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Impact of Wildland Fire Smoke $PM_{2.5}$ on Birth Weight in California

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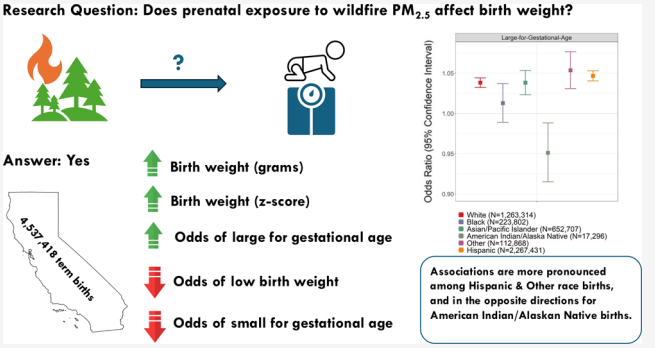
ABSTRACT: The increase in the frequency, duration, and intensity of wildland fires is a significant source of air pollution that can impact perinatal outcomes. This study assessed associations between wildfire fine particulate matter <2.5 μm ($PM_{2.5}$) and adverse birth weight outcomes among singleton term births in California for 2007−2018. Exposure was assessed using bias-corrected Community Multiscale Air Quality Model, linked to residence at delivery. Logistic and linear regression models estimated associations between average daily wildfire $PM_{2.5}$ and birth weight outcomes, adjusting for individual-level sociodemographic covariates and seasonality. We conducted race/ethnicity-stratified analyses to assess whether the influence of wildfire $PM_{2.5}$ differed among racially marginalized populations. In a sample of 4,537,418 term births, a 1 $\mu g/m^3$ increase in wildfire $PM_{2.5}$ during pregnancy was associated with increased odds of large for gestational age and an increase in birth weight, as well as moderately decreased odds of low birth weight and small for gestational age. These associations were more pronounced among Hispanic individuals and those in the Other race category. Conversely, among American Indian and Alaska Native births, exposure to wildfire $PM_{2.5}$ was associated with decreased odds of large for gestational age. Results underscore the importance of understanding how wildfire $PM_{2.5}$ impacts fetal growth, especially among marginalized groups.



KEYWORDS: *wildfire, birth outcomes, pregnancy, large for gestational age, small for gestational age, birth weight*

INTRODUCTION

In the face of rising temperatures and prolonged drought due to climate change, wildland fires are increasing in length, intensity, and frequency across the globe, including in the United States.[1,2] Rising population growth in the wildland−urban interface may be accompanied by increased human exposure to wildfires and worsening air quality.[3] Wildfires are a significant contributor to ambient air pollution, including particulate matter (PM), polycyclic aromatic hydrocarbons, toxic gases, and volatile organic compounds.[2,4] Fine inhalable particles with diameters 2.5 μm and smaller ($PM_{2.5}$) that are generated by wildfires may be more harmful, compared to $PM_{2.5}$ from other sources, due to the chemical mixtures emitted from burning biomass and built structures.[5,6] In California, wildfires contribute half of the total annual ambient $PM_{2.5}$, and this proportion is expected to increase in the next decades.[2] In light of increasingly ubiquitous and extreme exposures to wildfire-related $PM_{2.5}$, understanding its effects on health outcomes, particularly during critical developmental windows such as pregnancy, can provide a more comprehensive picture of escalating wildfires' environmental and social implications for vulnerable populations.[6]

Wildland fire $PM_{2.5}$ may have important impacts on birth weight and fetal growth outcomes.[6] Air pollution resulting from wildfires can cross the placental barrier, disrupting the maternal−fetal oxygen delivery and nutrient transportation, which may affect fetal growth.[6,7] Furthermore, exposure to air pollutants may cause systemic inflammation, which results in oxidative stress that also hinders placental nutrient exchange.[8] Wildfire $PM_{2.5}$ can affect birth weight by increasing psychosocial stress during pregnancy and modifying health behaviors, due to coping with fire-related evacuations or worsening air pollution.[9−11] Infants born with abnormal birth weight are at elevated risk of short- and long-term adverse health outcomes.[12,13] Reduced birth weight is a well-established risk factor for multiple negative outcomes, including increased risk of infant morbidity and mortality, impaired neurodevelopment, and chronic conditions later in life.[12,14] Similarly, infants with higher-than-normal birth weight may experience complications during delivery, including birth

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injury, as well as higher risk of obesity and metabolic disorders during childhood and adulthood.[13,15] Though evidence on the effects of wildfire $PM_{2.5}$ on birth weight is more limited, existing studies examining total ambient $PM_{2.5}$ have reported associations with reduced birth weight, highlighting the potential harmful effects of $PM_{2.5}$ on fetal development.[16]

While a growing body of literature has documented associations between wildfire $PM_{2.5}$ exposure and increased risk of preterm birth, evidence on its impact on birth weight and fetal growth outcomes has been mixed.[17−19] A systematic review of studies examining wildfire exposure during pregnancy and adverse birth outcomes found preliminary evidence, with low certainty, that prenatal exposure may be associated with reduced birth weight, and this association may be more pronounced when exposure occurred during the second and third trimesters.[20] For example, a study examining the 2003 Southern California wildfires documented an average of 9.7 g reduction in birth weight among deliveries exposed to wildfire smoke during the second trimester.[21] In contrast, a study in Australia documented higher average birth weight among male infants in high wildfire regions, compared to their counterparts born in least and moderately affected regions[22] Studies evaluating wildfire $PM_{2.5}$ on small and large for gestational age are more limited, with preliminary evidence for positive associations for both outcomes.[23,24] A study examining wildfire smoke exposure in San Francisco Bay Area, California, found that exposure to wildfire-specific $PM_{2.5}$ was associated with increased risk of large for gestational age.[24] Wildfire exposure during the second trimester in Colorado was associated with small for gestational age.[23]

Given that racially and ethnically marginalized populations have been shown to be more vulnerable to the adverse effects of nonwildfire $PM_{2.5}$, they may also be especially vulnerable to the effects of wildfire-related $PM_{2.5}$.[25] There are persistent racial and ethnic inequities in birth weight outcomes, with Black, Indigenous, and Asian populations experiencing elevated risk of small for gestational age or low birth weight.[26−28] Evidence evaluating whether wildfire $PM_{2.5}$ disproportionately impacts environmental justice communities with higher proportion of people of color, Indigenous people, and low-income residents has been more mixed, with some studies documenting higher exposure in areas with higher proportion of White population while another study found that areas that were more disadvantaged or had higher proportion of marginalized population, such as non-Hispanic American Indian and Alaskan Native people, experienced higher exposure of wildfire $PM_{2.5}$.[1,29,30] These patterns of exposure may also vary by urban and rural locations.[1] Exposure to wildfire smoke may exacerbate existing racial and ethnic inequities in adverse pregnancy outcomes through several pathways. Social marginalization can reduce access to resources that buffer against the effects of wildfire smoke on birth outcomes, such as housing quality, access to air purifiers, ability to relocate during wildfire events, and occupational constraints that impede efforts to reduce exposures, for example among agricultural workers.[10,31,32] Furthermore, marginalized populations may be contending with wildfire-related stressors, such as social and financial challenges during wildfire recovery, due to discriminatory systems of disaster recovery and under-insurance, which in turn can affect birth outcomes.[33−36]

This study investigated associations between daily average prenatal exposure to wildland fire-related $PM_{2.5}$, during the entire pregnancy and within each trimester, in relation to birth weight for all term births (>37 and ≤42 weeks of gestation) in California for 2007−2018. The study population included term births to delineate wildfire exposure's effect on fetal growth and birth weight outcomes, separate from its impact on preterm birth. We assessed whether the magnitude of association was more pronounced among racially/ethnically marginalized populations, specifically non-Hispanic Black, Asian, American Indian and Alaska Native, and Hispanic populations.

METHODS

Study Population

This study leveraged a population-based state-wide cohort of all singleton term births in California for 2007−2018, using birth certificate data. This data set included information about the characteristics of birthing people and their newborns: maternal health and sociodemographic factors, gestational age, birth weight, and address at the time of delivery. Addresses were geocoded to latitudes and longitudes using ArcGIS, which enabled linkage to wildland fire $PM_{2.5}$. We excluded births that were missing sex, birth weight, wildfire exposure, and covariates (birthing parent age, insurance type at delivery, education), and births with gestational age <37 weeks or ≥42 weeks.[37] Births with implausible birth weight (<100 g or >9000 g) were also excluded (Supplemental Figure S1). Study protocols, with a waiver of informed consent for this records-based study, were approved by the California Health and Human Services Agency (#13-05-1231), as well as the Institutional Review Boards of the University of California, San Francisco (#19-28443) and the University of California, Berkeley (#2013-10-5693).

Exposure Assessment

A fused data product based on the U.S. Environmental Protection Agency (EPA)'s Community Multiscale Air Quality Model (CMAQ) was used to assess location-specific exposure to air pollution from fire emission. CMAQ is a multipollutant, three-dimensional Eulerian chemical transport model (CTM) that estimates total ambient concentrations of pollutants such as $PM_{2.5}$ mass, $PM_{2.5}$ chemical components, or ozone using input emission sources, including wildfires. Fire emissions were estimated using the BlueSky framework that considers the area burned, fuel loading, the fraction of biomass fuel consumed by fire, and emission factors.[38] SmartFire2 determined fire dates, size, types, and locations based on sources including satellites and incident report.[39] Fuel Characteristic Classification System was used to derive fuel type and loading data.[40] Fuel consumption and resulting emissions were calculated using fuel type, loading and fuel moisture, which was acquired from the Weather Information Management System.[41] The EPA's CMAQ simulations were made using five different versions of the model (5.01, 5.02, 5.2, 5.21, and 5.3). The configurations were based on the best available CMAQ versions at the time of simulation. The contribution of wildfires to ambient $PM_{2.5}$ concentrations was calculated as the difference between model runs including and excluding wildfire smoke emissions. The CMAQ model was applied to the continental U.S. with 12 km grid resolution for years 2007−2018. Details of the model methodology have been published elsewhere.[17,42,43]

Bias correction was implemented to address CMAQ estimates' tendency to underestimate $PM_{2.5}$ and minimize exposure assignment errors. Briefly, the 12 km CMAQ model daily estimates were fused with the EPA Air Quality System (AQS) ambient air quality using an adapted three-step method

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Table 1. Participant Characteristics by Average Daily Wildland Fire $PM_{2.5}$ during Pregnancy, 2007−2018 (N = 4,537,418)[a,b,c]

	overall sample	wildland fire $PM_{2.5}$ low-tertile 1	wildland fire $PM_{2.5}$ medium-tertile 2	wildland fire $PM_{2.5}$ high-tertile 3	wildland fire $PM_{2.5}$mean (SD)
term birth (N)	4,537,418	1,512,473	1,512,473	1,512,472	
birth weight outcome [N (Prevalence %)]					
low birth weight	86,426 (1.9)	29,423 (1.9)	28,503 (1.9)	28,500 (1.9)	0.84 (0.8)
small for gestational age	390,377 (8.6)	132,342 (8.8)	130,554 (8.6)	127,481 (8.4)	0.83 (0.8)
large for gestational age	442,049 (9.7)	142,293 (9.4)	145,689 (9.6)	154,067 (10.2)	0.88 (0.8)
birth weight outcome [mean (SD)]					
birth weight	3394.24 (450.30)	3386.26 (448.3)	3394.15 (449.0)	3402.31 (453.6)	–
birth weight Z-score	0.02 (0.98)	0.01 (0.97)	0.02 (0.98)	0.04 (0.98)	–
race and ethnicity					
Black	223,802 (4.9)	5.3	4.9	4.6	0.79 (0.7)
Asian and Pacific Islander	652,707 (14.4)	15.2	14.8	13.2	0.81 (0.7)
Hispanic	2,267,431 (50.0)	51.6	50.2	48.1	0.81 (0.7)
American Indian & Alaska Native	17,296 (0.4)	0.3	0.4	0.5	1.20 (1.2)
Other	112,868 (2.5)	2.3	2.5	2.7	0.93 (0.9)
White	1,263,314 (27.8)	25.3	27.2	31.0	0.95 (0.9)
age					
<20	297,085 (6.5)	6.7	6.4	6.5	0.84 (0.8)
20−34	3,362,459 (74.1)	73.4	74.3	74.6	0.85 (0.8)
≥35	877,874 (19.3)	19.9	19.3	18.9	0.84 (0.8)
payment type at delivery					
private	2,184,378 (48.1)	48.2	48.1	48.1	0.86 (0.8)
public	2,166,092 (47.7)	47.5	47.5	48.2	0.85 (0.8)
other	186,948 (4.1)	4.3	4.4	3.7	0.77 (0.7)
education					
less than high school	874,779 (19.3)	20.3	18.9	18.7	0.82 (0.8)
high school	1164,944 (25.7)	24.7	25.8	26.6	0.87 (0.8)
some college	1,172,634 (25.8)	24.6	25.9	27.1	0.88 (0.8)
Bachelor's or Graduate Degree	1,325,061 (29.2)	30.5	29.4	27.7	0.83 (0.8)
season of conception					
spring (march to may)	1,114,412 (24.6)	18.6	21.9	33.3	1.00 (0.9)
summer (june to august)	1,081,131 (23.8)	21.0	25.7	24.8	0.87 (0.7)
fall (september to november)	1,134,527 (25.0)	36.2	24.6	14.2	0.62 (0.6)
winter (december to february)	1,207,369 (26.6)	24.3	27.8	27.8	0.87 (0.8)

[a]Overall distribution is displayed by count and column percentage in parentheses. [b]Categorical exposure distribution: dichotomous birth outcomes are displaced by count and prevalence percentage; continuous birth outcomes are displayed by mean and standard deviation; participant characteristics is displayed by percentage. [c]Continue exposure distribution: Mean and standard deviation are displayed by participant characteristics in $\mu g/m^3$ for categorical birth outcomes and participant characteristics.

to blend temporal details from observations and spatial information from modeling.[44] This method involved ordinary Kriging of the observations using the annual mean CMAQ to provide spatial structure, scaling daily CMAQ using mean observations, and calculating a weighted average based on prediction of temporal variance. Furthermore, to account for situations where the bias corrections resulted in nonwildfire concentrations that far exceed expectations, we calculated the 95th percentile of daily $PM_{2.5}$ concentrations on smoke-free days for each grid, based on the National Oceanic and Atmospheric Administration (NOAA) Hazard Mapping System. Adjustments in nonwildfire $PM_{2.5}$ were capped at this 95th percentile if bias corrections increased concentrations by > 5 $\mu g/m^3$, with the remainder attributed to wildfire $PM_{2.5}$. As described in a previous study, bias correction of the CMAQ estimates increased the R^2 from 0.27 to 0.55 compared to weekly measurements from reference grade monitors, in addition to reducing bias and mean error substantially. More details about bias correction and performance improvement are described elsewhere.[17]

Using the bias-corrected CMAQ models, we assigned daily average $PM_{2.5}$ concentrations with all sources and without wildfire emissions sources from the grids to the birthing person's residence at the time of delivery. The difference between the total and nonwildfire $PM_{2.5}$ concentrations was used to estimate the wildfire emissions exposure. The exposure measures included average $PM_{2.5}$ concentrations due to wildfire smoke over the entire pregnancy, and for each of the three trimesters.

Outcomes

Small for gestational age (SGA) term births had a birth weight less than the United States sex-specific 10th percentile of weight for each week of gestation.[45] Large for gestational age (LGA) term births had a birth weight more than the United States sex-specific 90th percentile of weight for each week of gestation.[45] We assessed low birth weight (LBW) cases as term

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births in which the newborn weighs less than 2500 g. We also examined term birth weight continuously, using birth weight *z*-scores for all infants and birth weight in grams[45]

Covariates

The sociodemographic covariates from birth certificate data included the pregnant person's age (years), the principal source of payment of delivery costs (private, public, or other), and educational attainment (less than high school, high school diploma, some college, college degree or higher). To account for seasonality of conception, we used two continuous functions (sine and cosine of 2π times the elapsed fraction of the year on the date of conception).

We used self-reported information from the birth certificates to determine the pregnant person's race and ethnicity: non-Hispanic (NH) Black, NH Asian/Pacific Islander (API), NH American Indian/Alaska Native (AIAN), NH White, other (multiracial, other race, and unknown), and Hispanic. This analysis positioned the variable of race and ethnicity as a proxy for the exposure to past and present social marginalization that racialized people experience, which can affect birth outcomes and wildland fire smoke exposure.[46]

Statistical Analysis

Descriptive analysis assessed the distribution of participant characteristics and birth weight outcomes by tertile of wildfire $PM_{2.5}$ exposure.

We used logistic regression models to assess associations between exposures (average daily exposure to wildfire $PM_{2.5}$ over the entire pregnancy, and average daily exposure during the first, second, and third trimester) and the outcomes (LBW, SGA, and LGA). Linear regression models were used to assess associations between average daily wildfire $PM_{2.5}$ exposure and continuous birth weight outcomes. Models adjusted for sociodemographic factors, including birthing parent age, education, and payment method of delivery costs, as well as seasonality. We used race-stratified models to assess whether the magnitude of association between wildfire $PM_{2.5}$ and birth outcomes may be differential for racially and ethnically marginalized groups.

We conducted several sets of sensitivity analyses to test the robustness of our results. To assess potential nonlinearity in the relationship between wildfire $PM_{2.5}$ and birth weight outcomes, we used linear and logistic regression modeling to examine daily average exposure over the entire pregnancy as a categorical exposure variable using tertile of wildfire $PM_{2.5}$ (referent group: low). We also examined the impact of nonfire $PM_{2.5}$ (i.e., traffic and industrial pollution) and total $PM_{2.5}$ (i.e., both wildland fire and nonfire $PM_{2.5}$) on birth weight outcomes, to assess whether associations with nonfire $PM_{2.5}$ would be consistent with literature, and to investigate associations with cumulative exposure to all sources of $PM_{2.5}$. To account for spatial autocorrelation in the residuals, we used two approaches: mixed effects logistic and linear models, with a random intercept at the census tract level; logistic and linear models with county fixed effect. Lastly, to ensure that our results are robust across different exposure assessment methods, we conducted a sensitivity analysis examining whole pregnancy daily average, calculated from census tract-level machine learning-based wildfire-specific $PM_{2.5}$ estimates and linked to participants based on gestational days.[47]

RESULTS

The study sample included 4,537,418 singleton term births (Table 1). The prevalence of term LBW was 1.9%, SGA was 8.6%, and LGA was 9.7%. The average term birth weight was 3394 g. In terms of wildfire exposure, the mean average daily wildfire $PM_{2.5}$ was 0.85 $\mu g/m^3$ (range: 0.2−15.5, standard deviation: 0.79). Individuals who were exposed to the high tertile of whole pregnancy average daily wildfire $PM_{2.5}$ were more likely to have been AIAN, Other race, or White, had high school or some college level of education attainment, or were conceived during the spring, compared to sample average.

Multivariate modeling results showed that among term births, a 1 $\mu g/m^3$ increase in whole pregnancy average daily exposure to wildland fire $PM_{2.5}$ was associated with decreased odds of LBW (OR = 0.98, 95% CI 0.98−0.99) and SGA (OR = 0.97, 95% CI 0.96−0.97), adjusting for sociodemographic factors and seasonality (Table 2). These associations were statistically significant for exposure in the first and third trimester for LBW, and for all trimesters for SGA. In contrast, a 1 $\mu g/m^3$ increase in whole pregnancy average daily exposure to wildland fire $PM_{2.5}$ was associated with increased odds of LGA among term births (OR = 1.06, 95% CI 1.05−1.06), as well as increased term birth weight (estimate = 11.31, 95% CI 10.78−11.84) and term birth weight *z*-score (estimate = 0.02, 95% CI 0.02−0.02), among term births, independent of sociodemographic covariates and seasonality. These associations were also observed in average daily exposure to wildfire $PM_{2.5}$ within the first, second, and third trimesters.

Figure 1 displays the estimates from models stratified by race/ethnicity. Models stratified by race/ethnicity showed that among term births, the direction and magnitude of associations were similar across racial/ethnic groups for LBW among Other racial (OR = 0.94, 95% CI 0.90−0.99) and Hispanic (OR = 0.98, 95% CI 0.97−0.99) groups, and for SGA among White (OR = 0.99, 95% CI 0.98−1.00), Other (OR = 0.97, 95% CI 0.95−1.00), and Hispanic (OR = 0.97, 95% CI 0.96−0.98) groups (Figure 1). For LGA, term birth weight, and term birth weight z-score, the magnitude of association was the largest among the Other racial group (LGA OR = 1.05, 95% CI 1.03−1.08; birth weight estimate = 8.51, 95% CI 5.40, 11.61; birth weight z-score estimate = 0.02, 95% CI 0.01, 0.02) and Hispanic (LGA OR = 1.05, 95% CI 1.04−1.05; birth weight estimate = 9.26, 95% CI 8.44, 10.08; birth weight z-score estimate = 0.02, 95% CI 0.02, 0.02) birthing people, and the smallest among Black birthing people (LGA OR = 1.01, 95% CI 0.99−1.04; birth weight estimate = 3.09, 95% CI 0.34, 5.83; birth weight z-score estimate = 0.00, 95% CI 0.00, 0.01). Notably, the direction of effects differed for AIAN population. Specifically, while a 1 $\mu g/m^3$ increase in whole pregnancy daily average wildland fire $PM_{2.5}$ was associated with increased odds of LGA in the overall study sample and within most racial and ethnic groups, it was associated with decreased odds of LGA for term births among AIAN birthing people (OR = 0.95, 95% CI 0.92−0.99). For the other birth weight outcomes, the direction of association among AIAN people was also in the opposite direction compared to results for other racial and ethnic groups and in the overall study sample, though the confidence intervals were wide.

Sensitivity analyses assessed average daily exposure to wildfire $PM_{2.5}$ categorically, with the lowest tertile of exposure as the referent group. Results showed that the highest tertile of exposure was associated with greater magnitude of decreased

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Table 2. Adjusted Estimates of Birth Weight Outcomes Associated with 1 $\mu g/m^3$ Increase in Wildland Fire $PM_{2.5}$, California, 2007–2018 (N = 4,537,418)[a,b]

	low birth weight		small for gestational age		large for gestational age		birth weight (gram)		birth weight Z-score	
wildland fire $PM_{2.5}$ (average daily total)	model 1 OR (95% CI)	model 2 OR (95% CI)	model 1 OR (95% CI)	model 2 OR (95% CI)	model 1 OR (95% CI)	model 2 OR (95% CI)	model 1 Coef (95% CI)	model 2 Coef (95% CI)	model 1 Coef (95% CI)	model 2 Coef (95% CI)
whole pregnancy	0.98	0.98	0.97	0.97	1.05	1.06	9.94	11.31	0.02	0.02
	(0.97–0.99)	(0.97–0.99)	(0.97–0.98)	(0.96–0.97)	(1.05–1.06)	(1.05–1.06)	(9.42, 10.47)	(10.78, 11.84)	(0.02, 0.02)	(0.02, 0.02)
first trimester	0.98	0.99	0.98	0.98	1.03	1.03	6.53	5.53	0.01	0.01
	(0.98–0.98)	(0.98–0.99)	(0.97–0.98)	(0.98–0.99)	(1.03–1.03)	(1.03–1.03)	(6.17, 6.88)	(5.14, 5.92)	(0.01, 0.01)	(0.01, 0.01)
second trimester	1.00	1.00	0.99	0.99	1.02	1.03	3.19	4.94	0.01	0.01
	(1.00–1.01)	(0.99–1.00)	(0.99–0.99)	(0.98–0.99)	(1.02–1.02)	(1.02–1.03)	(2.85, 3.53)	(4.57, 5.32)	(0.01, 0.01)	(0.01, 0.01)
third trimester	1.00	0.99	1.00	0.99	1.01	1.03	2.39	4.95	0.00	0.01
	(0.99–1.00)	(0.98–1.00)	(0.99–1.00)	(0.98–0.99)	(1.01–1.02)	(1.02–1.03)	(2.08, 2.69)	(4.61, 5.29)	(0.00, 0.01)	(0.01, 0.01)

[a]Model 1: adjusted for age, insurance type at delivery, and education. [b]Model 2: additionally adjusted for seasonality (sine and cosine pair).

odds of LBW and SGA, and increased odds and estimates of LGA and term birth weight in gram and z-score, compared to the medium tertile of exposure (Supplemental Table S1). Examining nonfire $PM_{2.5}$ and total $PM_{2.5}$, we found that 1 $\mu g/m^3$ increase in whole pregnancy daily average exposure was associated with increased odds of term LBW and SGA, and decreased odds of LGA and units of term birth weight in gram and in z-score (Supplemental Table S2). Lastly, results from mixed effects models with a random intercept accounting for spatial clustering by census tract were comparable to the main model, with slightly attenuated odds ratios and estimates but still statistically significant confidence intervals (Supplemental Table S3). Models with county fixed effects produced similar results for SGA and LGA, and attenuated estimates and confidence intervals for the other outcomes (Supplemental Table S4). Estimated odds ratios and differences were slightly larger, using machine learning-based wildfire $PM_{2.5}$, and inference from the confidence intervals were consistent with results from our main exposure assessment methods (Supplemental Table S5).

DISCUSSION

In a racially and ethnically diverse, population-based cohort of all term births in California, we found that increased exposure to wildland fire $PM_{2.5}$ during pregnancy was associated with LGA and increased birth weight. This relationship was also observed for exposure within the first, second, and third trimesters. Furthermore, findings demonstrated that wildfire $PM_{2.5}$ may differentially affect racially and ethnically marginalized populations. Specifically, the magnitude of association for higher birth weight outcomes was larger among Hispanic population and Other racial groups. Among AIAN birthing people, the relationship between exposure to wildfire $PM_{2.5}$ and birthweight outcomes was in the opposite direction, compared to the overall study sample and other racial and ethnic groups. This study makes several novel contributions by investigating the effects of wildfire-related $PM_{2.5}$, an increasingly important source of air pollution, on term birth weight outcomes, thus filling gaps in the literature related to fetal growth impacts and centering implications for health equity by assessing differential effects by race and ethnicity.

Extant studies examining the relationship between wildfire $PM_{2.5}$ and birth weight outcomes have more frequently documented that an increase in exposure was associated with low or reduced birth weight, in contrast to our findings. In a 2021 systematic review, 6 out of 7 studies published between 2011 and 2019 documented an inverse relationship between wildfire $PM_{2.5}$, PM_{10}, and proximity to wildfire events with birth weight outcomes, though the risk of bias was assessed to be high across these studies.[20] For example, a study conducted in California compared birth weight for infants born before and after a series of 2003 wildfires in the South Coast Air Basin, and found that mean birth weight saw an average decrement of 7.0 g (95% CI: −11.8, −2.2) when the wildfire occurred during the third trimester, 9.7 g when it occurred during the second trimester (95% CI: −14.5, −4.8), and 3.3 g when it occurred during the first trimester (95% CI: −7.2, 0.6), compared with pregnancies after the wildfires.[21] Similarly, a study in Colorado that integrated NOAA's satellite imagery-measured daily smoke plume extent with interpolated values from $PM_{2.5}$ monitors found that exposure to 1 $\mu g/m^3$ of wildfire $PM_{2.5}$ during the first trimester was associated with 5 g decrement in birth weight and increased risk of SGA.[23] Differences in study

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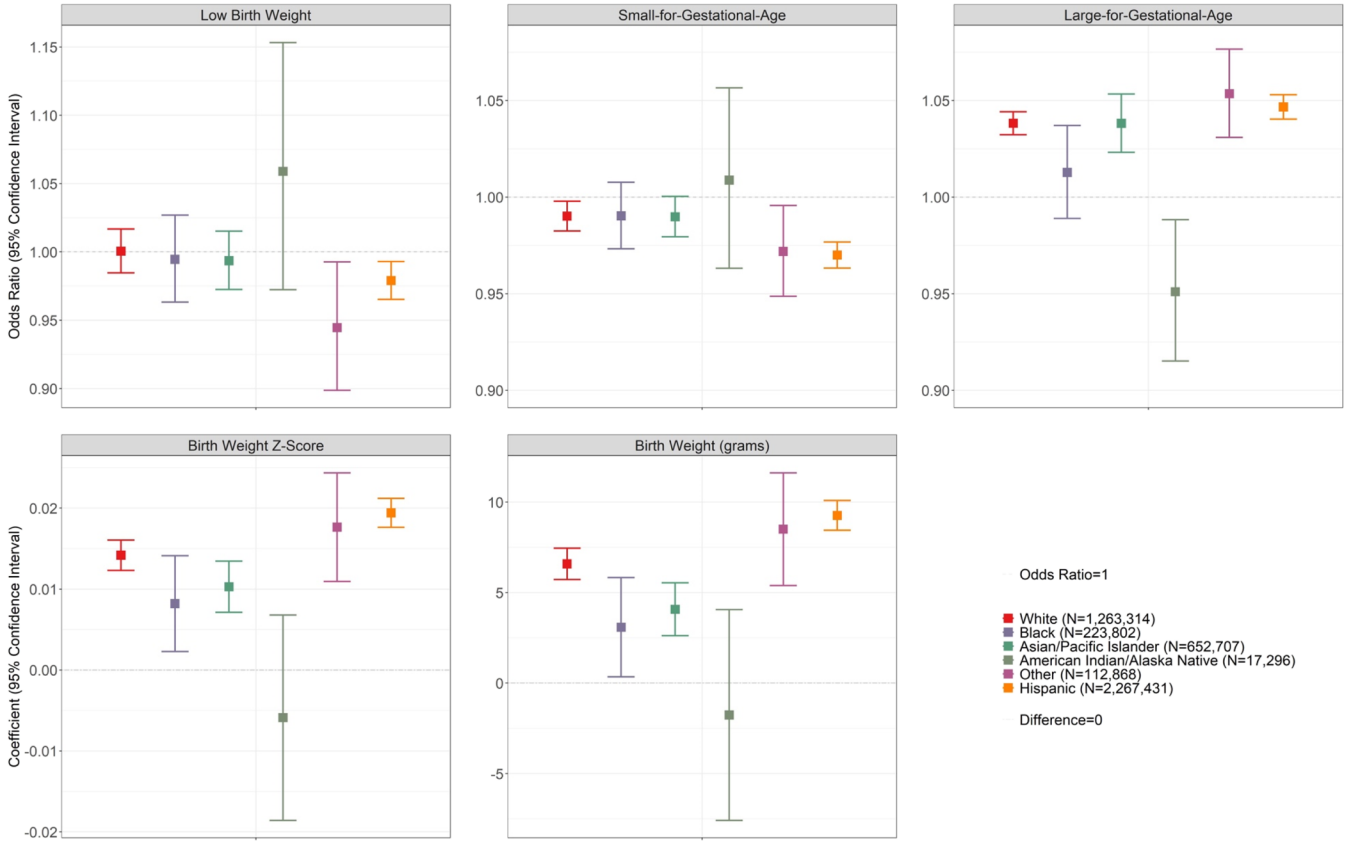

Figure 1. Adjusted odd ratios of adverse birth outcomes associated with 1 $\mu g/m^3$ increase in pregnancy daily average wildland fire $PM_{2.5}$, California, by race and ethnicity, 2007−2018 (N = 4,537,418). Models adjusted for age, insurance type at delivery, education, and seasonality.

design, methodology, and setting may explain the heterogeneity in study findings. For example, our study used a different exposure assessment method that measured wildland fire-specific $PM_{2.5}$ using CMAQ, which provided more granularity in assessing fire-related pollution and differentiated fire and nonfire $PM_{2.5}$ sources, compared to proxy measures, such as residence in affected areas. In a supplemental analysis, we found that exposure to nonfire $PM_{2.5}$ and total exposure to $PM_{2.5}$ from all sources were inversely associated with birth weight outcomes. This suggests that measuring wildfire-specific $PM_{2.5}$ may reveal distinct effects on birth weight not captured in studies of total $PM_{2.5}$ exposure, due to the unique chemical composition, higher toxicity, and exposure patterns of wildfire $PM_{2.5}$. In contrast, our study findings were consistent with a study set in Australia documenting that proximity of the birthing person's residence to the Canberra fires in 2003 was associated with higher birth weight for male infants.[22] Another study in the San Francisco Bay Area found that exposure to wildfire-specific $PM_{2.5}$ and more days of wildfire-specific $PM_{2.5}$ above 5 $\mu g/m^3$ in the second trimester were associated with increased risk of LGA, which aligns with our study's findings.[24] On the other hand, results from our study showed that the estimates were similar across all three trimesters, rather than highlighting an especially sensitive period during which the effects of wildland fire are more impactful. Furthermore, this study only included term births to disentangle the effects on preterm birth and birth weight, given existing evidence that wildfire smoke may be associated with increased risk of preterm birth, and analyses of birth weights in all births may also be capturing the effects on preterm birth.[17,18] Lastly, compared to existing studies with shorter study period or limited geographic coverage around specific wildfire events, our study included more than four million births spanning across a decade with multiple fire seasons, which increased statistical power to detect associations.[1]

Several possible mechanisms may explain the relationships between wildfire $PM_{2.5}$ and elevated birth weight and LGA, which may adversely affect both infants and birthing people. LGA infants may be more likely to be delivered via caesarean section, and these deliveries can be complicated by maternal morbidities such as postpartum hemorrhage, and neonatal complications such as birthing injury and hypoglycemia.[15,48] First, epigenetic mechanisms related to wildfire $PM_{2.5}$ may increase birth weight due to interactions between genetic factors, excess nutrition, and exposure to adverse intrauterine environment.[48] For example, LGA infants showed greater placental DNA methylation, an epigenetic mechanism that may be influenced by pollutants and may be associated with fetal overgrowth.[49−51] Second, studies have documented associations between wildfire-specific $PM_{2.5}$, as well as ambient $PM_{2.5}$, and gestational diabetes, which can elevate the risk of delivering LGA infants.[23,52,53] Existing evidence has documented that $PM_{2.5}$ may result in increased inflammation, the activation of immune cells, and oxidative stress, or an imbalance between free radical generation and antioxidant defense, which are associated with increased risk of gestational diabetes.[6,54−56] Lastly, exposure to wildfire can alter health promoting behaviors, such as staying indoors to limit exposure and reduction in physical activities, which may influence pregnancy and infant outcomes.[10,57] Understanding how

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wildfire related $PM_{2.5}$ influences birth weight outcomes through the interplay between epigenetic mechanisms, individual-level factors, and environmental influence can inform efforts to protect the wellbeing of pregnant people and infants.

Differential results by race and ethnicity highlight the importance of understanding wildfires' impact on diverse population groups.[46] Notably, our study showed that the relationship between wildfire $PM_{2.5}$ and birth weight in AIAN people differed from the directions of association in the overall sample, and in other racial and ethnic groups, such that exposure to wildfire was associated with lower birth weight. Indigenous peoples are disproportionately affected by wildfires and resulting evacuation in the United States and Canada.[58−60] For instance, a previous study in California found that census tracts with a higher proportion of AIAN residents, compared to their state-wide representation, were up to 2.8 times more likely to have been exposed to wildfire $PM_{2.5}$ overall, particularly in rural areas.[29] This was consistent with the descriptive finding in our study regarding the elevated representation of AIAN in the high tertile of average daily wildfire exposure across pregnancy in our study. The United States has a history of colonization and land dispossession that forcibly moved Indigenous peoples to areas that are now more susceptible to climate extremes, including higher temperatures and wildfire risks.[61,62] The suppression of Indigenous land management practices in California has further worsened wildfire risks.[60,63] This history of oppression and the excess burden of exposure affirm calls for Indigenous peoples' fire knowledges and practices to lead wildfire management.[60,63,64] Moreover, Indigenous populations contend with lack of access to emergency and medical services, persistent health inequities, including in perinatal health, and other social stressors that together may amplify the effects of wildfire on adverse birth outcomes.[61,65,66]

Second, we also found that the magnitudes of association for LGA and birth weight were more pronounced among Hispanic and Other racial and ethnic groups. Though there is some evidence that wildfire $PM_{2.5}$ concentration may be impacting White and higher income populations, particularly those living in the wildland−urban interface, other studies have documented that more recently, Hispanic and other racialized groups are experiencing higher wildfire $PM_{2.5}$, in addition to the existing inequities around exposure to all-source ambient $PM_{2.5}$.[18,67,68] Studies assessing the differential impact of wildfire $PM_{2.5}$ on birth weight are limited, but a previous study has documented that its effects on preterm birth were also more pronounced among Black, Hispanic, Asian, and AIAN participants in California, and simultaneous exposure to both heatwave days and smoke days was associated with greater odds of preterm birth.[19] This evidence highlights the importance of further investigating the effects of wildfires in the context of extreme weather events, such as heatwaves. Racially and ethnically marginalized populations may be contending with the dual burden of social marginalization, which can lead to poor housing quality or indoor air quality and an inability to reduce outdoor physical activity due to occupational constraints or being unhoused, all of which can amplify their inequitable exposure to wildfire $PM_{2.5}$.[31,32,69,70] Furthermore, these populations may have a harder time responding to wildfires due to financial strain and lack of transportation, which could impede their capacity to relocate or evacuate.[33,71]

The strengths of this study include the utilization of a state-wide population-based cohort offering racial and ethnic diversity and comprehensive geographic coverage over a robust time period to characterize wildfire events, a rigorous exposure classification method that estimated wildland fire-specific $PM_{2.5}$, assessment of multiple birth weight outcomes, and adjustment of individual-level confounders in regression modeling. One limitation is potential misclassification of the exposure. While the CMAQ model has several advantages, it does not capture the more local sources of burning, such as agricultural waste or residential wood burning, resulting in underestimation of the exposure. Furthermore, we assigned exposure to residential address at the time of delivery, which does not capture changes in exposures for those that moved residences during pregnancy, possibly to cope with the impact of wildfire events or due to evacuation orders. However, there is some evidence suggesting that the potential for exposure misclassification may be small on average.[72] Another limitation is that we used one method, the bias-corrected CMAQ, to assign wildfire $PM_{2.5}$ exposure at a time when multiple credible methods are available and no single method is recognized as "the gold-standard". While incorporation of multiple exposure models was beyond the scope of this analysis, we recognize that the strength and nature of associations may still depend on the choice of exposure models.[73] The wildfire $PM_{2.5}$ predictions of physics-based CTMs, like CMAQ, are dependent on the accuracy of the wildfire emission inputs, including their magnitude, timing, spatial distribution, and plume rise, which are still uncertain. Utilization of protective health resources, such as indoor air filtration and masks, may also impact exposure, and future studies can collect survey and behavioral data to examine how the perception of wildfire risk and health-protective behaviors during pregnancy shape birthing people's wildfire exposure and their implications for perinatal outcomes. While our study design and available information did not allow examination of health behaviors, we adjusted for socioeconomic factors as potential confounders, since they may influence people's ability to evacuate or undertake other protective measures, and future studies can more closely examine the relationship between socioeconomic resources and both individual- and community-level measures to reduce wildfire exposure. There may also be residual confounding from other unmeasured variables, such as area-level temperature or rainfall. Future studies can investigate the interplay between wildfire, place-based indictors of marginalization related to housing quality, transportation access, occupation, residential segregation, and access to fire prevention and firefighting resources on perinatal outcomes. Despite these limitations, this study contributes important evidence that exposure to wildfire $PM_{2.5}$ is associated with increased birth weight outcomes and highlights differential effects for racialized populations. Future research that enhances scientific understanding of how wildfire-related $PM_{2.5}$ shapes birth weight outcomes through the interplay between structural factors and epigenetic mechanisms can inform efforts to protect the wellbeing of pregnant people and infants.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.5c05040.

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Tables with estimates from sensitivity analyses assessing wildfire exposure and birth weight outcomes, and flowchart of analytic sample selection (PDF)

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Notes

The authors declare no competing financial interest.

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