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Article

Climate Justice and California's Methane Superemitters: Environmental Equity Assessment of Community Proximity and Exposure Intensity

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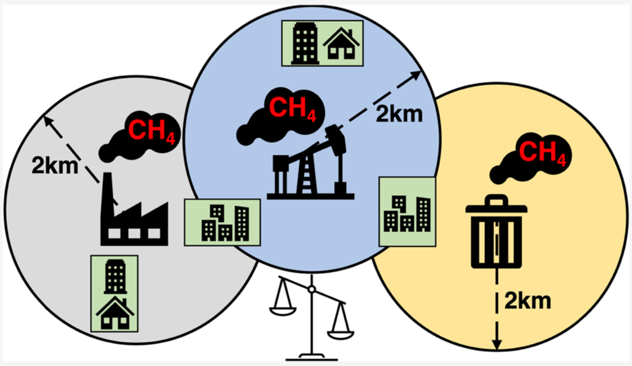

ABSTRACT: Methane superemitters emit non-methane copollutants that are harmful to human health. Yet, no prior studies have assessed disparities in exposure to methane superemitters with respect to race/ethnicity, socioeconomic status, and civic engagement. To do so, we obtained the location, category (e.g., landfill, refinery), and emission rate of California methane superemitters from Next Generation Airborne Visible/Infrared Imaging Spectrometer (AVIRIS-NG) flights conducted between 2016 and 2018. We identified block groups within 2 km of superemitters (exposed) and 5−10 km away (unexposed) using dasymetric mapping and assigned level of exposure among block groups within 2 km (measured via number of superemitter categories and total methane emissions). Analyses included 483 superemitters. The majority were dairy/manure (n = 213) and oil/gas production sites (n = 127). Results from fully adjusted logistic mixed models indicate environmental injustice in methane superemitter locations. For example, for every 10% increase in non-Hispanic Black residents, the odds of exposure increased by 10% (95% confidence interval (CI): 1.04, 1.17). We observed similar disparities for Hispanics and Native Americans but not with indicators of socioeconomic status. Among block groups located within 2 km, increasing proportions of non-White populations and lower voter turnout were associated with higher superemitter emission intensity. Previously unrecognized racial/ethnic disparities in exposure to California methane superemitters should be considered in policies to tackle methane emissions.

KEYWORDS: *methane, socioeconomic factors, race, ethnic groups, environmental justice, California*

■ INTRODUCTION

Since studies first documented the disproportionate siting of solid and hazardous waste facilities in Black communities in the 1980s,[1,2] subsequent environmental justice scholarship has demonstrated a consistent correlation between race, poverty, and pollution burden across diverse environmental hazards and geographies. Literature reviews conclude that people of color reside in neighborhoods with worse air quality[3−5] and more environmental hazards[6−9] than White people in the United States. In California, environmental hazards including clean-up, hazardous waste, and solid waste sites are more regressively distributed with respect to race/ethnicity than poverty, suggesting that structural racism as opposed to class predominates in shaping inequalities.[10] This pattern is consistent with the history of legal racial discrimination in civil rights, housing, employment, and education that has produced staggering gaps in present-day distributions of wealth across racial groups and led to persistent racial residential segregation.[11−13]

In the current analysis, we investigate the social characteristics of communities near methane superemitters to assess potential environmental justice concerns. Methane superemitters are point sources of large methane releases that span a wide range of industries. Though methane spends less time in the atmosphere than carbon dioxide (CO_2), its higher potency as a greenhouse gas makes its per-ton "Global Warming Potential" some 84−86 times that of CO_2 over a 20-year period.[14] Therefore, compared to CO_2, reductions in methane emissions can more rapidly slow climate change. As a result, emission reductions at large point sources of methane, including landfills, the oil and gas supply chain, livestock operations, and power plants, are being prioritized for near-term climate mitigation.[15,16] Atmospheric methane concentrations, however, have increased rapidly since 2008, driven

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primarily by the agriculture, waste, and fossil fuel sectors.[17] Moreover, studies suggest methane emissions in the U.S. substantially eclipse emission inventory estimates, implying that methane releases are under-reported.[18,19] In the natural gas sector, studies show that a small fraction of "superemitters" (responsible for ~5% of leaks) contributes a disproportionate and under-reported amount of total methane emissions (~50% of emissions from leaks), often due to abnormal and avoidable operating conditions, including equipment malfunctions.[20,21]

While methane superemitters are of significant interest due to their climate impacts, and specific types of superemitters have been investigated from an environmental justice perspective (e.g., landfills, oil and gas wells, and concentrated animal feeding operations [CAFOs]), the possibility that superemitters overall are disproportionately located in communities of color has not been examined. Although not directly toxic to humans, methane is co-emitted with other pollutants that do threaten the health of nearby communities. For example, upstream processes involved in the production and distribution of oil and natural gas emit numerous hazardous air pollutants in addition to methane, including particulate matter (PM), secondary ozone formation, and non-methane volatile organic compounds (VOCs),[22−28] several of which are associated with neurological damage, birth defects, and cancer.[29,30] California studies indicate that living in proximity to active oil and gas production wells is associated with an increased risk of adverse birth outcomes.[31,32] Air quality sampling during the largest point-source methane release ever recorded in the U.S.—the Aliso Canyon Natural Gas Storage field active blowout in 2015—revealed elevated levels of several hazardous air pollutants including benzene, a carcinogen, and reproductive toxicant.[33] Policies aimed at reducing methane emissions also show co-benefits for non-methane VOC and criteria air pollutant emissions. For example, a global study estimated air quality health co-benefits of climate policy in the range of \$8 to \$40 per ton of greenhouse gas.[34]

Landfills can contaminate local drinking water supplies with hazardous chemicals via leachate and also release "biogas," an odorous chemical mixture of methane, CO_2, and other VOCs. Residence near landfills has been associated with elevated rates of cancer, low birth weight, and birth defects.[35,36]

Research has also documented releases of ammonia, hydrogen sulfide, endotoxins, pathogens, and other airborne contaminants, along with methane from CAFOs. Residence near these operations is associated with asthma, decreased lung function, stress, and infection with antibiotic-resistant bacteria.[37] Several studies report correlations between dairy farm ammonia and greenhouse gas emissions.[38−40] These releases can further contribute to PM formation and exceedance of National Ambient Air Quality Standards for $PM_{2.5}$ in intense CAFO areas like California's San Joaquin Valley.[40−42]

Refineries emit hazardous air pollutants, including benzene, toluene, ethylbenzene, and xylene (BTEX) compounds, and criteria air pollutants;[43−45] gas power plants may co-emit the same pollutants along with leaked or incompletely combusted methane.[46,47] Such emissions can impact community health, including higher risks of cancer[48,49] and respiratory problems.[50−52]

Methane also contributes to the formation of ground-level ozone, which is linked to premature mortality, impaired respiratory health, and metabolic effects.[53,54] By one estimate, reducing global methane emissions by 20% would result in approximately 370 000 avoided deaths over 20 years via reductions in global background ozone concentrations.[55] Finally, many methane-emitting industries are predominately located in rural communities that also face reduced access to health care, higher rates of poverty, and lower rates of employment compared to urban areas.[56−58] These social stressors may worsen the health effects of pollutant exposures associated with methane superemitters.

In this study, we leverage data from a recent effort to identify methane superemitters in California using airborne remote sensing[59] and estimates of community demographics refined via novel dasymetric mapping techniques to characterize populations residing near methane superemitters with respect to race, ethnicity, and socioeconomic status (SES). Our analyses operationalize area-level measures of race/ethnicity and SES to assess inequities in community burdens of methane superemitters and inform strategies to address potential environmental injustices in regulatory enforcement and permitting of these sources of potent greenhouse gases and copollutants.

■ MATERIALS AND METHODS

In this cross-sectional environmental justice analysis of methane superemitters in California, we used the block group as our unit of analysis. Prior research indicates that this is an appropriate spatial scale to assess racial/ethnic and socioeconomic disparities in environmental exposure.[60] All California block groups included in the U.S. Census Bureau's 2016 TIGER/Line Files were eligible for inclusion.

Methane Superemitter Data. We obtained data on superemitters from the California Air Resources Board (CARB).[59] In brief, CARB provided data from the California Methane Survey conducted by NASA's Jet Propulsion Laboratory, which used Next Generation Airborne Visible/Infrared Imaging Spectrometer (AVIRIS-NG) flights conducted between 2016 and 2018 to provide systematic information on methane emission point sources. The AVIRIS-NG flights identified 564 distinct strong methane point sources and their average hourly emission rates (kg/h). The investigators assigned infrastructure elements within energy, agriculture, and waste sectors. From these descriptors, we created seven superemitters categories: landfill/compost, power plant, refinery, wastewater treatment, oil/gas distribution (i.e., compressors, storage facilities, distribution lines, processing plants, liquid natural gas stations, and gathering lines), oil/gas production (stacks, drill rigs, tanks, lagoons, pump-jacks, plugged wells, and unknown infrastructure), and dairy/manure. We excluded superemitters located >2 km from the boundary of a populated area ($n = 81$ (14%), Table S1).

Sociodemographic Data. For analyses, we used 2012−2016 American Community Survey data[61] to compute block group characteristics: population density (individuals per km^2), percent Hispanic and percent non-Hispanic Native American, Asian, Black, and White, percent rural dwellers, percent linguistically isolated households (i.e., no one in the household older than 14 speaks English "very well"), and six measures of SES: percent living below the federal poverty threshold, percent with less than a high school education, percent unemployed, percent renters (versus home owners), percent Supplemental Nutrition Assistance Program (SNAP) recipients, and median household income. Urban block groups consisted of 100% urban population, semirural contained >0 to

99% urban population, and rural 0%. A block group-level measure of voter turnout was created using precinct-level election data from the Statewide Database, California's redistricting database,[62] following Maizlish.[63] This measure is the average percent of registered voters who voted in the 2012 and 2016 general elections.

Superemitter Exposure Measures. To characterize populations living close to superemitters in California, we constructed a high-resolution spatial layer representing populated areas at sub-block granularity using novel dasymetric mapping methods. Dasymetric mapping refers to the process of disaggregating spatial data—in this case, census block boundaries—to finer spatial units of analysis using ancillary data. It has been used in prior environmental justice analyses[64] and helps to accurately identify residences in rural settings where census blocks (the smallest census geographic unit) can be large (i.e., >50 km^2) and sparsely populated. Two ancillary data sources were used along with census block population estimates to construct this layer: (1) a statewide database of tax parcel boundaries (smaller than census blocks) from DMP LightBox[65] and (2) a layer of building footprints for nearly 11 million buildings in California, part of a nationwide layer developed by Microsoft using satellite imagery and machine learning classification techniques.[66]

Creation of the final populated area layer using these data followed a tiered process. First, for each census block, we identified all residential parcels within it based on land use descriptions provided in the statewide parcel dataset for each individual parcel (Table S2 and Figure S1). If residential parcels were identified in a given block, its population was assumed to be located within these residential areas alone. This parcel-based apportionment accounted for 91.8% of California's population.

Second, for those blocks containing no residential parcels but which had a nonzero population count according to the 2010 census, we allocated population evenly across all building footprint areas identified within them. This was common for sparsely populated blocks in wilderness areas or zones of low-density agriculture, with parcels classified as "open space" or "agricultural" in the statewide parcel database, but which still contain residences. Apportioning population to all building footprint areas in these blocks has the advantage of masking out all open land from being considered as populated area but has the disadvantage of misallocating some population to nonresidential buildings (e.g., barns, warehouses, processing facilities). This building footprint-based apportionment accounted for 7.9% of California's population.

Finally, a small number of census blocks contained neither residential parcels nor building footprints but still had a nonzero population count. These blocks were predominantly in very low-density wilderness areas with parcels generally classified as forests/open space and where tree canopies occluded detection of building rooftops via satellite imagery. We assumed that these blocks' populations were evenly distributed across the entire block area. This "default" method of population apportionment was applied to 0.3% of the state's population. The final populated area's layer was created by merging the results of these three-tiered population apportionment steps into one statewide map.

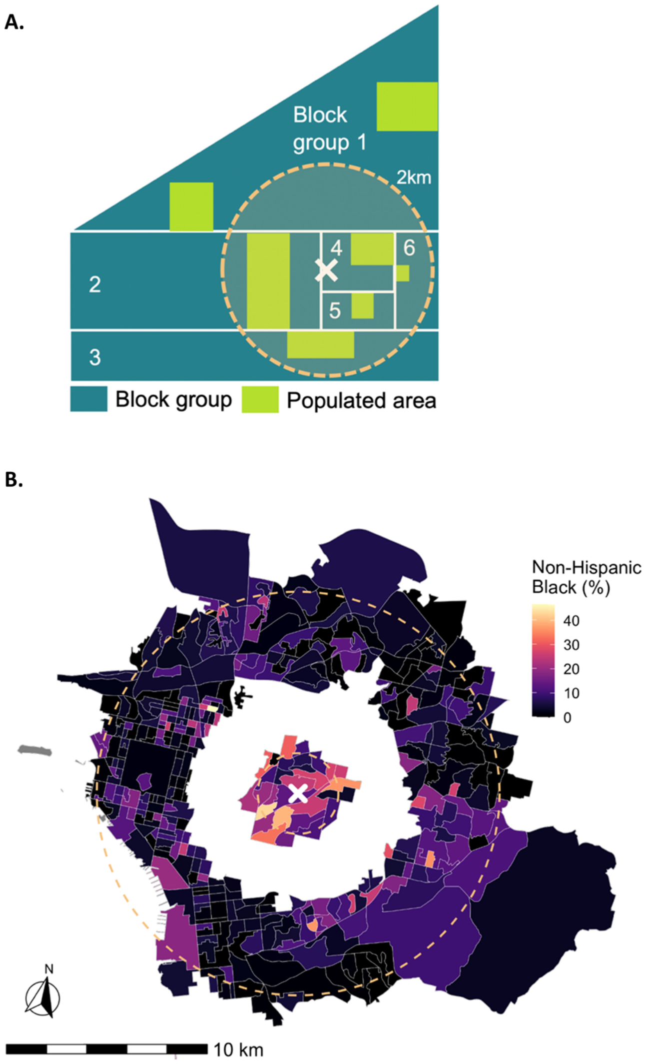

Figure 1. Example of exposure assignment of block groups. Panel (A) displays a schematic of block groups (turquoise) and populated areas (light green). Block groups 2–6 are exposed to a superemitter (white "X") but block group 1 is not because its populated areas are located >2 km from the superemitter. Panel (B) shows the location of a landfill superemitter in San Diego County, California, exposed block groups and the percent of non-Hispanic Black residents within 2 km and unexposed block groups 5–10 km away. Block groups located 2–4.9 km from superemitters were not included in analysis because we considered them intermediately exposed. The western side of the map crosses over water and thus does not contain block groups. The inner dashed orange line represents the 2 km radius around the superemitter and the outer dashed orange line the 10 km radius around the superemitter.

We used the distance between methane superemitters and the dasymetrically mapped populated areas to define exposed and unexposed block groups (Figure 1A). First, we identified populated areas with boundaries within 2 km of a superemitter (exposed). Next, we identified all populated areas with boundaries located within 5–10 km of a superemitter that were also located farther than 5 km from all superemitters (i.e., truly unexposed). Finally, we identified block groups containing the exposed (within 2 km of a superemitter) and unexposed (5–10 km from a superemitter) populated areas (Figure 1B). We opted to define unexposed block groups as those located 5–10 km from a superemitter to compare communities similar to the exposed block groups in terms of geographic location, rurality, and other factors but that differed in superemitter exposure status. After removing 24 (0.2%) block groups that were missing sociodemographic data, our study population consisted of 951 exposed and 8722 unexposed block groups.

We used two additional metrics to characterize the intensity of exposure to superemitters among block groups located within 2 km. We generated a binary multicategory superemitter variable that took the value 1 if a block group population area was located within 2 km of 2 or more superemitter categories (e.g., dairy and oil/gas production) and 0 if a block group population area was located within 2 km of a single category of superemitter (e.g., oil/gas distribution only, see Figure S2). We further characterized exposed block groups by the sum of methane emitted from all sources within 2 km: CH_4 exposure$_j$ = $\sum_{i=1}^{n} E_i$, where i is a superemitter located within 2 km of block group j's populated area's boundary and E is the emission rate at superemitter i in kg/h.

Statistical Analysis. We conducted descriptive analyses by exposure category. Then, we used generalized additive mixed models with a logit link to assess the association between block group-level sociodemographic variables and odds of exposure to a superemitter or, among exposed block groups (those within 2 km of a superemitter), odds of higher intensity exposure to multiple categories of superemitters. Mixed models included a random intercept for county. We allowed for deviations from linearity using penalized splines but included a linear term if the generalized cross-validation criterion indicated that a linear association was a better fit. We used likelihood ratio testing to select the degrees of freedom for splines. All analyses were conducted using R Statistical Software (Vienna, Austria).

We first ran univariate models, adjusting for population density, for the 14 sociodemographic variables of interest and the three outcomes: 2 versus 5−10 km from a superemitter, multiple versus 1 category of superemitter exposure, and high versus low CH_4 emissions. We then selected a pared group of variables to include in our fully adjusted models. These variables were selected based on a priori hypotheses (e.g., poverty would be associated with superemitter exposure), Spearman correlations between the variables, [e.g., did not include variables correlated at >0.75 (Figure S3)], and associations observed in the univariate models. The adjusted models included population density, percent individuals of non-Hispanic Asian, Black, and Native American race/ethnicity, and percent individuals of Hispanic race/ethnicity, percent individuals living below the federal poverty threshold, percent voter turnout, percent renters, percent limited English-speaking households, and percent uninsured individuals. We used semivariograms to assess residual spatial autocorrelation in our model results[67] and did not observe any (Figure S4).

In secondary analyses, we separately assessed the odds of being located within 2 vs 5−10 km from two specific types of superemitters: (1) oil and gas production and (2) dairy/manure sites. These two subcategories of the superemitter have been associated with environmental justice concerns and adverse health outcomes in prior studies.[68−73]

■ RESULTS

AVIRIS-NG flights conducted between 2016 and 2018 identified 564 methane superemitters in California, 483 (86%) of which we included in analyses as they were located within 2 km of a populated area of a block group. Figure 2 shows the spatial distribution of California superemitters and their relative emission rates. Dairy/manure facilities (N = 213) and oil/gas production sites (N = 127) made up the majority (70%) of the superemitters. Landfill/compost facilities had the highest emission rates (median [25th, 75th percentile] = 468 kg/h [254, 1195]) and refineries the lowest (median [25th, 75th percentile] = 20 kg/h [8, 49], Figure S5). One hundred percent of dairies, 84% of oil and gas production and distribution facilities, and 83% of landfills were in rural or semirural block groups, while 71% of power plants, 92% of refineries, and 71% of wastewater treatment plants were located in urban block groups.

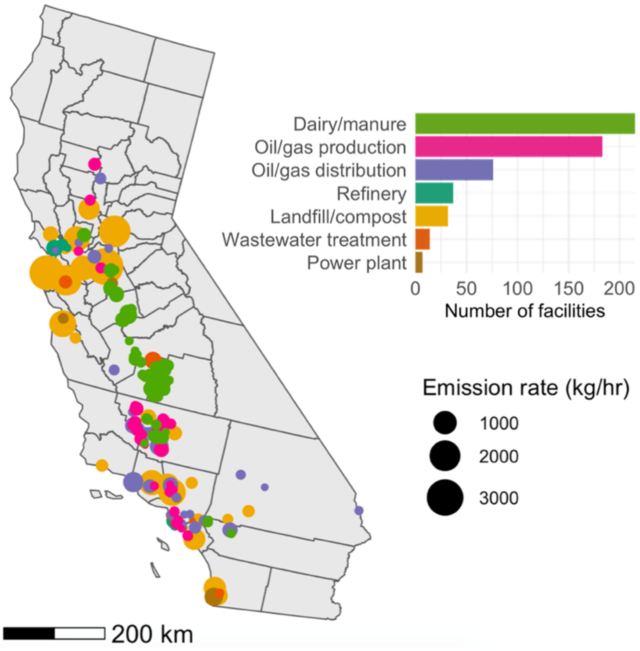

Figure 2. Location, type, and emission rate of methane superemitters (N = 483) in California.

We identified 951 block groups with populated areas located within 2 km of a superemitter. Of these, 131 (13.8%) were located within 2 km of more than one category of a superemitter (e.g., a dairy and an oil and gas well). The total hourly methane emissions at superemitters located within 2 km of block groups ranged from 2.8 to 3009 kg/h (median [25th, 75th percentile] = 93 [40, 185]). The 8722 block groups located 5−10 km from superemitters constituted our unexposed group.

In general, exposed and unexposed block groups had similar sociodemographic characteristics (Table S3). Superemitter-exposed block groups had lower median population density than unexposed block groups (3100 versus 4280 individuals/km^2). We observed minimal differences in exposed versus unexposed block groups by the superemitter category (Figure S6). Larger differences were apparent when comparing the number of categories of superemitter exposure among exposed block groups, though errors bars were still large (Figure S7). Exposed block groups with 2−4 versus 1 category of superemitters, on average, had a higher percentage of Hispanic (50 versus 38%) and a lower percentage of non-Hispanic White individuals (26 versus 39%), a higher percentage of individuals with less than a high school education (26 versus 19%), and lower voter turnout (63 versus 69%). Similar patterns emerged across categories of total CH_4 emission exposure within 2 km (Figure S8). For example, block groups exposed to high (>tertile 3, 185 kg/h) versus low (<tertile 1, 40 kg/h) contained a higher percentage of Hispanic individuals

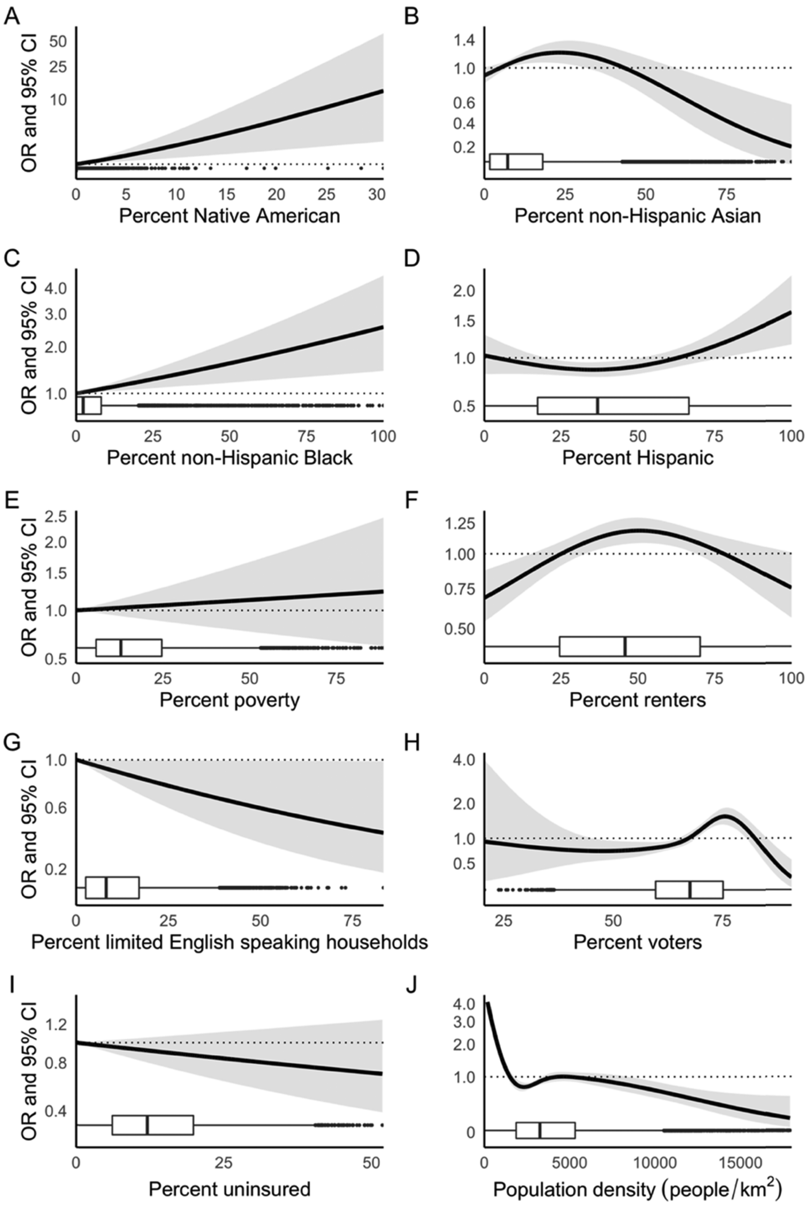

Figure 3. Association between sociodemographic variables and odds of being located within 2 versus 5−10 km from a CH_4 superemitter. Includes n = 951 exposed and n = 8722 unexposed block groups. Black lines are odds ratios (OR) and gray areas represent the 95% confidence intervals. The results from a generalized additive mixed model with a logit link and a random intercept for county adjusted for block group-level percent individuals of non-Hispanic Native American, Asian, and Black race/ethnicity, percent individuals of Hispanic race/ethnicity, percent individuals living below the federal poverty threshold, percent renters, percent limited English-speaking households, percent voter turnout, percent uninsured individuals, and population density. The rug plot displayed along the x-axis shows the number of observations at each level of the respective sociodemographic variable. Nonlinear associations in panels (B), (D), (F), (H), and (J) were all statistically significant at the α = 0.05 level. CI, confidence interval; OR, odds ratio.

(46 versus 36%), individuals living in poverty (17 versus 13%), linguistically isolated individuals (12 versus 8%), and individuals with less than a high school education (23 versus 16%). We observed strong correlations between several of the sociodemographic variables: for example, the Spearman ρ between educational attainment and Hispanic race/ethnicity was 0.8, poverty and SNAP use was 0.7, and median household income and poverty was −0.7 (Figure S3).

In unadjusted analyses, we observed multiple nonlinear relationships between sociodemographic variables and odds of being located within 2 versus 5−10 km from a superemitter (Figure S9). For example, as the percent non-Hispanic Asian individuals increased, odds of exposure increased until about 25% non-Hispanic Asians and then there was a steep decline in odds of exposure. The relationship between percent renters and exposure was an inverted U-shape, with the highest odds of being exposed at about 50% renters. Odds of exposure to superemitters increased linearly with the increasing percentage of non-Hispanic Black individuals and Native American individuals. We noted somewhat reduced odds of exposure to a superemitter with measures of lower SES, except for percent with <high school education. The lowest versus highest population density block groups had 3 times the odds of being exposed.

In unadjusted analyses, considering odds of higher intensity exposure to superemitters among block groups located within

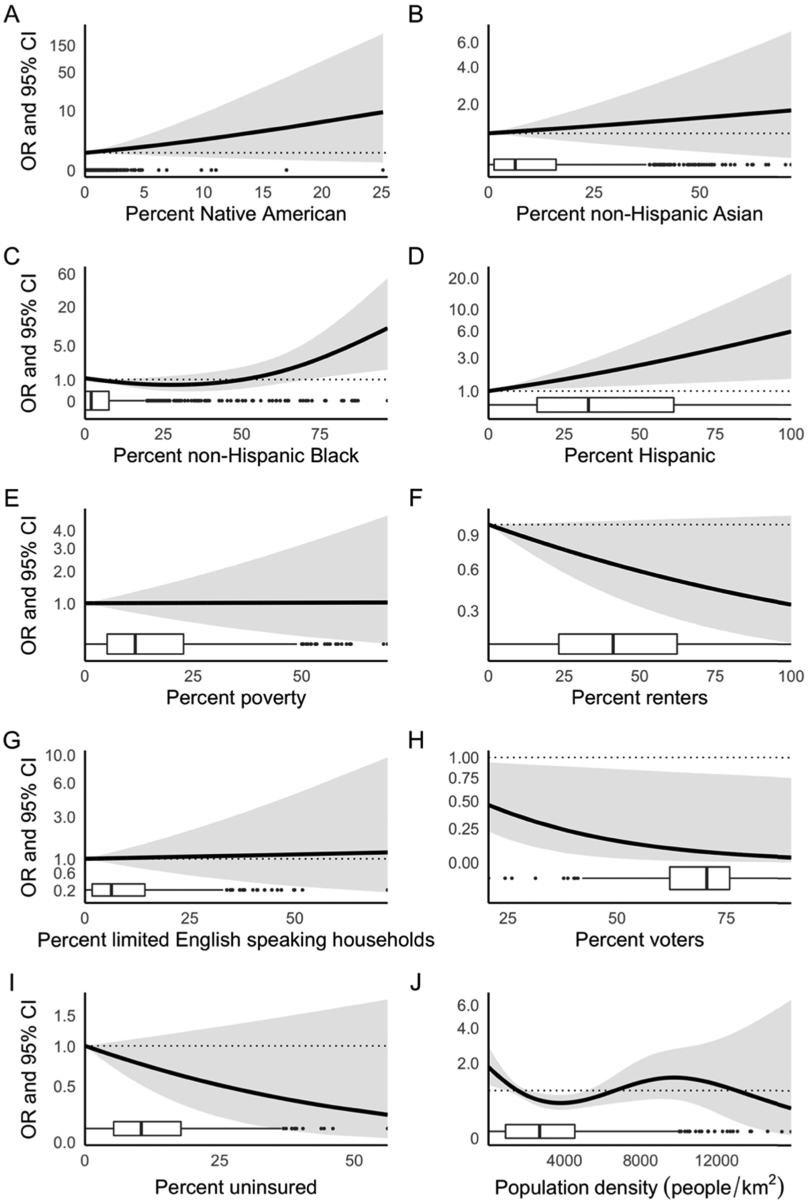

Figure 4. Association between sociodemographic variables and odds of being located within 2 km of 2−4 versus 1 class of CH_4 superemitters, among block groups located within 2 km of at least one superemitter (n = 951). Black lines are odds ratios and gray areas represent the 95% confidence interval. The results from a generalized additive mixed model with a logit link and a random intercept for county adjusted for block group level for percent individuals of non-Hispanic Native American, Asian, and Black race/ethnicity, percent individuals of Hispanic race/ethnicity, percent individuals living below the federal poverty threshold, percent renters, percent limited English-speaking households, percent voter turnout, percent uninsured individuals, and population density. The rug plot displayed along the x-axis shows the number of observations at each level of the respective sociodemographic variable. CI, confidence interval; OR, odds ratio. Nonlinear associations in panels (C) and (J) were statistically significant at the α = 0.05 level.

2 km of a superemitter, increased odds of exposure to multiple categories of a superemitter, and odds of high exposure to methane emissions were associated with increasing percent of Hispanic individuals, uninsured individuals, and individuals without a high school diploma (Figures S10 and S11). Increasing percent of individuals living in poverty and linguistically isolated households were additionally associated with increased odds of exposure to two or more categories of a superemitter. While income appeared inversely associated with odds of exposure to two or more categories of superemitters, it was positively associated with odds of exposure to high methane emissions. Finally, an increasing percent of Hispanic and non-Hispanic Asian individuals was linearly associated with increased odds of high methane emissions.

When we included 10 sociodemographic variables in a single model, race/ethnicity remained associated with increased odds of being within 2 km of a superemitter, but SES did not (Figures 3–5). For example, a 10% increase in percent non-Hispanic Black individuals and a 1% increase in non-Hispanic Native American individuals were each associated with a 10% increase in odds (95% confidence interval (CI): 1.04, 1.17 and 1.04, 1.15, respectively) of a block group being located within 2 km of a superemitter. The associations for non-Hispanic Asian and Hispanic individuals were nonlinear. For Hispanics, the relationship was relatively flat until about 50% of the

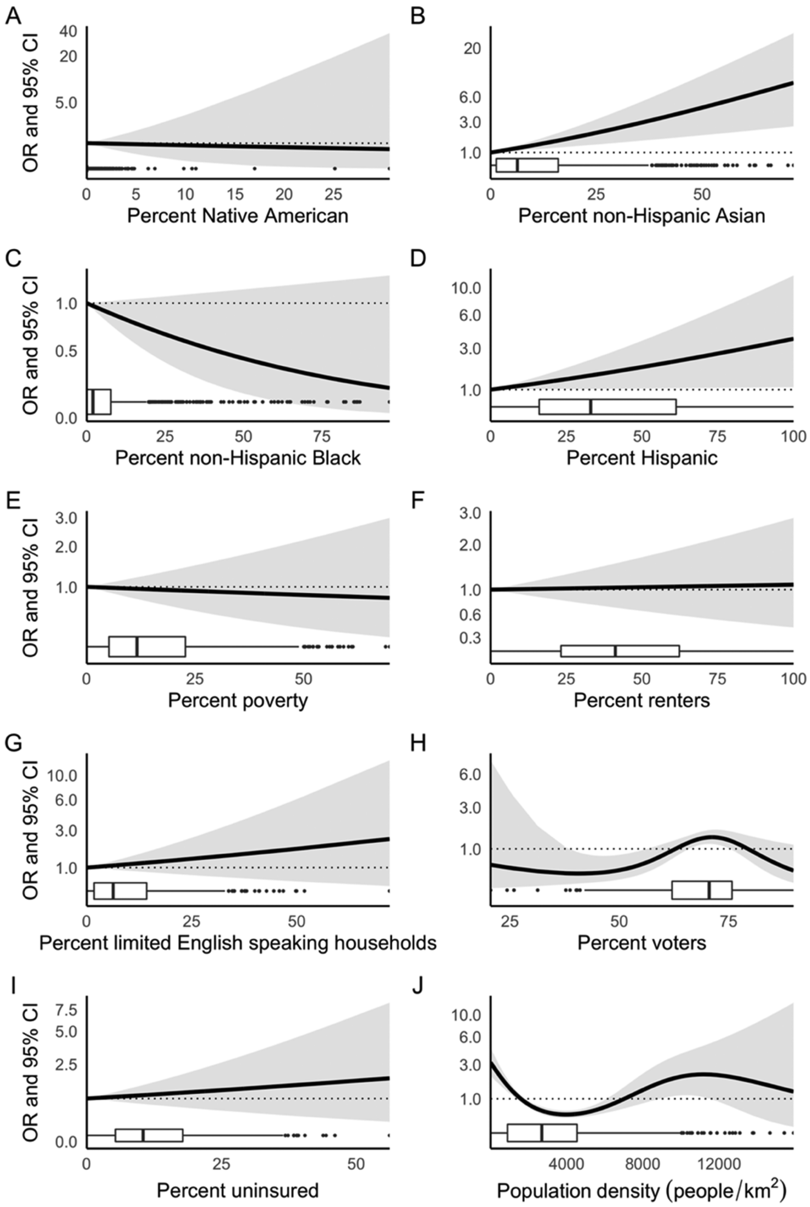

Figure 5. Association between sociodemographic variables and odds of being exposed to high (>tertile 3 [185 kg/h]) versus low (tertiles 1−3 [2.8−185 kg/h]) CH_4 emissions, among block groups located within 2 km of at least one superemitter (n = 951). Black lines are odds ratios and gray areas represent the 95% confidence interval. The results from a generalized additive mixed model with a logit link and a random intercept for county adjusted for the block group level for percent individuals of non-Hispanic Native American, Asian, and Black race/ethnicity, percent individuals of Hispanic race/ethnicity, percent individuals living below the federal poverty threshold, percent renters, percent limited English-speaking households, percent voter turnout, percent uninsured individuals, and population density. The rug plot displayed along the x-axis shows the number of observations at each level of the respective sociodemographic variable. CI, confidence interval; OR, odds ratio. Nonlinear associations in panels (H) and (J) were statistically significant at the α = 0.05 level.

population consisted of Hispanics and then the odds of exposure to a superemitter increased (Figure 3). Once a block group contained 25% non-Hispanic Asians, odds of exposure to a superemitter began to decline. Percentage voter turnout demonstrated a unique association with the odds of exposure to a superemitter peaking when around 75% of the block group voted and then rapidly declining as that proportion of voters increased.

Similar to unadjusted analyses, increasing percent non-Hispanic Black (at 70% Black individuals, OR = 2.33, 95% CI: 0.98, 5.55) and Hispanic individuals (OR = 1.19, 95% CI: 1.04, 1.36 for each 10% increase in Hispanic individuals) were associated with increased odds of being exposed to two or more categories of superemitters among block groups located within 2 km of a superemitter in adjusted analyses (Figure 4). Increasing percent renters (OR = 0.90, 95% CI: 0.80, 1.01 for each 10% increase) and voter turnout (OR = 0.67, 95% CI: 0.48, 0.95 for each 10% increase) were inversely associated with odds of exposure to two or more categories of superemitters. Non-Hispanic Black race/ethnicity was inversely associated with odds of high methane emissions (OR = 0.85, 95% CI: 0.69, 1.03 for each 10% increase in non-Hispanic Black individuals), while increasing percent non-Hispanic Asian (OR = 1.35, 95% CI: 1.14, 1.59) and Hispanic (OR = 1.14, 95% CI: 1.01, 1.29) individuals were associated with increased odds of high methane emissions among block groups within 2 km of a superemitter (Figure 5).

When we assessed the odds of being located within 2 km of an oil and gas production or a dairy/manure superemitter, we observed similar racial/ethnic disparities to those observed for superemitters overall, with some differences (Figures S12 and S13). For oil and gas production sites, we observed increased odds of exposure with increasing percent Native American, non-Hispanic Black, and non-Hispanic Asian populations. For example, for each 10% increase in non-Hispanic Asian individuals, there was a 26% increase in the odds of being located within 2 versus 5−10 km of an oil and gas production superemitter (OR = 1.26, 95% CI: 1.06, 1.50). For dairy/manure sites, odds of exposure increased with higher percentages of Native American, Hispanic, and non-Hispanic Black individuals, for whom we observed the strongest relationship (OR = 1.81, 95% CI: 1.07, 3.06) for each 10% increase in non-Hispanic Black individuals.

■ DISCUSSION

We examined the location of 483 methane superemitters in relation to community-level demographics based on race/ethnicity, SES, and civic engagement capacity. To our knowledge, this is the first environmental justice analysis to assess relationships between community characteristics and proximity to and intensity of exposure to multiple methane superemitter types, including landfills/composting facilities, power plants, refineries, wastewater treatment plants, oil and gas distribution and production sites, and dairies/manure management sites. Landfills and composting facilities accounted for the highest rates of methane emissions, while dairies and manure management sites as well as oil and gas production facilities made up the largest proportion of superemitter facilities in our analysis.[59] Unadjusted models showed racial/ethnic and SES disparities in the odds of living in close proximity to methane superemitters and intensity of exposure based on multiple industry categories and total methane emissions. In adjusted models, the associations with race/ethnicity persisted, while those for community-level SES (poverty rate, percent uninsured, and percent limited English-speaking households) were attenuated. Further, subanalyses restricted to dairies/manure management facilities and oil and gas production revealed similar racial disparities as the main analysis. Our sub- and overall analyses also showed many nonlinear relationships. Interestingly, once voter turnout, an indicator of community civic engagement, reached 75%, the odds of being exposed to a superemitter declined. This finding supports the idea that marginalized communities may be vulnerable to siting of environmental hazards due to the lack of political power and limited resources to engage in regulatory decision-making or challenge facility permits.[13,74] In addition, 84% of the methane superemitters included in our study were located in semirural or rural block groups, highlighting what some researchers argue is an understudied form of rural environmental injustice in which urban areas drive the intensity of food and energy production in rural areas and often return their wastes to these same rural communities.[56] Our results indicate that future methane emission reduction policies to slow climate change can also address exposure disparities to health-harming copollutants. This could be done by prioritizing and incentivizing deeper methane emission reductions in environmental justice communities.

Prior studies have examined equity patterns of specific sources of methane emissions included in our analysis. For example, U.S. studies of solid and hazardous waste landfills indicate their disproportionate siting in communities of color.[75,76] This body of work includes environmental justice assessments of CAFOs, showing that weak regulations have led to the disproportionate location of swine CAFOs in communities of color and poor communities[74,77−79] and near schools with predominantly low-income and non-White students.[80] None of these studies, however, have examined CAFO sites, such as dairies, in California. Our results showed that odds of exposure (within 2 km) to this category of the methane superemitter tended to increase with increasing percent Native American, non-Hispanic Black, and Hispanic individuals. In contrast to studies of all CAFOs, we did not observe increased odds of exposure among lower SES communities in adjusted models.

Similarly, environmental inequities associated with California's oil and gas industry, particularly production sites, emerged in large part due to historical redlining beginning in the late 1930s through the late 1960s, which restricted many African Americans and Latino immigrant home-buyers to the petro-industrial neighborhoods of South Los Angeles.[81,82] This legacy shapes present-day race- and class-based inequities in the "petro-riskscapes" of Los Angeles and rural communities in San Joaquin and Kern Counties—epicenters of California's oil and gas production.[83] Our data support this theory. We observed increased odds of being located within 2 versus 5−10 km from an oil and gas production superemitter with increasing percent Native American, non-Hispanic Asian, and non-Hispanic Black individuals. In addition, the proliferation of unconventional oil and gas extraction technologies, such as hydraulic fracturing, raises new concerns regarding methane emissions[84] and community health effects.[29,85] These sites tend to be located in low-income rural communities, such as the Marcellus Shale in Pennsylvania or the Eagle Ford Shale in Texas, and the few environmental justice studies conducted on unconventional drilling indicate that this development is often, though not always, disproportionately located in communities with lower home values and minority communities.[64,86−90] Strong federal and state methane emission regulations could also reduce non-methane VOC and criteria air pollutant emissions.[34]

This study has several strengths. First, this is the first environmental justice analysis of methane superemitters using several exposure metrics, including proximity to multiple sites, as well as airborne, remotely sensed estimates of cumulative methane emissions from diverse sources. Second, we used a high-resolution dataset of populated areas developed via dasymetric mapping to spatially characterize the location of populations within exposed and unexposed block groups. Third, we examined several demographic variables to assess patterns of inequity, including voter turnout, an indicator of community voice and political power that may be an important driver of environmental justice outcomes. Finally, we used splines and adjusted analyses to allow us to assess nonlinear trends and better isolate which community sociodemographic variables most likely explained observed associations. We found that race/ethnicity better predicted exposure than low SES, potentially indicating housing discrimination, segregation, or procedural environmental injustice as drivers.[91,92] We also highlight rurality as an important, yet understudied dimension of environmental injustice in California.[56]

Limitations include the cross-sectional design, which precludes assessment of temporal changes in block group demographic composition or distributional patterns of cumulative methane emissions; indeed, identification of methane superemitters took place between 2016 and 2018 and emissions trends likely vary over time. In addition, although studies indicate that harmful compounds are often co-emitted with methane,[29,30,34] which itself does not directly harm human health, we did not directly measure these copollutant emissions, and thus cannot characterize the potential health implications of these sites, which likely vary by superemitter category and facility, for host communities. Finally, we treated each facility as a point location even though some facilities, such as dairies, span larger areas. This may have resulted in underestimation of exposed populations.

Future research should reassess temporal fluctuations in methane emissions from superemitter sites and the extent to which these emissions correlate with potentially harmful copollutants across all facility types. Given that 10% of superemitters in California were estimated to have contributed roughly 60% of point-source methane emissions,[59] more targeted air quality monitoring, in collaboration with host communities, could provide much-needed data to better understand potential community health threats posed by these sites. While some analysts have cautioned against integrating air quality into climate policy, pointing out that copollutants are best regulated under existing laws such as the U.S. Clean Air Act,[93] more holistic regulatory strategies could target critical methane emission reductions to those communities where health co-benefits and health equity impacts are greatest.[94,95] California's Assembly Bill 617[96] provides an innovative and potentially transformational blueprint for enhanced community participation in air monitoring and development of emission reduction plans to improve local air quality and ultimately reduce environmental health disparities in disadvantaged communities.[97] This legislative strategy to localize air quality management from a regional scale to a community scale can also embed environmental justice objectives in efforts to identify and more effectively regulate methane superemitters. Indeed, harmonizing environmental justice and climate sustainability goals to incentivize greenhouse gas reductions in disadvantaged and highly polluted neighborhoods could enhance overall health benefits, particularly if a small number of methane superemitter facilities present the greatest opportunities to improve local and regional air quality. This would require systematic temporal and spatial tracking of methane and copollutant emissions to characterize the health and environmental justice implications of superemitters more fully. Such a strategy would also advance the overarching environmental justice goals articulated in California's landmark climate change laws.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.1c04328.

> Superemitters excluded from analyses, residential parcel classifications, distribution of sociodemographic variables by exposure status, example of generating populated areas and exposure to multiple classes of superemitters, correlation between analysis variables, semivariograms, distribution of methane emissions and sociodemographics by superemitter classifications, unadjusted model results, and correlation between methane emissions and copollutant emissions for refineries and power plants in California (PDF)

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