and late PTB constituted 4.14% (n = 43,824) of the total cohort. Most mothers were aged 25-29 years old (44.44%), had an education below the bachelor's degree (74.96%), and identified as Han ethnicity (96.84%). PTB cases were more common among older mothers (≥ 35 years), multiparous women, and those with higher pre-pregnancy BMI. Mothers aged ≥ 35 years had the highest prevalence in the early PTB group (15.46%) compared to the late PTB group (13.98%) and the overall

Table 1
Summary characteristics of the study participants.

Characteristics	Total (n = 1058772)	Term birth (n = 1006935)	PTB (n = 51837)	Early PTB (n = 8013)	Late PTB (n = 43824)
Maternal age, year, n (%)					
<25	187048 (17.67)	179016 (17.78)	8032 (15.49)	1284 (16.02)	6748 (15.40)
25-29	470478 (44.44)	449898 (44.68)	20580 (39.70)	3031 (37.83)	17549 (40.04)
30-34	300819 (28.41)	284958 (28.30)	15861 (30.60)	2459 (30.69)	13402 (30.58)
≥ 35	100427 (9.49)	93063 (9.24)	7364 (14.21)	1239 (15.46)	6125 (13.98)
Education, n (%)					
Less than bachelor	793616 (74.96)	753960 (74.88)	39656 (76.50)	6107 (76.21)	33549 (76.55)
Bachelor or above	265156 (25.04)	252975 (25.12)	12181 (23.50)	1906 (23.79)	10275 (23.45)
Ethnicity, n (%)					
Han	1025307 (96.84)	975061 (96.83)	50246 (96.93)	7737 (96.56)	42509 (97.00)
Others	33465 (3.16)	31874 (3.17)	1591 (3.07)	276 (3.44)	1315 (3.00)
Pre-pregnancy BMI, kg/m^2, n (%)					
<18.5	154509 (14.59)	147241 (14.62)	7268 (14.02)	1100 (13.73)	6168 (14.07)
18.5-23.9	710809 (67.14)	677769 (67.31)	33040 (63.74)	5016 (62.60)	28024 (63.95)
24.0-27.9	154740 (14.62)	145864 (14.49)	8876 (17.12)	1451 (18.11)	7425 (16.94)
≥ 28	38714 (3.66)	36061 (3.58)	2653 (5.12)	446 (5.57)	2207 (5.04)
Folic acid, n (%)					
Initiated before pregnancy	273648 (25.85)	260432 (25.86)	13216 (25.50)	2039 (25.45)	11177 (25.50)
Initiated during pregnancy	735809 (69.50)	700029 (69.52)	35780 (69.02)	5485 (68.45)	30295 (69.13)
None	49315 (4.66)	46474 (4.62)	2841 (5.48)	489 (6.10)	2352 (5.37)
Parity, n (%)					
Nulliparous	621313 (58.68)	592622 (58.85)	28691 (55.35)	4364 (54.46)	24327 (55.51)
Primiparous	410288 (38.75)	389203 (38.65)	21085 (40.68)	3348 (41.78)	17737 (40.47)
Multiparous	27171 (2.57)	25110 (2.49)	2061 (3.98)	301 (3.76)	1760 (4.02)
Delivery season, n (%)					
Spring (March-May)	210682 (19.90)	200707 (19.93)	9975 (19.24)	1625 (20.28)	8350 (19.05)
Summer (June-August)	269979 (25.50)	256160 (25.44)	13819 (26.66)	2254 (28.13)	11565 (26.39)
Autumn (September-November)	335066 (31.65)	319438 (31.72)	15628 (30.15)	2361 (29.46)	13267 (30.27)
Winter (December-February)	243045 (22.96)	230630 (22.90)	12415 (23.95)	1773 (22.13)	10642 (24.28)
Infant sex, n (%)					
Female	511062 (48.27)	488455 (48.51)	22607 (43.61)	3500 (43.68)	19107 (43.60)
Male	547710 (51.73)	518480 (51.49)	29230 (56.39)	4513 (56.32)	24717 (56.40)
Paternal age, year, n (%)					
<25	98606 (9.31)	94258 (9.36)	4348 (8.39)	691 (8.62)	3657 (8.34)
25-34	756080 (71.41)	721268 (71.63)	34812 (67.16)	5241 (65.41)	29571 (67.48)
≥ 35	204086 (19.28)	191409 (19.01)	12677 (24.46)	2081 (25.97)	10596 (24.18)
Landscape metrics, mean (SD)					
Total area (ha)	274.92 (102.44)	275.06 (102.43)	272.23 (102.78)	272.15 (102.05)	272.25 (102.92)
Patch density (patches per 100 ha)	384.11 (308.28)	384.06 (314.59)	385.11 (136.99)	385.50 (135.75)	385.04 (137.22)
Landscape shape index	56.19 (13.51)	56.21 (13.51)	55.87 (13.63)	55.98 (13.60)	55.85 (13.63)
NDVI, mean (SD)					
Mean NDVI during pregnancy	0.42 (0.10)	0.42 (0.10)	0.43 (0.11)	0.43 (0.11)	0.43 (0.11)
Climate, mean (SD)					
Mean temperature during pregnancy (°C)	17.57 (1.72)	17.56 (1.70)	17.70 (2.20)	17.72 (2.63)	17.69 (2.11)
Mean relative humidity during pregnancy (%)	92.67 (0.77)	92.67 (0.76)	92.69 (0.85)	92.68 (0.95)	92.69 (0.83)
Air pollution, mean (SD)					
Mean $PM_{2.5}$ during pregnancy (μg/m^3)	48.94 (12.49)	48.98 (12.46)	48.03 (12.94)	47.45 (13.33)	48.14 (12.87)
Mean NO_2 during pregnancy (μg/m^3)	43.22 (8.82)	43.25 (8.80)	42.65 (9.09)	42.29 (9.10)	42.72 (9.08)
Mean O_3 during pregnancy (μg/m^3)	94.92 (11.24)	94.88 (11.11)	95.64 (13.52)	96.20 (15.96)	95.54 (13.03)

Note: PTB = preterm birth; n = number of counts; SD = standard deviation; NDVI = normalized difference vegetation index; $PM_{2.5}$ = fine particulate matter.

cohort (9.49%). Most women (69.50%) began folic acid supplementation during pregnancy; however, non-users were more prevalent in the PTB group (5.48%) compared to term births (4.62%), with the highest rate observed in the early PTB group (6.10%). Nulliparous women accounted for a smaller proportion of PTB (55.35%) than term births (58.85%), whereas multiparity was more prevalent among PTB cases (3.98%), particularly in the late PTB group (4.02%). Male infants constituted 51.73% of the cohort, with a slight overrepresentation among PTB cases (56.39%).

For the entire cohort, the mean values (within the 2-km buffer) were 274.92 ha for TA, 384.11 patches per 100 ha for PD, and 56.19 for LSI. PTB cases were exposed to marginally lower TA (272.23 ha) and LSI (55.87), but slightly higher PD (385.11 patches per 100 ha) and NDVI (0.43) compared to term births. The average exposure during pregnancy was 17.57 °C for ambient temperature, 92.67% for relative humidity, 48.94 $\mu g/m^3$ for $PM_{2.5}$, 43.22 $\mu g/m^3$ for NO_2, and 94.92 $\mu g/m^3$ for O_3. PTB cases generally experienced slightly higher ambient temperatures, relative humidity, and O_3 levels, and lower $PM_{2.5}$ and NO_2 concentrations.

Greater green space area and morphological complexity were associated with a reduced risk of overall PTB (Fig. 1). For overall PTB, in crude models, each IQR increase in TA (133.75 ha) and LSI (17.46 units) was associated with an OR of 0.98 (95% CI: 0.96-0.99) and 0.98 (95% CI: 0.96-1.00), respectively. After full adjustment for covariates, these associations remained robust (adjusted OR = 0.98, 95% CI: 0.96-0.99 per 133.75-ha increase in TA; adjusted OR = 0.98, 95% CI: 0.97-0.99 per 17.46-unit increase in LSI).

Regarding PTB subtypes, each 133.75-ha increase in TA and 17.46-unit increase in LSI was associated with reduced risk of late PTB (TA: adjusted OR = 0.98, 95% CI: 0.96-1.00; LSI: adjusted OR = 0.98, 95% CI: 0.97-1.00). For early PTB, greater TA was associated with a reduced risk in the crude model (OR = 0.96, 95% CI: 0.93-0.99 per 133.75-ha increase), but this association was attenuated after full adjustment. No significant associations were observed for PD (162.26 patches per 100 ha) across any PTB outcomes.

The exposure-response curves for TA showed a generally downward trend for overall PTB, early PTB, and late PTB (Fig. 2). Associations with PD were characterized by fluctuating patterns, with wide confidence bands for early PTB. For LSI, the curve for early PTB declined sharply at lower values (LSI <30) and then plateaued, whereas the curves for overall PTB and late PTB exhibited a modest inverted U-shaped pattern, with slightly elevated ORs at lower LSI levels (LSI <30) followed by a gradual decrease at higher values.

The associations of maternal exposure to TA, PD, and LSI with PTB were generally similar in magnitude and direction across maternal, infant, seasonal, and NO_2 subgroups (Fig. 3), with no statistically significant interaction after FDR correction. In contrast, temperature, $PM_{2.5}$, and O_3 showed significant interaction effects with landscape metrics after FDR correction. The associations of greater TA and LSI with lower risk of PTB were more pronounced at higher temperature (TA: OR = 0.95, 95% CI: 0.93-0.96 per 130.48-ha increase; LSI: OR = 0.97, 95% CI: 0.95-0.98 per 17.03-unit increase).

For $PM_{2.5}$, greater TA and LSI were associated with a reduced risk of PTB in the low $PM_{2.5}$ exposure group (TA: OR = 0.96, 95% CI: 0.94-0.97 per 142.65-ha increase; LSI: OR = 0.97, 95% CI: 0.95-0.99 per 17.23-unit increase), whereas, greater PD (OR = 1.03, 95% CI: 1.02-1.05 per 154.99 patches/100-ha increase) were associated with an increased risk of PTB. Similar interaction patterns were observed for O_3 exposure. Under higher O_3 levels, each 131.49-ha increase in TA and 17.09-unit increase in LSI were associated with a lower risk of PTB (TA: OR = 0.96, 95% CI: 0.94-0.98; LSI: OR = 0.98, 95% CI: 0.97-1.00), whereas greater PD was associated with an increased risk (OR = 1.04, 95% CI: 1.02-1.05 per 154.77 patches/100-ha increase).

Mediation analysis identified contrasting pathways for $PM_{2.5}$ and temperature (Table 2). For overall PTB, $PM_{2.5}$ served as a significant partial mediator, explaining 8.08% (95% CI: 3.11%-13.20%) of the TA effect, 12.15% (95% CI: 4.94%-20.84%) of the LSI effect, and 1.51% (95% CI: 0.81%-2.91%) of the PD effect. For late PTB, $PM_{2.5}$ explained 7.32% (95% CI: 2.29%-12.87%) for TA and 10.32% (95% CI: 2.98%-18.92%) for LSI. No statistically significant $PM_{2.5}$ mediation was observed for early PTB.

Ambient temperature exhibited a suppressor pattern in the mediation models. Although landscape metrics were positively associated with temperature (Table S1), higher temperature was associated with increased PTB risk, resulting in negative mediated proportions for TA and LSI. This pattern indicates that the protective associations of green space would be even stronger after accounting for the temperature pathway.

Sensitivity analyses supported the robustness of the observed associations. First, restricting analyses to 2019-2020 yielded results consistent with the main analysis, with stronger associations for TA, PD, and LSI (Table S2). Second, the Monte Carlo simulations showed that the estimated associations were robust to plausible temporal exposure misclassification. For example, for TA and PTB, the original OR per IQR increase was 0.976, and the simulated ORs ranged from 0.971 to 0.975 (2.5th-97.5th percentile). Similar stability was observed for PD, LSI, and

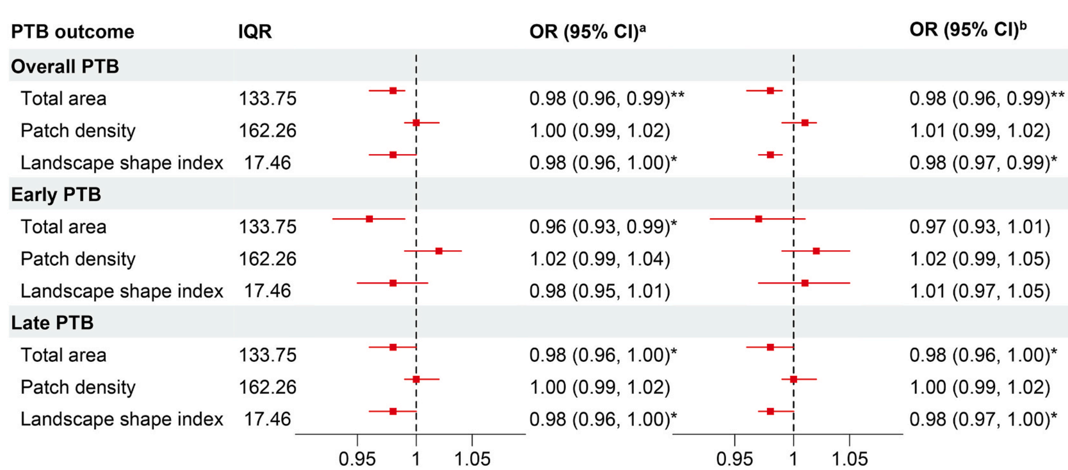

Fig. 1. Associations between urban green space landscape metrics and preterm birth outcomes.Note: PTB = preterm birth; OR = odds ratio; IQR = interquartile range; CI = confidence interval.All ORs and 95% CIs are expressed per IQR increase, with specific numerical values shown in the "IQR" column. The units for these IQR values are as follows: total area (hectares), patch density (patches per 100 ha), and landscape shape index. [a] Models were only adjusted for landscape metrics. [b] Models were additionally adjusted for maternal age, education level, ethnicity, pre-pregnancy BMI, folic acid supplementation, parity, infant sex, paternal age, season of delivery, birth year, COVID period, and average pregnancy exposures to NDVI, temperature, relative humidity, $PM_{2.5}$, O_3, and NO_2.

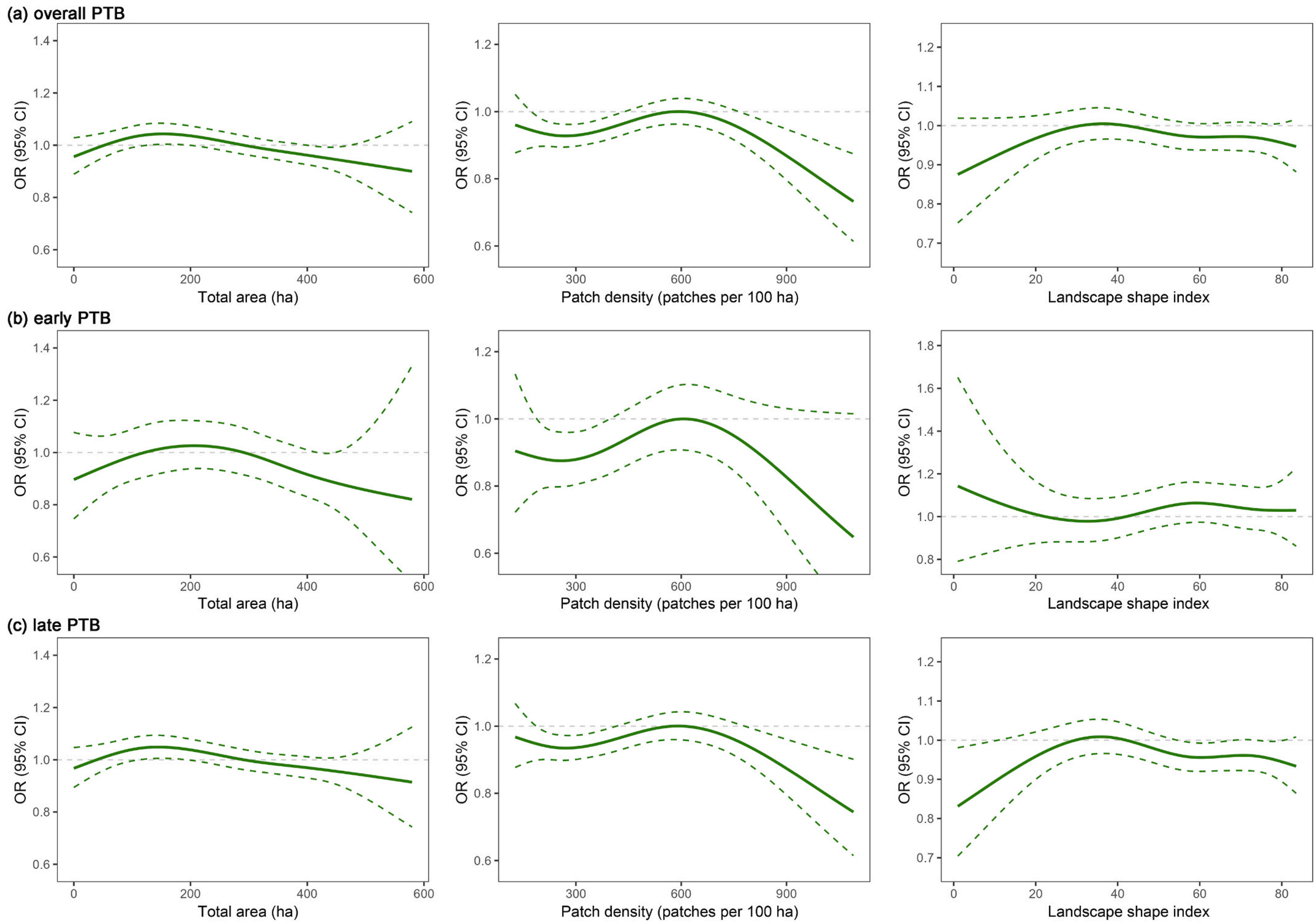

Fig. 2. Exposure-response relationships between landscape metrics and preterm birth outcomes. Note: PTB = preterm birth; OR = odds ratio; CI = confidence interval. Curves were estimated using fully adjusted logistic regression models, adjusting for maternal age, education level, ethnicity, pre-pregnancy BMI, folic acid supplementation, parity, infant sex, paternal age, season of delivery, birth year, COVID period, and average pregnancy exposures to NDVI, temperature, relative humidity, $PM_{2.5}$, O_3, and NO_2.

all outcomes (Table S3). Third, adjusting for trimester-specific exposures produced similar estimates, with greater TA and LSI consistently associated with a reduced PTB risk across all trimesters (Table S4). Fourth, the associations for TA and LSI were consistent across vaginal and cesarean deliveries (Table S5).

4. Discussion

In this large-scale cohort study of over one million births in Chengdu, we advanced beyond traditional greenness quantity metrics and showed that the spatial configuration of urban green space plays a critical role in maternal health. Specifically, we found that both greater green space area and higher morphological complexity were associated with reduced risks of overall PTB and late PTB. These effects were more pronounced at higher ambient temperatures, higher O_3 levels, and lower $PM_{2.5}$ levels. Mediation analyses further revealed that the effects of green space landscape metrics were partially mediated by reductions in $PM_{2.5}$ exposure, while ambient temperature appeared to attenuate part of the effect. Although the estimated effect sizes were modest, such magnitudes are typical for population-level environmental exposures and may still have meaningful public health implications when applied across large populations.

Most prior studies on landscape metrics have focused on non-communicable diseases (e.g., cardiovascular disease, diabetes, and mental health disorders) (Wang and Tassinary, 2024), respiratory disease (Shen and Lung, 2017; Jaafari et al., 2020), childhood obesity (Kim et al., 2014), and life expectancy (Tsai et al., 2019). Evidence for perinatal outcomes is comparatively limited; one study reported lower PTB risk among pregnant individuals living in neighborhoods with larger and more complexly shaped green spaces (Wang et al., 2024a), but findings remain sparse. Our study extends this emerging literature by providing robust population-level evidence that landscape configuration is relevant to maternal health, by evaluating potential pathways through the integration of air pollution and temperature exposures.

Our findings suggest that green space quality and configuration may be as important as overall quantity, and that different landscape features can show distinct (and sometimes opposing) associations with PTB. Larger green areas can plausibly support healthier pregnancies through multiple pathways, including improved air quality, mitigation of heat exposure, and psychological restoration (Lei et al., 2021; Yin et al., 2019; Wang et al., 2024b). Higher morphological complexity (e.g., higher LSI) reflects longer edges and more irregular boundaries, which increase the interface between green and grey infrastructure (Tian et al., 2014). Such interfaces may increase accessibility and enhance pollutant removal by promoting air turbulence and increasing leaf-air contact (Bi et al., 2022). The exposure-response curves suggest that the protective association of LSI appeared stronger at lower values and plateaued beyond a certain level, suggesting diminishing marginal benefits of increasing landscape complexity. The exposure-response curves suggest a steeper decline in PTB risk at lower LSI values (approximately LSI

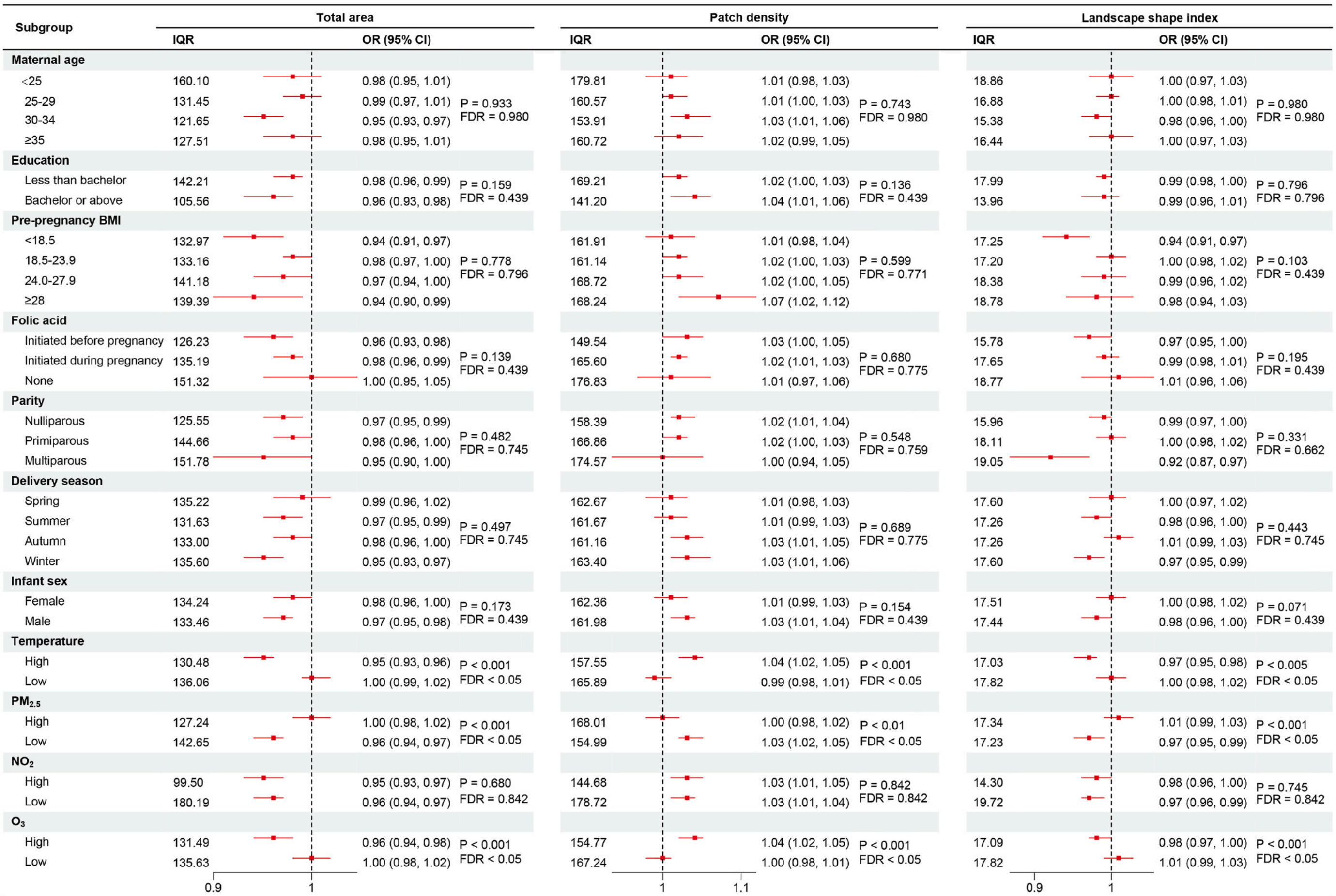

Fig. 3. The associations between urban green space landscape metrics and preterm birth across demographic and environmental subgroups. Note: OR = odds ratio; IQR = interquartile range; CI = confidence interval; P = p value from Wald tests for interaction; FDR = false discovery rate-adjusted p value (Benjamini-Hochberg procedure); $PM_{2.5}$ = fine particulate matter; NO_2 = nitrogen dioxide; O_3 = ozone. All ORs and 95% CIs are expressed per IQR increase, with specific numerical values shown in the "IQR" column. The units for these IQR values are as follows: total area (hectares), patch density (patches per 100 ha), and landscape shape index.

<30), followed by a plateau, indicating diminishing marginal benefits at higher levels. These data-driven inflection ranges may provide practical reference points for urban planning while acknowledging that absolute thresholds remain context-dependent.

The observed effect modification by ambient temperature supports the hypothesis that green space may mitigate heat-related risks. Our study found that larger and more morphologically complex green spaces were protective, and that more fragmented green space was associated with higher risk under high-temperature conditions. This suggests that green space can buffer maternal heat stress (Yin et al., 2019). Extreme heat is a well-documented trigger for PTB, potentially through dehydration and heat-related uterine contraction pathways (Bekkar et al., 2020). Large, morphologically complex green spaces can provide shade and evaporative cooling via evapotranspiration, which may be important during summer or heatwave periods. In contrast, highly fragmented green space lacks the dense canopy cover and stable cool-island cores necessary to shield residents from extreme heat intensity (Wang et al., 2025; Manoli et al., 2019). This finding aligns with previous evidence that residential greenness may mitigate heat-related PTB risk (Sun et al., 2020; Ye et al., 2024b).

However, the mediation results indicate that temperature operated as a suppressor, meaning that the protective effects of green space became stronger after accounting for the temperature pathway. This pattern arises because green space metrics were positively associated with temperature, while temperature itself remained a risk factor for PTB. Importantly, this finding should not be interpreted as evidence that green space increases temperature. Rather, the observed positive association between greenness and temperature likely reflects spatial heterogeneity in the urban environment. For example, densely built urban core areas in Chengdu, characterized by strong urban heat island effects, may have relatively limited green space, whereas some peri-urban or transitional areas may simultaneously exhibit higher greenness and elevated temperatures due to localized factors such as industrial activity or traffic-related heat emissions.

Taken together, these findings suggest that the net association reflects the combined influence of beneficial environmental regulation by green space and adverse physiological effects of heat exposure, rather than a direct causal warming effect of vegetation. These findings highlight the importance of considering both spatial context and environmental co-exposures when interpreting the health effects of urban green space.

Lower $PM_{2.5}$ exposure partially mediated the observed benefits. Green infrastructure, particularly larger and more morphologically complex vegetation, facilitates particulate deposition and dispersion (Lei et al., 2021; Łowicki, 2019). Given that maternal $PM_{2.5}$ exposure increases PTB risk by triggering systemic inflammation and placental oxidative stress (Chu et al., 2021; Zhang et al., 2022; Xiao et al., 2023), optimized green space that reduces particulate exposure represents a plausible biological pathway for PTB prevention. However, we observed a "saturation effect", with stronger benefits under lower $PM_{2.5}$ but

Table 2
Mediation effects of $PM_{2.5}$ and temperature on the associations between urban green space landscape metrics and preterm birth outcomes.

PTB outcome	Landscape metrics	Mediator	Indirect effect (ACME)	Direct effect (ADE)	Total effect	Percentage mediated (%) (95 % CI)
Overall PTB	Total area	$PM_{2.5}$	−0.0003 (−0.0005, −0.0001) ***	−0.0036 (−0.0045, −0.0027) ***	−0.0039 (−0.0047, −0.0030) ***	8.08 (3.11, 13.20) ***
		Temperature	0.002 (0.0019, 0.0022) ***	−0.0033 (−0.0042, −0.0024) ***	−0.0014 (−0.0022, −0.0005) **	−144.42 (−368.25, −92.95) **
	Patch density	$PM_{2.5}$	0 (0, 0) ***	0.0015 (0.0009, 0.0021) ***	0.0015 (0.001, 0.0021) ***	1.51 (0.81, 2.91) ***
		Temperature	−0.0007 (−0.0008, −0.0007)	0.0016 (0.001, 0.0022)	0.0008 (0.0003, 0.0015) **	−86.91 (−282.27, −44.73) **
	Landscape shape index	$PM_{2.5}$	−0.0004 (−0.0006, −0.0001) ***	−0.0027 (−0.0037, −0.0018) ***	−0.003 (−0.004, −0.0022) ***	12.15 (4.94, 20.84) ***
		Temperature	0.0014 (0.0013, 0.0015) ***	−0.0024 (−0.0033, −0.0015) ***	−0.0011 (−0.0019, −0.0001) *	−128.74 (−652.72, −70.46) *
Early PTB	Total area	$PM_{2.5}$	−0.0001 (−0.0001, 0)	−0.0006 (−0.0011, −0.0002) *	−0.0006 (−0.0011, −0.0003) *	9.90 (−3.64, 34.64)
		Temperature	0.0006 (0.0005, 0.0007) ***	−0.0005 (−0.0009, −0.0002) ***	0 (−0.0003, 0.0003)	258.21 (−4461, 7315.86)
	Patch density	$PM_{2.5}$	0 (0, 0)	0.0004 (0.0001, 0.0006) *	0.0004 (0.0001, 0.0006) *	1.16 (0.01, 3.31)
		Temperature	−0.0002 (−0.0003, −0.0002) ***	0.0004 (0.0002, 0.0006) **	0.0001 (−0.0001, 0.0004)	−116.36 (−1599.69, 878.89)
	Landscape shape index	$PM_{2.5}$	−0.0001 (−0.0002, 0)	−0.0002 (−0.0006, 0.0002)	−0.0003 (−0.0006, 0.0001)	27.35 (−20.73, 293.25)
		Temperature	0.0004 (0.0003, 0.0004) ***	−0.0002 (−0.0004, 0.0001)	0.0002 (−0.0001, 0.0004)	155.93 (−100.16, 199.00)
Late PTB	Total area	$PM_{2.5}$	−0.0003 (−0.0004, −0.0001)	−0.0032 (−0.0041, −0.0023)	−0.0034 (−0.0043, −0.0026)	7.32 (2.29, 12.87) ***
		Temperature	0.0016 (0.0015, 0.0018)	−0.0029 (−0.0037, −0.002)	−0.0014 (−0.0022, −0.0006)	−116.88 (−278.42, −75.98) ***
	Patch density	$PM_{2.5}$	0 (0, 0)	0.0013 (0.0007, 0.0018)	0.0013 (0.0007, 0.0019)	1.5 (0.71, 3.15) ***
		Temperature	−0.0006 (−0.0006, −0.0005)	0.0013 (0.0008, 0.0018)	0.0007 (0.0002, 0.0012)	−76.97 (−306.26, −44.7) **
	Landscape shape index	$PM_{2.5}$	−0.0003 (−0.0005, −0.0001)	−0.0026 (−0.0034, −0.0017)	−0.0029 (−0.0037, −0.002)	10.32 (2.98, 18.92) **
		Temperature	0.0011 (0.001, 0.0012)	−0.0024 (−0.0031, −0.0016)	−0.0013 (−0.002, −0.0006)	−82.59 (−176.61, −55.22) ***

Note: CI = confidence interval; $PM_{2.5}$ = fine particulate matter; ACME = average causal mediation effect; ADE = average direct effect.

attenuated associations in higher-pollution settings. This pattern suggests that when ambient air pollution is extremely high, vegetation deposition capacity may become saturated, or the incremental reduction attributable to green space becomes small relative to the total pollution burden (Bi et al., 2022; Chen et al., 2019). In addition, during heavy pollution periods, behavioral adaptations (e.g., reduced outdoor activity or mask use) may weaken the association between residential greenness and personal exposure (Giles et al., 2011).

Our findings indicate that larger and more morphologically complex green space was more effective at reducing PTB risk under high O_3 levels, whereas higher fragmentation was associated with increased PTB risk. Previous studies have shown that green space area may be positively associated with O_3 concentrations due to enhanced biogenic volatile organic compound emissions and photochemical activity; however, the spatial configuration of green space plays a decisive role in regulating O_3 distribution (Li et al., 2025). Complex landscape shapes increase the contact area between vegetation and the atmosphere, enhancing O_3 removal through dry deposition and providing a stronger microclimate cooling effect that inhibits photochemical O_3 formation (Li et al., 2025). Conversely, fragmented and isolated green patches are less efficient at regulating O_3 concentrations, potentially limiting pollutant dispersion and leading to localized accumulation of O_3 or its precursors (Li et al., 2024). No such modification was observed for NO_2, likely because NO_2 is mainly generated in built-up areas and is constrained by high-density buildings, which limited the contact area between green space and NO_2 (Wang et al., 2022)].

Increased TA and LSI were associated with a reduced risk of late PTB, but not early PTB. This discrepancy likely stems from the distinct etiological pathways of these two preterm subtypes. Early PTB is more strongly associated with internal biological determinants, such as intrauterine infection, genetic predisposition, and severe placental dysfunction, which may dominate over environmental influences (Goldenberg et al., 2008). In contrast, late PTB is generally more sensitive to cumulative environmental exposures during mid-to-late pregnancy (Ren et al., 2022; Zhang et al., 2023). As pregnancy progresses, green space may exert protective effects through gradual improvements in ambient environmental conditions, such as reductions in air pollutants and modification of local microclimates. Our mediation analysis showed significant $PM_{2.5}$-mediated effects for overall and late PTB, but not for early PTB. The wider CIs observed for early PTB mediation analyses likely reflect the smaller number of early PTB cases and the resulting statistical variability.

Our findings highlight the importance of integrating landscape-level green space planning into urban maternal and child health policies. First, while increasing green space area is beneficial, its spatial configuration also plays a critical role. Urban planning should prioritize the preservation of large, contiguous green cores to maintain stable cooling benefits and ecological integrity. Second, context-specific design is equally important. In hot and humid megacities like Chengdu, a mixed strategy that combines distributed small parks (to enhance access) with larger green cores (to provide stable cool islands) may better reduce heat stress and improve health benefits. Finally, given the attenuation of benefits in high-$PM_{2.5}$ environments, urban greening should be regarded as a complementary approach that supports, but cannot replace, stringent regional air pollution control measures.

This study has several important strengths. First, it advances beyond traditional greenness indicators by adopting a dimension-based framework that characterizes urban green space in terms of quantity, fragmentation, and morphological complexity. Rather than treating multiple landscape metrics as parallel indicators, this approach provides a more interpretable assessment of distinct structural properties of green space and their potential relevance to health outcomes. Second, the selected configuration metrics are not only descriptive but also mechanistically informed, as they capture spatial features that may influence environmental processes such as air pollutant dispersion and microclimate regulation. By integrating these structural indicators with air pollution and temperature, this study strengthens the ability to evaluate plausible environmental pathways linking green space to PTB. Third, the large sample size enabled us to distinguish between early and late PTB, allowing for the identification of potential heterogeneity. This distinction provides additional insight into the timing-specific vulnerability to environmental exposures during pregnancy.

Despite these advantages, some limitations should also be acknowledged. First, the unavailability of annual high-resolution green space data may introduce exposure misclassification. We prioritized 1-m spatial resolution to ensure the precise characterization of small-scale landscape configurations, which are often lost in coarser annual datasets. Although temporal mismatch could lead to non-differential misclassification, likely bias associations toward the null, the direction of bias may depend on urbanization trends. For example, if green space decreased over time due to urban expansion, the use of 2020 data may overestimate exposure for earlier years; conversely, if greening policies increased green space, exposure may be underestimated. The relative stability of metrics such as LSI in established urban districts, together with sensitivity analyses restricted to 2019-2020 and probabilistic perturbation, supports the robustness of the main findings. Second, exposures were assigned based on residential address and did not incorporate individual time-activity patterns, such as time spent outdoors, which may influence actual exposure levels. In addition, the landscape metrics used in this study characterized the structural attributes of surrounding green space but did not capture actual accessibility to or usage of green spaces by pregnant women. Variations in accessibility, perceived safety, or usability of green spaces may influence the extent to which individuals benefit from nearby green environments. Nevertheless, structural characteristics of green space may still influence environmental conditions (e.g., air quality and temperature) independent of direct human use. Third, residual confounding from missing socioeconomic, lifestyle, clinical, and individual-level factors could bias the observed associations. We lacked data on critical pregnancy-related conditions (e.g., gestational diabetes, hypertensive disorders) and prior history of PTB, which are strong determinants of birth outcomes. Furthermore, the inability to distinguish between spontaneous and medically indicated PTB, two subtypes with distinct etiologies, might have attenuated the observed effects. Fourth, the mediation analysis did not explicitly incorporate exposure-mediator interactions, which may limit the interpretation of pathway-specific effects. Finally, because the study was conducted in a single megacity with a subtropical monsoon climate, the generalizability to settings with different climates, urban forms, or green space planning patterns may be limited.

5. Conclusion

This large population-based study provides evidence that the spatial configuration of urban green space is relevant to PTB prevention. Large, more morphologically complex, and more contiguous green spaces were associated with lower PTB risk, with the protective associations partly mediated by reduced maternal $PM_{2.5}$ exposure. These findings suggest that urban greening strategies should move beyond expanding green cover alone and prioritize preserving large green cores while optimizing green space structural complexity in rapidly urbanizing cities.

CRediT authorship contribution statement

Jie Yin: Conceptualization, Formal analysis, Funding acquisition, Methodology, Software, Writing – original draft, Writing – review & editing. **Chunrong Li:** Data curation, Writing – review & editing. **Chenlu Li:** Writing – review & editing. **Guangheng Wu:** Formal analysis, Writing – review & editing. **Wangnan Cao:** Writing – review & editing. **Yuan Zhang:** Funding acquisition, Supervision, Writing – review & editing. **Shengzhi Sun:** Conceptualization, Funding acquisition, Resources, Supervision, Writing – review & editing.

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 data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2026.124811.

Data availability

The authors do not have permission to share data.

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