Association between urban green space and postpartum depression, and the role of physical activity: a retrospective cohort study in Southern California

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Summary

Background Little research exists regarding the relationships between green space and postpartum depression (PPD). We aimed to investigate the relationships between PPD and green space exposure, and the mediating role of physical activity (PA).

Methods Clinical data were obtained from Kaiser Permanente Southern California electronic health records in 2008–2018. PPD ascertainment was based on both diagnostic codes and prescription medications. Maternal residential green space exposures were assessed using street view-based measures and vegetation types (i.e., street tree, low-lying vegetation, and grass), satellite-based measures [i.e., Normalized Difference Vegetation Index (NDVI), land-cover green space, and tree canopy cover], and proximity to the nearest park. Multilevel logistic regression was applied to estimate the association between green space and PPD. A causal mediation analysis was performed to estimate the proportion mediated by PA during pregnancy in the total effects of green space on PPD.

Findings In total, we included 415,020 participants (30.2 ± 5.8 years) with 43,399 (10.5%) PPD cases. Hispanic mothers accounted for about half of the total population. A reduced risk for PPD was associated with total green space exposure based on street-view measure [500 m buffer, adjusted odds ratio (OR) per interquartile range: 0.98, 95% CI: 0.97–0.99], but not NDVI, land-cover greenness, or proximity to a park. Compared to other types of green space, tree coverage showed stronger protective effects (500 m buffer, OR = 0.98, 95% CI: 0.97–0.99). The proportions of mediation effects attributable to PA during pregnancy ranged from 2.7% to 7.2% across green space indicators.

Interpretation Street view-based green space and tree coverage were associated with a decreased risk of PPD. The observed association was primarily due to increased tree coverage, rather than low-lying vegetation or grass. Increased PA was a plausible pathway linking green space to lower risk for PPD.

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Keywords: Postpartum depression; Green space; Physical activity; Street view image; Mental health

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Research in context

Evidence before this study

We searched PubMed and Google Scholar for studies on green space exposure and maternal mental health from database inception until March 1, 2022, without language restrictions. We used a combination of search terms, including “green space”, “greenness”, “pregnancy”, “depression”, “maternal depression”, “postpartum depression”, “mental health”, and “physical activity”. No study has investigated the association between residential green space exposure and postpartum depression. Only one study in Australia explored symptoms of psychological distress during the postpartum period, and three other studies (in England, New Zealand, and the USA) analyzed the impacts of green space on antenatal depression, and reported inconsistent results. Existing studies measured green space exposure solely using satellite-based (e.g., normalized difference vegetation index and land-use greenness) or park-related green space metrics, without considering eye-level green space and vegetation types, and the mediating role of physical activity.

Added value of this study

To our knowledge, this is the first study that examined the relationship between diverse green space measurements, postpartum depression, and the role of physical activity. In this large obstetric population residing in southern California from 2008 to 2018, we found a reduced risk for postpartum depression associated with residential street view-based green space, but not satellited-based NDVI, land-cover greenness, or proximity to the nearest park. Tree coverage (i.e., street tree and total tree canopy cover) showed stronger protective associations with postpartum depression among different types of green space (i.e., low-lying vegetation and grass). Moreover, our results revealed that the effect of green space on postpartum depression was mediated by physical activity during pregnancy.

Implications of all the available evidence

This study provides a unique understanding of the relationship between green space and maternal mental health, which not only expands knowledge on mechanisms underlying green space and health, but also provides evidences to support specific public health practices. We found that street view green space and tree coverage were associated with a decreased risk of postpartum depression. Researchers, city planners, and public health professionals should work together to develop policies and interventions that increase the amount of tree coverage, especially street trees, to create a healthy built environment and optimize the potential benefits of green space for promoting physical activity and maternal mental health.

Introduction

Approximately 13% of new mothers experience postpartum depression (PPD) in the US,[1] and 20% of women in low- and middle-income countries.[2] Women are especially vulnerable to depression during the postpartum period, likely because of hormonal fluctuations, stress, and other biological and psychosocial factors.[3] PPD has been linked to both short- and long-term negative health-related behaviors and adverse outcomes, such as psychological and developmental disturbances for infants and children, and increasing emotional and behavioral problems among family members.[4,5]

The biophilia hypothesis and psycho-evolutionary theory suggest that humans have an inherent need for affiliation with nature which may affect mental health by bringing emotional stability, and helping with stress recovery.[6,7] Green space exposure has been associated with mental health benefits, including general mental health, depression and stress.[8–12] However, the existing evidence is mainly from the general population,[13–16] or confined to youth,[17,18] or elderly people.[12,18–20] Only a few studies focused on pregnant women,[21–24] and reported inconsistent results. A cross-sectional study in England found that pregnant women living in areas with higher quintiles of residential normalized difference vegetation index (NDVI) were 18–23% less likely to have depressive symptoms than those in the lowest green quintile,[21] while another study in New Zealand found no association between land-cover green space and antenatal depression.[22] To our knowledge, no study has investigated the association between green space exposure and depression during the postpartum period, nor has any investigated the underlying mechanisms linking green space with postpartum mental health.

Physical activity (PA) is an important pathway linking green space and mental well-being.[25,26] Epidemiological findings are limited and inconsistent regarding the role of PA on the relationship between green space and mental health in pregnant women.[21,22] Whether PA could be the mechanism by which green space impacts PPD is unclear. Therefore, it is necessary to examine the relationship between green space, PA, and PPD with rich exposure and outcome information rather than single-source (predominantly remote-sensing data) or regional (e.g., within an administrative unit, such as census tract) exposure metric and cross-sectional design.[27]

Green space measurements from remote sensing data such as NDVI[28] and land-use or land-cover databases[9,29,30] were most commonly used in environmental health studies.[31,32] However, the downward-facing remotely sensing imagery may not fully reflect the eye-level view that is perceived by people in daily life.[33] It is conceivable that eye-level green space can be perceived and experienced to cause physiological responses that could induce relaxation and reduced stress. Studies also suggest that eye-level but not bird’s eye view green space may promote PA[20] and walking behaviors.[34] Therefore, eye-level green space is critical to explore underlying mechanisms linking green space to human behaviors and health.

While types of green space might work through different pathways (e.g., reducing stress, promoting social cohesion, encouraging health-enhancing behaviors, and mitigating harmful environmental nuisances), only a few epidemiological studies have investigated the effects of different types of green space.[35–37] For example, higher tree density, but not grass density, was associated with better self-rated health in New York City.[37] Recently, street view data coupled with machine learning has been increasingly used to measure green space in health-related studies.[20,38] Our previous work has used machine learning technique to accurately distinguish types of green space based on street view imagery.[39]

In this study, we aimed to investigate the relationships between PPD and green space exposure, and the mediating role of PA. We hypothesized that 1) associations between PPD and green space exposure would differ by measurement methods and types of green space and 2) the effect of green space on PPD would be partially mediated by PA.

Methods

Study population

This retrospective cohort study used electronic health records (EHRs) of over 430,000 singleton pregnancies between 2008 and 2018 at Kaiser Permanente Southern California (KPSC) facilities. KPSC serves approximately 19% of the population in Southern California and validly represents its sociodemographic diversity.[40,41] Population selection process was outlined in Supplementary Figure S1. In total, 415,020 pregnancies with singleton live births were included in the main analysis after excluding participants with the following criteria: pregnancies who were not KPSC members or with gestational age <20 or >47 weeks (n = 8912), with multiple birth (n = 7454), with still birth (n = 1961), or without residential address (n = 680). We also excluded pregnancies who lived in rural area (n = 14,819). Urban areas were defined as those with a rural-urban commuting area codes of 1.0.[42] All maternal residential addresses were geocoded. A wide range of information on demographic characteristics, medical records, birth records and self-reported individual lifestyles was extracted from KPSC EHRs. More details of this population have been described elsewhere.[43] This study was approved by the Institutional Review Board of KPSC and the University of California, Irvine.

Outcome: PPD

The clinical practice adopted by KPSC is based on 2019 depression guidelines for all pregnant and postpartum women to be screened for depression using the Edinburgh Postnatal Depression Scale (EPDS).[44] Mothers who score of 10 or above on the EPDS during postpartum visits, suggesting minor or major depressive disorder, were referred to a specialist in the field for further assessment and follow-up care including diagnosis and treatment.[45] Our previous work suggested that the completeness and accuracy of PPD diagnosis solely based on diagnostic codes in EHRs is not reliable, and the accuracy of PPD identification can be improved by supplementing clinical diagnosis with pharmacy utilization records.[46] Thus, PPD was defined by using depression diagnostic codes along with medications prescribed specifically for depression during the first 12 months after delivery (Supplementary Table S1). PPD diagnostic codes and related pharmacy records were extracted from KPSC EHRs.

Green space exposures

Green space exposures were assessed using eight indicators: four street view-based measures, (i.e., total street green space, tree, low-lying vegetation, and grass), three satellite-based measures (i.e., NDVI, land-cover based green space, and tree canopy cover), and proximity to the nearest park. Individual green space exposures were measured within 200 m, 500 m and 1000 m buffers (about a 5-10-min walk) around the residential address at delivery.

Street view green space

We requested high resolution street view images using Microsoft Bing Maps Application Programming Interface. Sampling points for street view images were constructed along the road network from the U.S. Census Bureau,[47] with a 200 m space interval between each point.[48] The entire streetscape from four main cardinal directions (i.e., 0°, 90°, 180°, and 270°) at each point were retrieved.[20]

We applied a validated deep learning model using semantic segmentation to identify three types of vegetation: tree (e.g., canopy), low-lying vegetation (e.g., shrub, bush), and grass. The accuracy of our deep learning model was high with a 92.5% mean intersection over union.[39] Total green space was defined as the sum of proportion of these three types of green space. For each address, the proportion of green space for all points within a circular buffer around the residential address were averaged to assess the street green space exposure. The number of sampling points (e.g., 500 m buffer: 83 ± 27) per address varies depending on the buffer size and street density. Further details of the street view green space model have been previously described.[39]

NDVI

Satellite-based NDVI[28] measures the vegetation density on the ground based on the difference in land surface reflectance between visible red (VIS R) and near-infrared (NIR) wavelength of vegetation: NDVI = (NIR − VIS R)/(NIR + VIS R). NDVI ranges from −1 to 1, with higher values indicating a higher density of greenness. Negative values, usually representing water bodies, were recorded as zero before further analyses were performed.[31] In this study, we used the Terra (MOD13Q1) satellite instrument of Moderate Resolution Imaging Spectroradiometer products from NASA, with a spatial resolution of 250 m × 250 m and a temporal resolution of every 16-days.

A previous study showed the NDVI values do not change substantially across seasons in California in areas where population reside.[49] Therefore, we calculated the annual mean NDVI by averaging the NDVI values in all grids within a circular buffer for the year 2013 (the mid-year of the study period).

Land-cover based green space and tree canopy cover

Land cover data were obtained from the National Land Cover Database (NLCD).[50] The NLCD provides nationwide data on land cover at a 30 m resolution with 16 classes.[51] Natural environment-related categories from the NLCD, including forest, shrubland, herbaceous, wetlands, developed—open space (i.e., >80% vegetation cover) were aggregated as one measure of green space. Additionally, we obtained the NLCD tree canopy data, which contains the percentage of total tree canopy cover at a 30 m resolution.[52] The percentages of the area within or intersecting the circular buffers were assessed as land-cover based green space exposures.

Proximity to the nearest park

Using the California Protected Areas Database[53] that provides data depicting the wide diversity of parks and open spaces in California, we estimated proximity to parks as a straight-line distance from the residence to the nearest park. In this study, only parks and open spaces defined as "Open Access" were included. A binary variable was also used to assess whether the maternal residence was within a 500 m buffer from the boundaries of the nearest park.

Mediator: PA during pregnancy

The PA measurements were based on self-reported data at the time of the visit encounter (7 ± 4 times during the entire pregnancy) in KPSC EHRs. Participants were asked two questions to capture frequency and average daily time spent engaging in PA over the most recent 7 days at the time of their visit: 1) number of days exercised per week and 2) number of minutes exercised per day. The date of the survey, and the total number of minutes exercised per week (number of minutes exercised per day × number of days exercised per week) were extracted. PA during the entire pregnancy was calculated by averaging the PA measurements from the date of conception to the date of delivery.

Statistical analyses

The distribution of selected population characteristics and green space indicators were assessed. Pearson's correlation was employed to examine the correlation between green space indicators. Chi-square was applied to determine the difference between PPD and non-PPD groups; analyses of variance (ANOVA) were used to test the difference of green space levels by population characteristics. We used multilevel logistic regressions to examine the association between PPD and green space and PA level separately. Each model included one of the green space indicators as the exposure. All green space indicators were treated as continuous variables. Odds ratios (ORs) and 95% confidence intervals (CIs) were calculated per interquartile range (IQR) increment for each green space indicator. Moran's I was used to test the spatial clustering for PPD given the large spatial extent of the study population. The Moran's I was low with a value of 0.0002 ($p < 0.0001$). The spatial correlation is weak despite its statistical significance. Zip code was fitted as a random effect to account for potential spatial clustering for PPD. Zip Code Tabulation Areas defined by the U.S. Census Bureau were used to represent zip codes.[54] Multiple linear regression models were applied to estimate the difference in PA during pregnancy associated with green space exposure. PA levels were log-transformed. All results were expressed as the percent change in PA levels with 95% CIs relative to one unit increment of each green space indicator.

We also conducted causal mediation analysis (R package "mediation") to assess whether PA during the pregnancy contributes to the observed effects, if any, between green space exposures and PPD.[55] Green space indicators with hypothesized protective effects on the risk of PPD were identified and selected to further perform the mediation analysis. In the causal mediation analysis, we did not identify any exposure-mediator interactions so Natural Direct Effects and Controlled Direct Effects can be interpreted similarly. The total causal effect of the exposure on the outcome can be decomposed into two pathways: the natural direct effects (i.e., due to unspecified causal mechanisms of green space on PPD) and natural indirect effects (i.e., due to the mediation of PA). Given that the green space indicators were continuous variables, we specified two values of the exposure (Q3 vs. Q1) to make the contrast in the mediation models. We used 1000 bootstrap simulations to obtain 95% CIs. For this causal mediation analysis, we relied on the potential outcomes framework and made the following assumptions: no unmeasured confounding and no mediator-outcome confounder affected by the exposure itself.[56]

In our main analysis, we adjusted for maternal age, race/ethnicity, educational level, and household income (block group-level median household income in 2013). Moreover, we performed sensitivity analyses to examine the influence of maternal smoking status during pregnancy, season of conception, year of infant birth, insurance type, preterm birth, and pregnancy-related comorbidities (preeclampsia, gestational hypertension and gestational diabetes). We included all the above covariates and pre-pregnancy BMI in the mediation models. We performed sensitivity analysis by further excluding infants conceived >19 weeks before 1 January 2008 (n = 13,304), or <43 weeks before 31 December 2018 (n = 3100) to avoid fixed cohort bias.[57] Gestational age was calculated from date of last menstrual period (LMP) and corroborated by early pregnancy ultrasonography. We also conducted sensitivity analysis adding multiple deliveries as a random effect in the models as women with multiple deliveries are represented in the study population. In addition, we used the within-between random effects model[58] to account for the effects of both individual-level (i.e., within a circular buffer around the maternal residence) and neighborhood-level (i.e., average of all individual green space values within a given zip code) green space exposures concurrently. Due to potential differential susceptibility of green space effects on health across populations with different demographic factors, socioeconomic status and health conditions,[59] we performed stratified analyses to examine whether the hypothesized associations with green space differ by maternal age, race/ethnicity, educational level, neighborhood household income, and pregnancy-related comorbidities. Cochran Q tests were applied to measure the heterogeneity among subgroups. Participants with missing or invalid data for the exposure (e.g., living in regions where green space could not be calculated), PA or confounder variables were excluded from the analysis. All analyses were conducted with SAS version 9.4 (SAS Institute, Inc., Cary, NC) and R software (version 4.0.5). A p-value <0.05 is considered statistically significant.

Role of the funding source

The funders of the study had no role in study design, data collection, data analysis, data interpretation, or writing of the report.

Results

Among 415,020 births included in our study, 43,399 (10.5%) PPD cases were identified. Table 1 presents the distribution of population characteristics, green space exposures, and PA levels. The mean maternal age was 30.2 (SD 5.8) years at delivery. Hispanic mothers accounted for 51.5% of the total population, followed by non-Hispanic white mothers (25.5%). About a third of the study population had an education level with high school or below, and 44.3% with education ≥ college. PPD cases were more frequent among mothers over the age of 35, African American or non-Hispanic white mothers, mothers with college education <4 years, mothers who live in middle- and high-income neighborhoods, smoking mothers, and mothers with less PA during pregnancy ($p < 0.0001$).

Significant differences were observed for street view green space exposure by maternal characteristics ($p < 0.0001$). On average, total street green space levels were higher among older mothers (≥35, years), non-Hispanic white or Asian mothers, mothers with higher education, and mothers who live in high-income neighborhoods. Overall, a similar distribution occurred for street trees and low-lying vegetation, while grass levels showed an opposite trend. Satellite-based NDVI, land-cover green space and tree canopy cover had a similar pattern with street total green space.

The relationship between green space indicators

Table 2 provides summary statistics and Pearson's correlation coefficients between green space measures. Positive correlations between street total green space and vegetation types were most pronounced for tree (r = 0.86), followed by grass (r = 0.17) and low-lying vegetation (r = 0.11). Street tree coverage was negatively correlated with low-lying vegetation and grass. Satellite-based NDVI was moderately correlated with street total green space and trees (r = 0.44 and 0.38, respectively), and weakly correlated with street low-lying vegetation and grass. The tree canopy cover from satellite imagery was moderately correlated with street tree coverage (r = 0.63), street total green space (r = 0.62), and NDVI (r = 0.52). Increased distance to park was negatively correlated with street tree coverage. Supplementary Table S2 shows additional summary statistics of green space indicators and PA levels. All the correlation coefficients are statistically significant ($p < 0.0001$).

The association between green space, PA and PPD

Fig. 1 illustrates the associations between various measures of green space exposures and the risk of PPD. Exposure to total street green space showed consistent protective effects on PPD for all buffer sizes, with the strongest association for the 500 m buffer (OR = 0.98, 95% CI: 0.97–0.99, per IQR increase) (Supplementary Table S3). For different types of street green space, higher street tree coverage was associated with a decreased risk of PPD, indicating approximately 2% lower PPD risks for an IQR increase in street tree exposure (OR = 0.98, 95% CI: 0.97–0.99). Protective effect of low-lying vegetation was only observed for 200 m buffer (OR = 0.98, 95% CI: 0.97–0.99) around the residential address, while an increased OR was found for grass within a 1000 m buffer (OR = 1.02, 95% CI: 1.01–1.03) (per IQR increase). For satellite-based green space indicators, no clear trend was observed between residential surrounding NDVI, land-cover greenness, and proximity to parks and PPD risk, while consistent higher tree canopy cover was associated with a lower risk of PPD (500 m, OR = 0.98, 95% CI: 0.97–0.99).

Moreover, PA during pregnancy showed protective effects on PPD (OR = 0.93, 95% CI: 0.91–0.94) (Supplementary Table S3).

In sensitivity analyses (Supplementary Table S3), associations between green space and PPD were slightly stronger after further adjusting for additional potential confounders. The results from the main analysis and sensitivity analysis were close after controlling for the fixed cohort bias or random effect of multiple deliveries. The pattern of results from within-between random effects models was similar to the main analysis. Overall, larger buffer sizes or neighborhood (i.e., zip code) green space exposure showed stronger associations. In subgroup analyses (Supplementary Table S4), the protective associations of PPD and street green space were significantly stronger among mothers over the age of 35, non-Hispanic white mothers and Asian mothers, mothers who live in higher income neighborhoods, and mothers with higher education.

The association between green space exposure and PA mediator

Overall, PA levels were positively associated with most green space indicators, including street view-based total

Characteristics	Total births, N = 415,020 (%)	Postpartum depression, N = 43,399 (%)	Total street green space	Tree	Low-lying vegetation	Grass	NDVI	Land-cover green space	Tree canopy cover	Distance to the nearest park
Physical activity, minutes/week, mean (SD)	79.5 (80.8)	74.9 (76.3)	-	-	-	-	-	-	-	-
Maternal age, years										
<25	80,513 (19.4)	6758 (15.7)	24.5 (3.5)	14.7 (3.7)	4.4 (1.4)	5.4 (1.5)	0.26 (0.06)	11.8 (17.5)	1.5 (1.8)	0.56 (0.49)
25–34	245,934 (59.3)	25,936 (59.8)	25.2 (4.0)	15.3 (4.1)	4.5 (1.4)	5.3 (1.4)	0.26 (0.06)	12.4 (17.6)	2.0 (2.2)	0.52 (0.45)
≥35	88,573 (21.3)	10,705 (24.5)	25.7 (4.3)	15.9 (4.4)	4.6 (1.4)	5.2 (1.4)	0.27 (0.06)	12.1 (17.1)	2.4 (2.6)	0.49 (0.42)
Maternal race/ethnicity										
African American	31,896 (7.7)	3602 (8.3)	24.4 (3.3)	14.3 (3.7)	4.4 (1.3)	5.6 (1.4)	0.25 (0.05)	9.8 (15.7)	1.3 (1.7)	0.53 (0.43)
Non-Hispanic Asian	52,946 (12.8)	2639 (6.1)	25.7 (4.2)	15.9 (4.4)	4.7 (1.3)	5.1 (1.2)	0.27 (0.06)	11.5 (16.1)	2.6 (2.5)	0.45 (0.36)
Hispanic	213,543 (51.5)	21,525 (49.6)	24.6 (3.6)	15.0 (3.8)	4.3 (1.3)	5.3 (1.4)	0.26 (0.06)	10.4 (16.0)	1.6 (1.8)	0.54 (0.45)
Non-Hispanic white	105,728 (25.5)	14,308 (33.0)	26.2 (4.4)	15.9 (4.7)	4.9 (1.6)	5.3 (1.6)	0.28 (0.06)	17.0 (20.3)	2.6 (2.8)	0.53 (0.50)
Multiple/other	10,865 (2.6)	1324 (3.0)	25.3 (4.1)	15.2 (4.3)	4.8 (1.5)	5.3 (1.5)	0.27 (0.06)	14.0 (18.2)	2.1 (2.4)	0.51 (0.44)
Maternal education										
<College	137,387 (33.1)	13,258 (30.6)	24.5 (3.6)	14.7 (3.7)	4.4 (1.4)	5.3 (1.4)	0.26 (0.06)	11.7 (17.3)	1.5 (1.8)	0.55 (0.47)
College (<4 years)	93,590 (22.6)	11,342 (26.1)	24.9 (3.7)	15.1 (3.9)	4.4 (1.4)	5.4 (1.5)	0.26 (0.06)	11.4 (17.2)	1.7 (2.0)	0.55 (0.48)
College (≥4 years)	184,043 (44.3)	11,799 (43.3)	25.8 (4.3)	15.9 (4.4)	4.7 (1.4)	5.2 (1.4)	0.27 (0.06)	13.1 (17.7)	2.5 (2.6)	0.49 (0.42)
Block group median household income in 2013										
≤$43,696	103,493 (25.0)	9640 (22.3)	24.0 (3.2)	14.7 (3.3)	4.2 (1.2)	5.0 (1.4)	0.24 (0.05)	7.7 (14.5)	1.2 (1.4)	0.53 (0.44)
$43,697–$55,962	103,411 (25.0)	10,846 (25.0)	24.9 (3.6)	15.3 (3.9)	4.3 (1.3)	5.4 (1.4)	0.26 (0.05)	10.5 (16.4)	1.7 (1.8)	0.57 (0.47)
$55,963–$71,602	103,473 (25.0)	11,365 (26.3)	25.4 (3.8)	15.4 (4.2)	4.6 (1.5)	5.4 (1.4)	0.27 (0.06)	12.6 (17.1)	2.1 (2.1)	0.52 (0.45)
>$71,602	103,431 (25.0)	11,427 (26.4)	26.4 (4.7)	16.0 (4.8)	5.1 (1.5)	5.3 (1.4)	0.29 (0.06)	18.2 (19.8)	3.1 (3.0)	0.46 (0.44)
Smoking										
Never Smoker	346,811 (83.6)	32,546 (75.0)	25.1 (4.0)	15.3 (4.1)	4.5 (1.4)	5.3 (1.4)	0.26 (0.06)	12.1 (17.4)	2.0 (2.3)	0.52 (0.45)
Ever Smoker	47,260 (11.4)	7305 (16.8)	25.4 (4.1)	15.5 (4.2)	4.6 (1.4)	5.3 (1.5)	0.26 (0.06)	12.8 (17.8)	2.1 (2.4)	0.52 (0.44)
Smoking during pregnancy	20,915 (5.0)	3547 (8.2)	25.1 (3.0)	15.1 (4.0)	4.5 (1.5)	5.4 (1.5)	0.26 (0.06)	12.7 (18.3)	1.8 (2.2)	0.55 (0.51)
Passive smoker										
Yes	8789 (2.1)	1080 (2.5)	24.7 (3.7)	14.8 (3.9)	4.4 (1.5)	5.5 (1.5)	0.26 (0.06)	12.3 (17.8)	1.6 (1.9)	0.56 (0.49)
No	404,119 (97.9)	42,212 (97.5)	25.2 (4.0)	15.3 (4.1)	4.5 (1.4)	5.3 (1.4)	0.26 (0.06)	12.2 (17.5)	2.0 (2.3)	0.52 (0.45)
Insurance type										
MediCal (or Medicaid)	40,142 (9.8)	4996 (11.6)	24.5 (3.4)	14.7 (3.6)	4.4 (1.4)	5.4 (1.5)	0.25 (0.06)	11.7 (17.5)	1.4 (1.7)	0.56 (0.48)
Other	367,918 (90.2)	37,971 (88.4)	25.2 (4.0)	15.4 (4.2)	4.6 (1.4)	5.3 (1.4)	0.26 (0.06)	12.3 (17.4)	2.1 (2.3)	0.52 (0.45)
Season of conception										
Warm (May–October)	204,728 (49.3)	20,976 (48.3)	25.1 (4.0)	15.3 (4.1)	4.5 (1.4)	5.3 (1.4)	0.26 (0.06)	12.3 (17.5)	2.0 (2.3)	0.52 (0.45)
Cool (November–April)	210,292 (50.7)	22,423 (51.7)	25.2 (4.0)	15.3 (4.1)	4.5 (1.4)	5.3 (1.4)	0.26 (0.06)	12.2 (17.4)	2.0 (2.2)	0.52 (0.45)

NDVI, Normalized Difference Vegetation Index; Medical is Medicaid for Californians. Green space measures: mean (standard deviation, SD). The units are % for total street green space, tree, low-lying vegetation, grass, land-cover green space and tree canopy cover, and km for distance to the nearest park.

Table 1: **Description of the study population and residential green space levels (500 m) by maternal characteristics, 2008-2018.**

Green space indicators	Mean (SD)	IQR	Total street green space	Tree	Low-lying vegetation	Grass	NDVI	Land-cover green space	Tree canopy cover	Distance to nearest park
Total street green space, %	25.15 (3.97)	4.63	1.00							
Tree, %	15.32 (4.12)	4.94	0.86	1.00						
Low-lying vegetation, %	4.53 (1.41)	1.67	0.11	−0.27	1.00					
Grass, %	5.30 (1.43)	1.71	0.17	−0.22	0.11	1.00				
NDVI, (0–1)	0.27 (0.06)	0.08	0.44	0.38	0.04	0.10	1.00			
Land-cover green space, %	12.24 (17.47)	14.92	0.20	−0.14	0.57	0.38	0.29	1.00		
Tree canopy cover, %	2.00 (2.27)	2.13	0.62	0.63	0.10	−0.19	0.52	0.05	1.00	
Distance to nearest park, km	0.58 (0.48)	0.47	0.02	−0.11	0.10	0.26	−0.09	0.16	−0.13	1.00

SD, standard deviation; IQR, interquartile range; NDVI, normalized difference vegetation index.

Table 2: **Summary statistics and Pearson correlation coefficients between residential green space measures (500 m).**

green space, tree, and low-lying vegetation, satellite-based NDVI, tree canopy cover, and proximity to the nearest park (Fig. 2, Supplementary Table S5). For example, every ten-percent increase in street tree within a 500 m buffer was associated with a 2.70% (95% CI: 1.46%–3.95%) increase in PA during pregnancy. In contrast, exposures to more grasses were associated with decreased PA during pregnancy.

Relative contribution of PA mediator

Table 3 shows results from the mediation analysis for green space indicators that were significantly associated with decreased risk of PPD, including street view-based total green space and tree and satellite-based tree canopy cover. The proportions of mediation effects attributable to PA during the entire pregnancy ranged from 2.7% to 7.2%. Among all green space indicators, PA explained the largest portion of association between PPD and street tree coverage (1000 m: 7.2%, 95% CI: 2.7%–60.0%).

Discussion

To the best of our knowledge, this is the first study that examined the relationship between comprehensive green space measurements, PPD, and the mediating role of PA. In this large obstetric population in southern California, we found that a lower PPD associated with maternal exposure to green space in residential neighborhood assessed by street-view measures, but not by NDVI, land-cover green space or proximity to parks. The observed association was largely due to tree coverage (i.e., street tree and total tree canopy cover), which showed a stronger protective effect, as compared to other types of green space. Moreover, the effect of green space on PPD was modestly mediated by PA during pregnancy (2.7%–7.2%).

Relationships between green space exposure and PPD have not been studied; previous reports mainly focused on antenatal depression, and found inconsistent results.[21–23] In this study, we examined a comprehensive

Exposures	OR 95% CI
Street view green space, %	
Total green space	0.98 (0.97, 0.99)
Tree	0.98 (0.97, 0.99)
Low-lying vegetation	0.99 (0.97, 1.00)
Grass	1.01 (0.99, 1.02)
Green space indicators	
Mean annual NDVI (0-1)	1.02 (1.00, 1.03)
Land-cover green space, %	1.00 (0.99, 1.02)
Tree canopy cover, %	0.98 (0.97, 0.99)
Proximity to the nearest park	1.00 (0.99, 1.01)

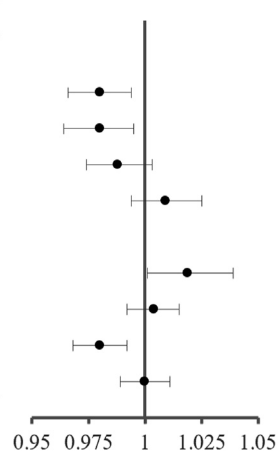

Fig. 1: **Associations between residential green space (500 m) and maternal postpartum depression.** NDVI, normalized difference vegetation index. Odds ratios (ORs) and 95% confidence intervals (CIs) were calculated for per interquartile range (IQR) increment for green space indicators. Models adjusted for maternal age, race/ethnicity, educational level, and block group household income. Zip code was fitted as a random effect.

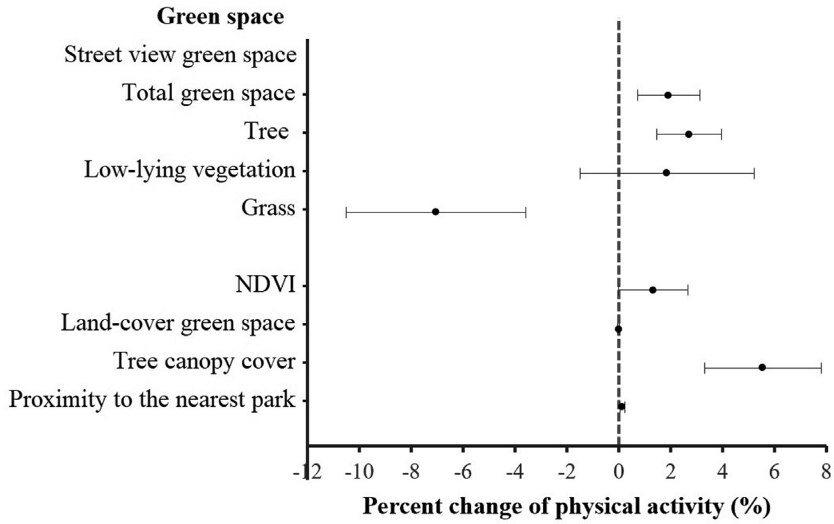

Fig. 2: **Percent change and 95% confidence intervals for the associations between green space (500 m) and physical activity during pregnancy.** NDVI, normalized difference vegetation index. Models adjusted for maternal age, race/ethnicity, educational level, and block group household income. Zip code was fitted as a random effect. The units are ten-percent for street view-based green space, land-cover green space and tree canopy cover, 0.1 for NDVI, and 0.1 km for proximity to the nearest park.

set of green space measures, including the innovative street view-based total and types of green space, and commonly-used satellite-based and park-related measures to facilitate comparison with other work. Consistent and protective associations between eye-level total street green space and PPD were observed, but not NDVI, land-cover green space, or distance to parks. Unlike parks, street green space can be more frequently and routinely experienced and is easily accessible in daily activities to all residents whether used or not (visual or presence). While remote sensing images may better capture the total amount of green space (e.g., not publicly accessible green spaces, or parks and forests away from the road), street view green space may more readily facilitate PA, social contacts, neighborhood safety and stress reduction,[20,33,60] which are important mental health-related factors. Although we observed potential increased PPD risk for NDVI, we cannot conclude that green space is detrimental to PPD as such measures only reflect the top-viewed and total amount of

Green space indicators	Percentage mediated by physical activity and 95% CI, %	p value
Street view green space 200 m		
Total green space	1.9 (−0.3 to 9.0)	0.10
Tree	4.2 (−4.9 to 32.0)	0.08
Street view green space 500 m		
Total green space	2.7 (0.7–7.0)	0.02
Tree	5.5 (1.5–37.0)	0.03
Street view green space 1000 m		
Total green space	3.4 (0.7–15.0)	0.03
Tree	7.2 (2.7–60.0)	0.02
Tree canopy cover		
Tree canopy 200 m	8.4 (−78.2 to 67.0)	0.22
Tree canopy 500 m	6.2 (1.8–50.0)	0.02
Tree canopy 1000 m	6.9 (1.5–58.0)	0.05

CI, confidence interval. Models adjusted for maternal age, race/ethnicity, educational level, block group household income, smoking during pregnancy, pre-pregnancy BMI and season of conception. Zip code was fitted as a random effect.

Table 3: **Proportions of the effects of green space exposure on postpartum depression due to mediation effects of physical activity during the entire pregnancy.**

greenness and miss valuable information on the type and quality of green space. For example, the most consistent results of crime reduction were reported in studies involving vegetated streets compared to large undeveloped green areas.[60] More land use dedicated to grass without tree canopy was associated with higher odds of poor general health.[35] Indeed, our findings showed that PPD was negatively associated with satellite-based tree canopy cover, but not satellite-based total greenness represented by NDVI. Different land cover classes may also have different roles in affecting mental health.[61] Therefore, the choice of exposure indicators can greatly impact the relationship between green space and mental health outcomes. Future studies should carefully select green space measures and analyze green space–health associations using multiple indicators.

Despite the importance of type of green space in understanding mechanisms and developing targeted interventions, studies considering types of green space and mental health are sparse. A study in Singapore reported that tree canopy showed stronger associations with mental health than total green space or park area.[36] An Australian study associated exposure to higher total green space and tree canopy with lower incidence of psychological distress among adults older than 45 years, higher grass levels with higher risk, and low-lying vegetation with no consistent risk.[35] However, no prior study has explored green space types and maternal mental health, and existing studies relied solely on satellite-based green space data. Both satellite-based and street view-based green space types were considered in our study to overcome the constraints of remote sensing metrics, better classify eye-level green space types, and make a comparison. Our results are partially consistent with previous findings among the general populations. We found consistent associations between lower PPD risks and tree coverage from both satellite and street view imagery. The observed negative association of depression with trees might be partially explained by the tree canopy blocking the sun and providing shade to mitigate environmental nuisances caused by noise, heat and air pollution[62–64]; larger stature and biomass of trees on visual greenness; the esthetic purpose of street trees[34]; the canopy ecosystem in relation to higher levels of biodiversity[65]; and providing settings for recreation activities, such as PA and social interaction.[66]

We also found residential low-lying vegetation within a smaller (200 m) but not larger buffer might have benefits on PPD. Compared to trees and grasses, the low-lying vegetation surrounding home (e.g., streets close to home, well-maintained yards) may provide a better visual effect on the landscape with their unique physical characteristics (e.g., form and color), which can help release negative affect and improve mental health. More appealing landscaping of residential yard could lead to more checks on dangerous behavior and discourage criminal behavior.[67] Hedge, a tightly planted cluster of tall shrubs, can help provide homeowner shade and privacy. In contrast, no clear trend was observed for grass. Our findings ought not to be interpreted as evidence for reducing grassy areas (e.g., open grassland, grass playfield), which may bring possible health benefits, such as mental disorder and allergy, for other populations.[68] Nevertheless, given a fixed amount of space, tree and grass compete with each other on the land use. Decision-makers and city planners may consider increasing the amount of tree coverage, especially street trees, to create a healthy built environment.

We observed that different types of green space metrics were differently associated with PA during pregnancy. Two previous studies showed that PA may not explain[22] or may explain a small portion (5.6%–7.8%)[21] of the effect of green space exposures on antenatal depression. The role of PA on the association of green space and PPD was unclear. Results from the current study suggest similar mediation effect of PA between green space and PPD ranging from 2.7% to 7.2%. In addition, stronger mediating effects of PA were observed for residential green space within 500 m and 1000 m buffer compared to 200 m, implying that green space exposure in larger buffer sizes had stronger associations with PA, which in turn reduced PPD risk. To date, little research has been reported examining the interactions between green space, vegetation types, PA and PPD. Further studies are warranted to investigate the role of PA and explore other significant pathways linking green space to maternal mental health.

A review study indicated that the associations of demographic factors with PPD are mixed and complex.[69] In our study, a higher incidence of PPD was observed among older mothers (≥35, years), African American or non-Hispanic white mothers, mothers with college education <4 years, and mothers who live in middle- and high-income neighborhoods. Overall, results from stratified models suggest that the protective associations of street green space with PPD were stronger for these susceptible sub-populations.

From mother's perspective, more contact with green space, especially easy-access street green space, may effectively improve mental health and well-being. A recent study reported that even a short visual exposure to green space environment was associated with both physiological and affective stress reduction among pregnant women.[70] In addition, exercise (outdoors in nature or indoors) during and after pregnancy are recommended, which could have beneficial effects for maternal mental health.

The main strengths of our study include the use of street view-based green space data and vegetation types, as well as the comparison with the multiple green space indicators, including satellite-based metrics, and parks; the large and diverse population from the KPSC pregnancy cohort; the high-quality clinical data from

KPSC EHRs, especially PPD identification based on both clinical diagnosis and prescription; and comprehensive data that allowed us to test the mediation effect of PA and control for a wide range of potential confounders.

Limitations should be considered when interpreting our findings. First, given that temporal variations of green space levels were not taken into account, potential exposure misclassifications may exist. For example, most street view images from Bing Maps were randomly captured in different dates between 2014 and 2015 (99%). Thus, this database may not reflect seasonal or higher temporal resolution changes, and we assumed the green space across our study region remained stable over the study period. Nevertheless, the variation of green space over seasons[49] and years (Supplementary Table S2) tends to be small and we included year of birth to control for potential temporal confounding. Second, although a number of green space indicators were applied to reflect different aspects of green space exposures, perceived quality and use of green space, which might be more important than quantity,[24] were not considered. Moreover, we relied solely on estimated postpartum exposures at maternal residential address at delivery. The mobility of women during the postpartum period were unavailable. Nonetheless, based on the residential history during pregnancy for this population, most of women who relocated during pregnancy may likely have moved within the same sub-region (median distance: 6 km), which would not significantly change their estimated exposure levels and neighborhood socioeconomic status. Another limitation is the lack of information on other potential confounders, such as psychiatric history and adverse life events, which may affect mental health and lead to potential bias. Further, future research needs to use objective PA measures (e.g., accelerometer-based measurements) and consider PA in the postpartum period, which could minimize recall bias in comparison to the self-reported prenatal exercise. Finally, risk factors for PPD (e.g., social support)[71] and distributions of green space could vary by region or urban-rural status; and attitudes of pregnant women toward PA could vary among cultures.[72] Thus, studies in other geographical settings and populations are needed.

In conclusion, this large study provides a unique understanding of the relationship between green space and PPD. Eye-level street view green space was associated with a decreased risk of PPD. PA could serve as one of the plausible mediators of the relationship of green space and depression. In addition, protection and restoration of trees, rather than low-lying vegetation or grass, may translate into a more pronounced reduction of PPD and optimize the potential benefits of green space exposure for promotion of PA and maternal mental health.

Contributors
YS: Methodology, Software, Data curation, Formal analysis, Visualization, Writing – original draft. JM: Methodology, Writing – review & editing. TB: Methodology, Writing – review & editing. CA: Data curation, Writing – review & editing. VC: Software, Data curation, Writing – review & editing. JS: Writing – review & editing. DAS: Writing – review & editing. JCC: Methodology, Writing – review & editing. DG: Conceptualization, Supervision, Project administration, Funding acquisition, Methodology, Data curation, Writing – review & editing. JW: Conceptualization, Supervision, Project administration, Funding acquisition, Methodology, Data curation, Writing – review & editing. YS and JW: accessed and verified the data. The authors were not precluded from accessing data in the study, and they accept responsibility to submit for publication.

Data sharing statement
The individual data from KPSC electronic health records that underlie the findings of this study are not publicly available. The study protocol is available from the corresponding authors upon reasonable request.

Additional information
This study is part of a dissertation (Yi Sun). https://escholarship.org/uc/item/3mp1f7z1.

Declaration of interests
We declare no competing interests.

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Appendix A. Supplementary data
Supplementary data related to this article can be found at https://doi.org/10.1016/j.lana.2023.100462.

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