Exposure and Equity Assessment of Natural Gas Appliances in the San Francisco Bay Area

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Overview

This document analyzes the intensities and distributions of annual average exposures (modeled outdoor concentrations weighted by residential population) attributed to emissions targeted by proposed amendments to Bay Area Air Quality Management District (Air District or BAAQMD) Rules 9-4 and 9-6. These proposed rule amendments (Elwell 2022) would limit emissions of oxides of nitrogen (NO_x) from natural gas-fired furnaces (9-4) and water heaters and boilers (9-6). They would impose a zero-NO_x standard on natural gas-fired commercial and residential building space and water heating appliances.

The impacts evaluated in this analysis are taken to be equivalent to the difference between a baseline scenario and a control scenario, in which the latter represents a world where those NO_x and fine particulate matter ($PM_{2.5}$) emissions have been eliminated. The elimination of NO_x emissions is consistent with the proposed zero-NO_x standard; if electric appliances are adopted to meet this standard, direct, or primary, $PM_{2.5}$ emissions would also be eliminated.

As explained in the accompanying appendices and in the main document, the emission reductions attributed to the proposed rulemaking (hereafter, “targeted emissions”) would be in addition to those realized by full compliance with existing NO_x regulations. The analyses in this document are restricted to those additional emission reductions and the resulting reductions in exposures for Bay Area residents. In addition to results for the total Bay Area residential population, staff calculated results for four different racial/ethnic groups. The focus in this document, motivated by the results of the health benefits assessment (Tanrikulu et al. 2022), is on differences in annual average $PM_{2.5}$ exposure intensities for those groups.

Modeled Air Quality Impacts

The emissions and air quality modeling used as the basis for this analysis are described in Tanrikulu et al (2022). Figures **1** through **4** depict modeled annual average baseline concentrations and reductions attributed to elimination of the targeted emissions (baseline minus control) of NO_x and secondary, primary, and total $PM_{2.5}$ within the study area. Secondary $PM_{2.5}$ is formed in the atmosphere from precursors such as NO_x, while primary $PM_{2.5}$ is directly emitted; total $PM_{2.5}$ is the sum of the two.

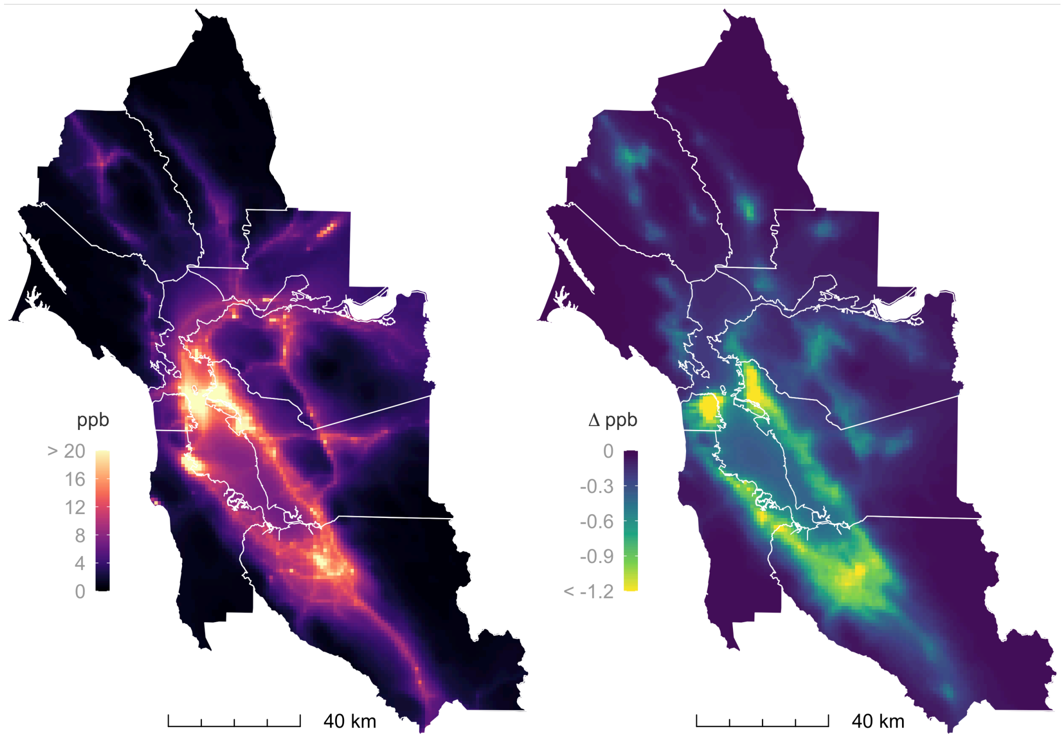

Figure 1: Baseline concentrations (left) and reductions (right) for NO_x.

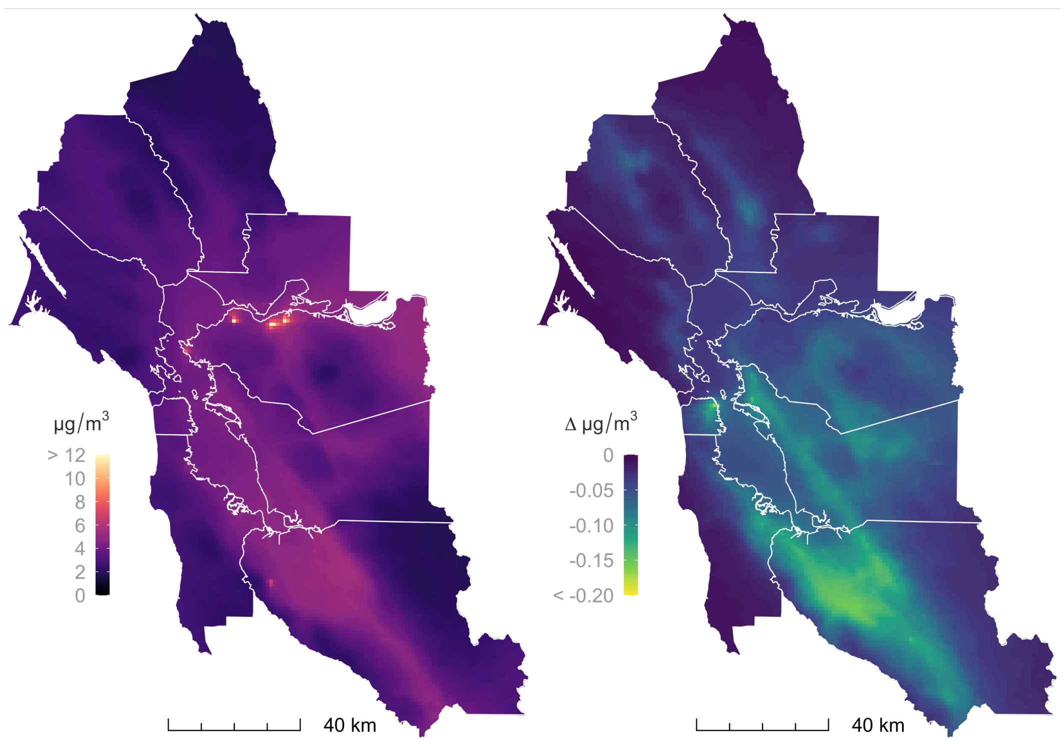

Figure 2: Baseline concentrations (left) and reductions (right) for secondary $PM_{2.5}$.

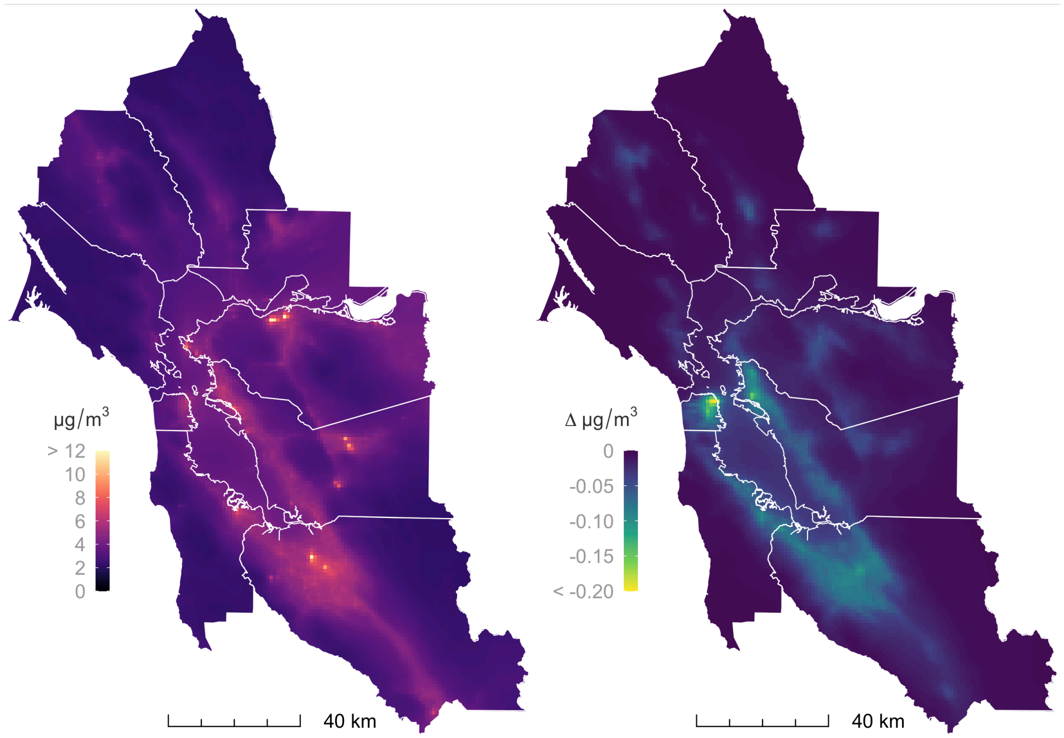

Figure 3: Baseline concentrations (left) and reductions (right) for primary $PM_{2.5}$.

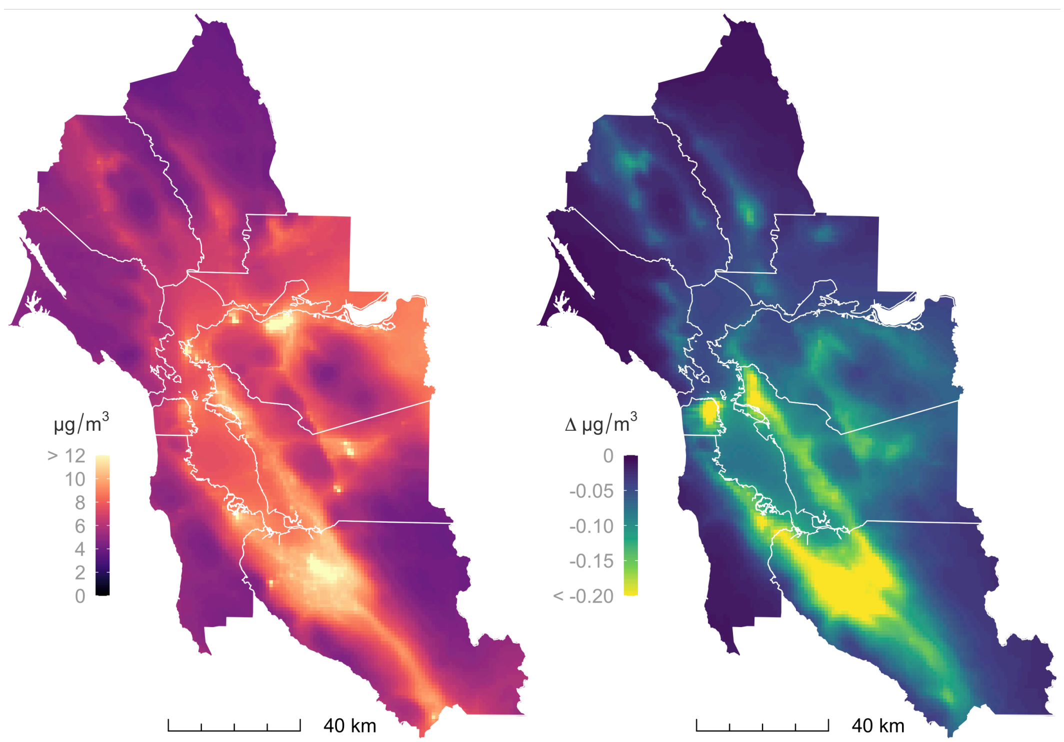

Figure 4: Baseline concentrations (left) and reductions (right) for total $PM_{2.5}$.

Exposure Calculations

Annual average exposures were computed for this analysis using weighted sums of 1x1 km grid-cell concentrations, with the modeled population (also on the same 1x1 km grid) serving as the weights. This is consistent with the approach taken in most large-scale epidemiological studies of outdoor air pollution. In this document, we use the term "exposure intensity" interchangeably with "population-weighted concentration", or, equivalently, exposure "per capita." These all have the same units as concentrations. For $PM_{2.5}$, for example, the units are micrograms per cubic meter (µg/m^3).

Total population exposure, in contrast to the above, has units of persons multiplied by intensity (e.g., person-µg/m^3). We computed average exposure intensities by first computing total population exposures. The total exposure X_{ijk} of a population group k, in cell j, to pollutant i, is:

$$X_{ijk} = C_{ij} \cdot P_{jk}$$

… where C_{ij} is the modeled annual average concentration (e.g., µg/m^3) of pollutant i in cell j, and P_{jk} the size (in persons) of that population subgroup k within that cell j.

Across a region corresponding to a set of cells indexed by $j \in J$, consisting of more than one cell (for example, the set of cells equated with a particular county), different summary statistics for subgroup k may be computed. Below is the formula we used to calculate the average exposure intensity for a member of group k, to pollutant i, across all cells j in J. It is the total population exposure for group k, within that region, divided by the total number of persons in group k, again within that region:

$$\frac{\sum_{j \in J} X_{ijk}}{\sum_{j \in J} P_{jk}}$$

Computing an average exposure intensity for all residents, for pollutant i, across all cells j in J is similar: it is again the sum of population exposure divided by the sum of population:

$$\frac{\sum_{j \in J} \sum_{k \in K} X_{ijk}}{\sum_{j \in J} \sum_{k \in K} P_{jk}}$$

For county-specific calculations, cells were assigned to counties by calculating the intersections of cells and county polygons. For each cell, the county with the largest amount of overlap (i.e., the largest share of that cell's area) was used as the label for that cell.

Simplified Example

This simplified set of example calculations uses real data from the main analysis (Table **1**, below). It illustrates the counter-intuitive result, found in the main analysis, that one group can be the most impacted overall while not being the most impacted within most counties.

For clarity, this example is restricted to just two counties and two racial/ethnic groups. In both counties, the impact on African-American/Black residents is larger. Santa Clara county, which is more impacted overall, is home to the majority of Asian/Pacific Islander residents. The majority of African-American/Black residents, on the other hand, live in Alameda County.

Table 1: Example data.

	Average Exposure	Population
Asian/Pacific Islander		
Santa Clara	0.195 µg/m^3	760,000
Alameda	0.152 µg/m^3	540,000
African-American/Black		
Santa Clara	0.199 µg/m^3	60,000
Alameda	0.165 µg/m^3	180,000

If the Asian/Pacific Islander population were the same size in both counties, the "regional" (two-county) average for Asian/Pacific Islander residents would simply be the average of 0.195 and 0.152, or 0.174 µg/m^3. Similarly, if the African-American/Black population were the same size in both counties, the result would be the average of 0.199 and 0.165, or 0.182 µg/m^3.

However, there are many more Asian/Pacific Islander residents in Santa Clara than in Alameda, and Santa Clara is more impacted. So, the "regional" average in this example, for Asian/Pacific Islander residents, is closer to Santa Clara's:

$$\frac{(0.195 * 760{,}000) + (0.152 * 540{,}000)}{760{,}000 + 540{,}000} = 0.177$$

In contrast, the majority of African-American/Black residents live in Alameda. Since Alameda is less impacted, the "regional" average for African-American/Black residents is weighted in the opposite direction:

$$\frac{(0.199 * 60{,}000) + (0.165 * 180{,}000)}{60{,}000 + 180{,}000} = 0.174$$

… resulting in a slightly smaller value than that for Asian/Pacific Islander residents.

In our main analysis, the effect is more complex, because there are more areas and more racial/ethnic groups. However, the elements are the same: (1) more variation between areas than between racial/ethnic groups; and (2) a demographic picture with sufficiently distinct racial/ethnic compositions at a sub-regional level.

This effect does not appear in all datasets, but it can arise at any geographic scale. For example, a large exposure disparity has been reported for $PM_{2.5}$ from residential gas combustion at the national level: across the US, Asian/Pacific Islander residents were estimated to be 92% more impacted than average by $PM_{2.5}$ from those sources (Tessum et al. 2021). The published data for that analysis suggest that New York exerts high leverage on the national result—New York has both a large Asian/Pacific Islander population and a much larger average impact from residential gas combustion, relative to other states. Without additional information, one cannot say for certain whether the national-level findings apply *within* New York, or within other states in that analysis. They might, but the patterns of disparity might be different in terms of magnitudes or directions. We have not analyzed Bay Area results using areal units other than counties (for example, ZIP Code Tabulation Areas, Census Places, or Metropolitan Statistical Areas), but we may do so in future work.

Main Analysis

The study area included the portions of the 9-county Bay Area that are under the jurisdiction of the Bay Area Air Quality Management District (Figure **5**). The modeled population was projected by BenMAP (PopGrid) for the year 2020, using Census 2010 data as a base year. This population was estimated to be approximately 7.7 million residents. A breakdown by county and race/ethnicity, using categories supplied by BenMAP/PopGrid, is given in Table **2**. The focus in this section, motivated by the results of the health benefits assessment, is on differences in annual average $PM_{2.5}$ impacts for those groups.

Table 2: Modeled residential population. Percentages are row-wise; they indicate shares of that county's population. Basis: BenMAP/PopGrid projection from 2010 to 2020.

	Asian	**Hispanic**	**Black**	**White**	**(all)**
Alameda	32.6%	24.3%	11.0%	32.1%	*1,668,306*
Contra Costa	18.5%	28.7%	9.2%	43.6%	*1,180,605*
Marin	7.4%	18.3%	3.2%	71.1%	*266,439*
Napa	8.5%	36.8%	2.3%	52.5%	*147,553*
San Francisco	34.6%	15.1%	5.2%	45.1%	*866,833*
San Mateo	31.5%	26.6%	2.7%	39.1%	*797,428*
Santa Clara	38.3%	27.7%	2.8%	31.2%	*1,991,116*
Solano	21.7%	27.8%	17.3%	33.2%	*311,782*
Sonoma	5.6%	30.5%	2.2%	61.7%	*461,976*
(all)	*28.6%*	*25.6%*	*6.4%*	*39.4%*	*7,692,039*

Baseline conditions: impacts from all sources

Under baseline conditions, the annual average exposure intensity (modeled outdoor concentration weighted by residential population) was calculated to be 8.53 $\mu g/m^3$. This is from all modeled sources of $PM_{2.5}$, including sources other than space and water heating appliances, and including sources beyond the Air District's jurisdictional boundary. Of this 8.53 $\mu g/m^3$, 49% was attributed to secondary $PM_{2.5}$. The remaining 51% was attributed to primary $PM_{2.5}$.

In addition to regional annual averages for $PM_{2.5}$ and NO_x, staff calculated impacts for residents within particular racial/ethnic groups. At a regional level, White residents were found to be less impacted than people of color by $PM_{2.5}$ from all sources combined (Table **3**, column "Baseline"). Secondary $PM_{2.5}$ from all sources had the largest impact on Asian/Pacific Islander residents, while primary $PM_{2.5}$ and total $PM_{2.5}$ from all sources had the largest impacts on Hispanic/Latino residents.

Exposures to $PM_{2.5}$ from targeted emissions

Approximately **0.14 $\mu g/m^3$**, or 1.6% of the 8.53 $\mu g/m^3$ baseline, was attributed to targeted emissions from space and water heating appliances. Of this 0.14 $\mu g/m^3$ contribution, 61% was attributed to secondary $PM_{2.5}$. The remaining 39% was attributed to directly emitted ("primary") $PM_{2.5}$.

Table 3: Modeled exposures (outdoor concentrations, weighted by residential population) under baseline and control scenarios. Reductions are expressed relative to baseline exposures.

	Baseline	Control	Reduction
Total $PM_{2.5}$ (μg/m³)			
Asian/Pacific Islander	8.817	8.667	0.150 (1.7%)
Hispanic/Latino	8.826	8.687	0.139 (1.6%)
African-American/Black	8.670	8.536	0.134 (1.5%)
White	8.116	7.988	0.128 (1.6%)
(average)	*8.534*	*8.397*	*0.138 (1.6%)*
Primary $PM_{2.5}$ (μg/m³)			
Asian/Pacific Islander	4.496	4.437	0.059 (1.3%)
Hispanic/Latino	4.558	4.505	0.054 (1.2%)
African-American/Black	4.491	4.436	0.055 (1.2%)
White	4.140	4.091	0.050 (1.2%)
(average)	*4.371*	*4.318*	*0.054 (1.2%)*
Secondary $PM_{2.5}$ (μg/m³)			
Asian/Pacific Islander	4.321	4.230	0.091 (2.1%)
Hispanic/Latino	4.268	4.182	0.086 (2.0%)
African-American/Black	4.179	4.099	0.079 (1.9%)
White	3.976	3.898	0.079 (2.0%)
(average)	*4.163*	*4.079*	*0.084 (2.0%)*
NO_x (ppb)			
Asian/Pacific Islander	10.079	9.324	0.755 (7.5%)
Hispanic/Latino	9.958	9.268	0.690 (6.9%)
African-American/Black	10.930	10.212	0.718 (6.6%)
White	8.113	7.470	0.643 (7.9%)
(average)	*9.328*	*8.636*	*0.692 (7.4%)*

Figure **5** depicts the same data summarized in Figure **4** (right panel) and Table **2**, but in the form of contours overlaid on the residential population. The outermost contour represents a contribution of +0.05 μg/m3 of total $PM_{2.5}$ attributed to targeted emissions from space and water heating appliances. This amount is approximately one-half of 1 percent of the population-weighted annual average from all modeled sources, including sources outside the study area.

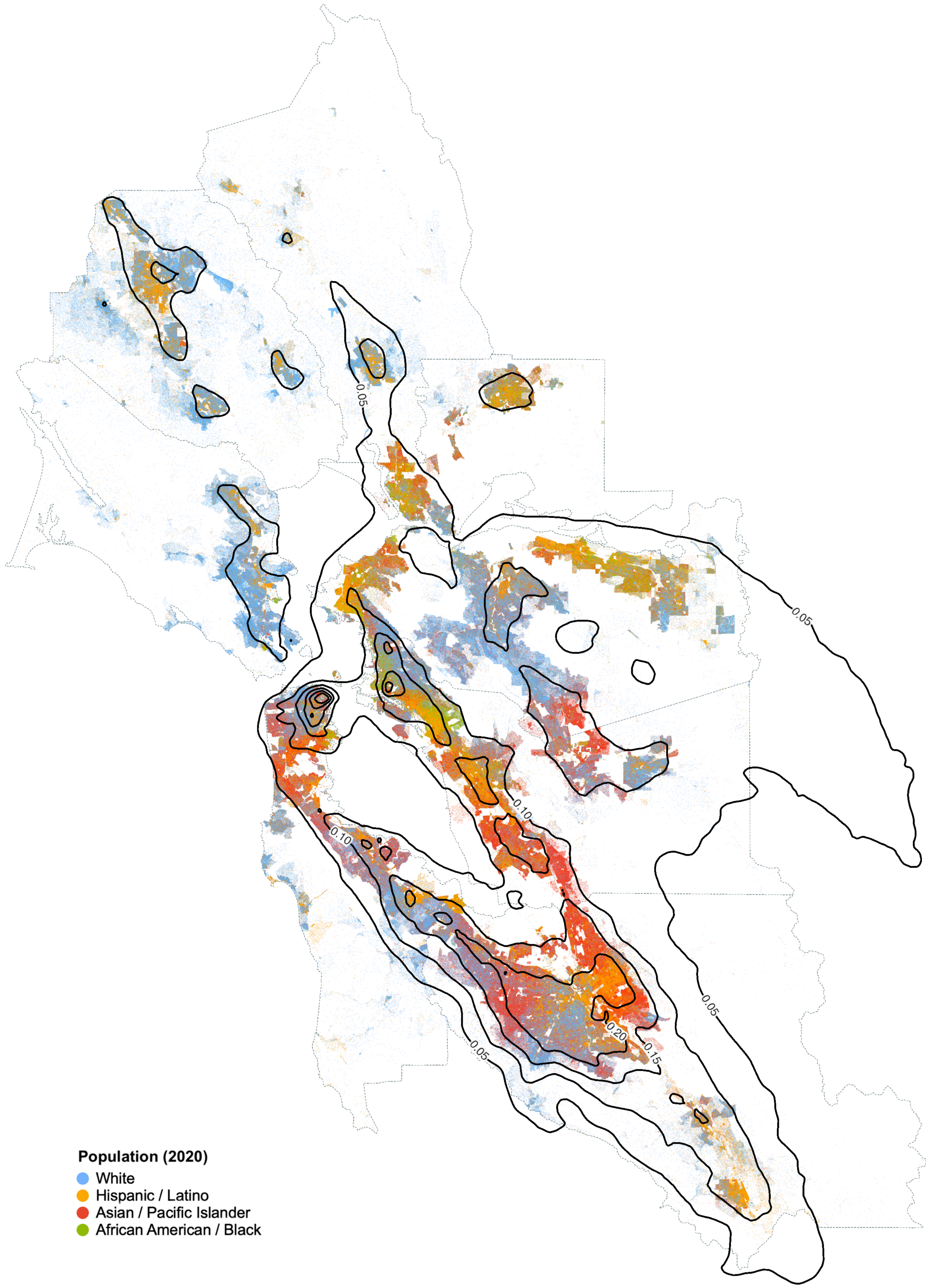

Figure 5: Contours of total $PM_{2.5}$ attributed to targeted emissions from space and water heating appliances, overlaid on residential population (n = 7.7 million).

In the scenario where both NO_x and $PM_{2.5}$ emissions were eliminated, resulting in reductions to primary $PM_{2.5}$ as well as secondary $PM_{2.5}$, the Bay Area's Asian/Pacific Islander population realized the largest reductions in average total $PM_{2.5}$ exposure intensity. This was true in both relative and absolute terms (Table **3**, column "Reduction"), and it was true for both $PM_{2.5}$ components (primary and secondary) as well as the total. For total $PM_{2.5}$, the reduction for Asian/Pacific Islander residents was 9% more than average; for Hispanic/Latino residents, 1% more; for African-American/Black residents, 2% less; and for White residents, 7% less. These differences from the average are evident in the right panel of Figure **6**, where the dotted horizontal line represents the average.

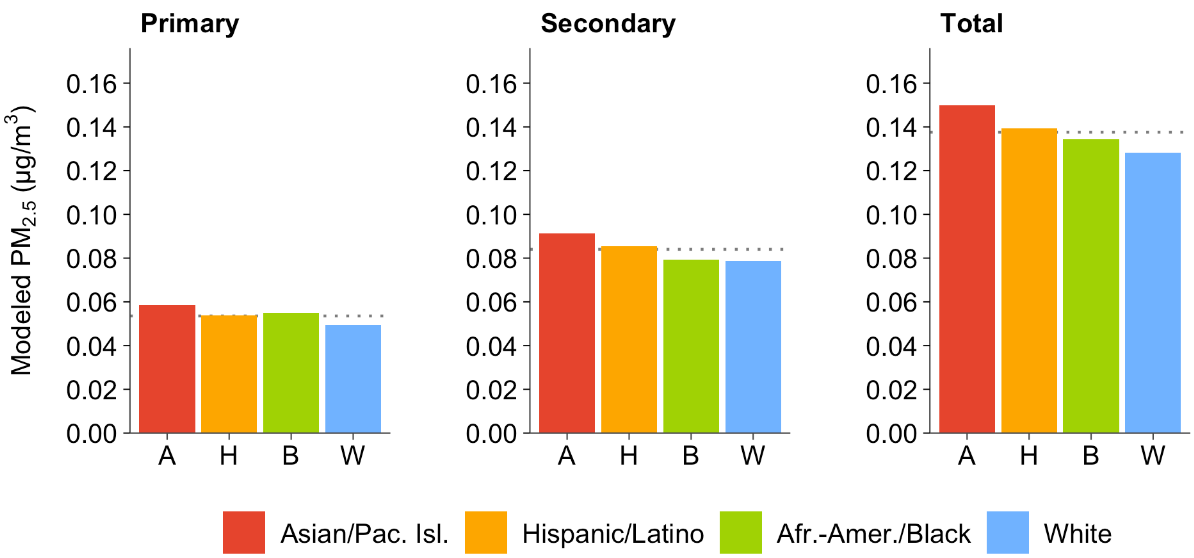

Figure 6: $PM_{2.5}$ impacts (annual average outdoor concentrations, weighted by residential population) attributed to targeted emissions from space and water heating appliances. Total = primary + secondary. Dotted horizontal lines indicate averages.

Figure **7** illustrates patterns of exposure using tertiles of total $PM_{2.5}$ attributed to these appliances. Tertiles are constructed so that one-third of the total population falls into each bin: here, the bins are 0.00 to 0.10 μg/m^3, 0.10 to 0.17 μg/m^3, and 0.17 to 0.42 μg/m^3 $PM_{2.5}$ attributed to targeted emissions from space and water heating appliances.

In a situation where exposures are equal, exactly one-third of each racial/ethnic group will also fall into each tertile. However, the modeling indicates that almost twice as many Asian/Pacific Islander residents live in locations corresponding to the highest tertile (0.17 to 0.42 μg/m^3), compared to the lowest (0.00 to 0.10 μg/m^3). For White residents, the pattern is reversed.

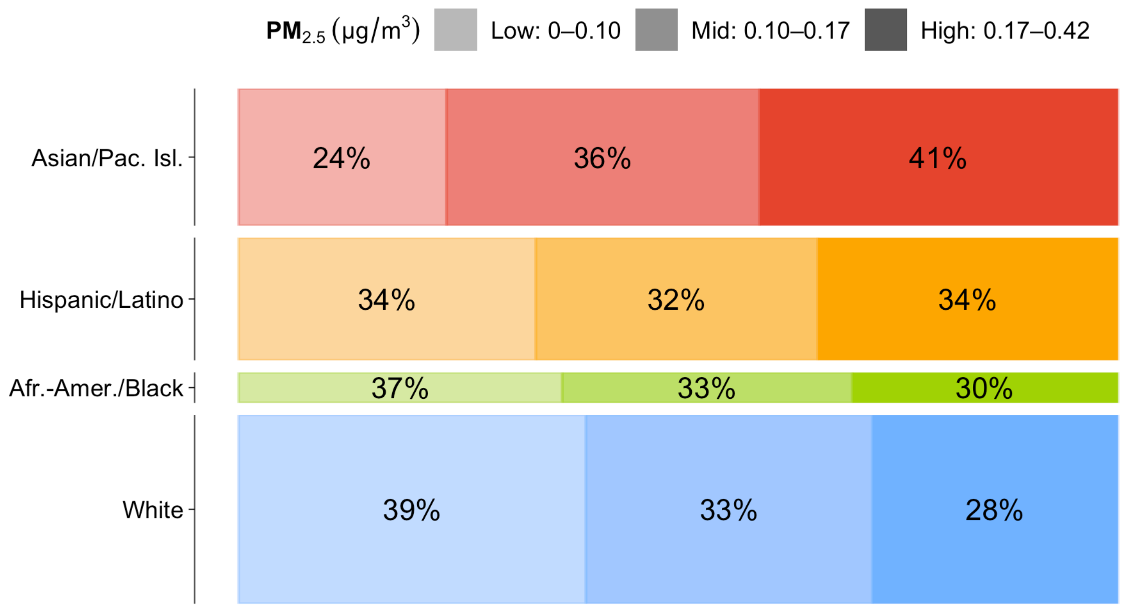

Figure 7: Share of total population within each racial/ethnic group and tertile of exposure. Tertiles are from left to right, and represent total $PM_{2.5}$ impacts from targeted emissions from space and water heating appliances. One-third of the total population falls into each tertile: 0.00 to 0.10 µg/m^3; 0.10 to 0.17 µg/m^3; or 0.17 to 0.42 µg/m^3. The thickness of each bar is proportional to the number of residents in that racial/ethnic category.

Patterns within and between counties

Within counties, the patterns of racial/ethnic inequality are different. Focusing on impacts from targeted emissions from space and water heating appliances, Tables **4** through **7** show this by unpacking the "reduction" data from Table **3**. From these tables, it is apparent that variation between counties is much larger than variation between racial/ethnic groups. It is also apparent that, in every county except Contra Costa, African-American/Black and Hispanic/Latino residents, rather than Asian/Pacific Islander residents, are the most impacted by total $PM_{2.5}$ from targeted emissions from space and water heating appliances (Table **4**). This recalls the example data presented in the previous section on Exposure Calculations.

The three most-impacted counties, in terms of per-capita total $PM_{2.5}$ impacts attributed to space and water heating appliances, are Santa Clara, San Francisco, and Alameda, and they are approximately twice as impacted as others (0.17 vs 0.09 µg/m^3, respectively).

The association between exposure and demographics at the county level is further illustrated by Figure **8**, which ranks all Bay Area counties by average exposure to $PM_{2.5}$ attributed to targeted emissions from space and water heating appliances, and then shows the demographics within each county. Santa Clara, San Francisco, and Alameda counties comprise approximately 59% of the Bay Area's total population, 73% of its Asian/Pacific Islander population, and 51% of its White population.

Additional detail is supplied by Figure **9**, which depicts the distributions of attributable exposures within each combination of county and race/ethnicity. Like Figure **8**, Figure **9** also communicates the relative number of people within each group: it is proportional to the area of each histogram. So, the same demographic patterns can be observed, with (for example) three-quarters of the Asian/Pacific Islander population found in the top three counties.

The overall association is strong enough, and the variation between counties large enough (compared to variation between racial/ethnic groups) that, while African-American/Black or Hispanic/Latino residents are the most impacted *within* all counties but Contra Costa, on a regional basis it is Asian/Pacific Islander residents who are the most impacted.

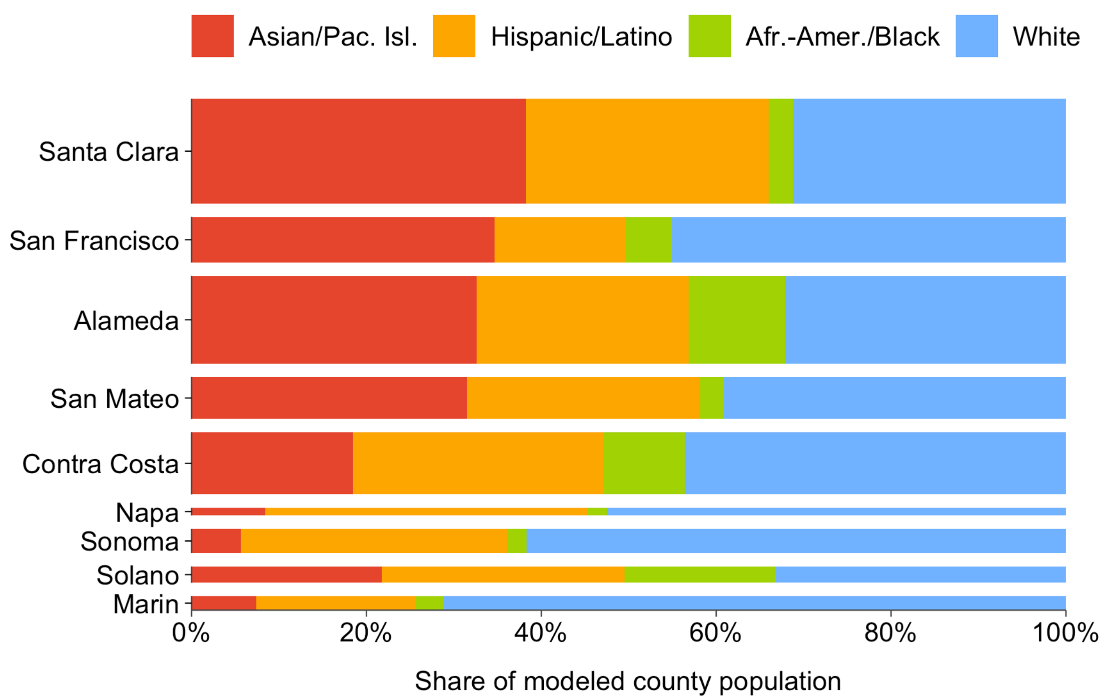

Figure 8: Demographics by county. Counties are ranked by average $PM_{2.5}$ impact from targeted emissions from space and water heating appliances, with the most impacted at the top. The thickness of each bar is proportional to the number of residents in that county. See also Table **2**.

Table 4: Average exposures (outdoor concentrations, weighted by residential population) to total (primary + secondary) $PM_{2.5}$ attributed to targeted emissions from space and water heating appliances.

	Asian	**Hispanic**	**Black**	**White**	**(average)**
Total $PM_{2.5}$ ($\mu g/m^3$)					
Santa Clara	0.195	0.198	0.199	0.194	*0.196*
San Francisco	0.154	0.175	0.171	0.168	*0.165*
Alameda	0.152	0.155	0.165	0.148	*0.153*
San Mateo	0.097	0.121	0.117	0.113	*0.110*
Contra Costa	0.092	0.090	0.086	0.092	*0.091*
Napa	0.069	0.088	0.069	0.076	*0.080*
Sonoma	0.066	0.069	0.070	0.061	*0.064*
Solano	0.062	0.066	0.065	0.060	*0.063*
Marin	0.058	0.062	0.057	0.055	*0.056*
(average)	*0.150*	*0.139*	*0.134*	*0.128*	0.138

Table 5: Average exposures (outdoor concentrations, weighted by residential population) to secondary $PM_{2.5}$ attributed to targeted emissions from space and water heating appliances.

	Asian	**Hispanic**	**Black**	**White**	**(average)**
Secondary $PM_{2.5}$ ($\mu g/m^3$)					
Santa Clara	0.126	0.126	0.127	0.127	*0.126*
San Francisco	0.073	0.082	0.081	0.079	*0.077*
Alameda	0.093	0.094	0.095	0.091	*0.093*
San Mateo	0.055	0.069	0.068	0.067	*0.064*
Contra Costa	0.063	0.059	0.056	0.064	*0.062*
Napa	0.047	0.056	0.047	0.051	*0.052*
Sonoma	0.043	0.045	0.045	0.040	*0.042*
Solano	0.041	0.042	0.042	0.040	*0.041*
Marin	0.037	0.039	0.037	0.035	*0.036*
(average)	*0.091*	*0.086*	*0.079*	*0.079*	0.084

Table 6: Average exposures (outdoor concentrations, weighted by residential population) to primary $PM_{2.5}$ attributed to targeted emissions from space and water heating appliances.

	Asian	Hispanic	Black	White	(average)
Primary $PM_{2.5}$ ($\mu g/m^3$)					
Santa Clara	0.069	0.072	0.072	0.067	*0.069*
San Francisco	0.082	0.093	0.090	0.090	*0.088*
Alameda	0.059	0.061	0.070	0.057	*0.060*
San Mateo	0.041	0.052	0.049	0.046	*0.046*
Contra Costa	0.029	0.031	0.030	0.028	*0.029*
Napa	0.023	0.031	0.022	0.025	*0.027*
Sonoma	0.023	0.024	0.025	0.021	*0.022*
Solano	0.021	0.024	0.023	0.020	*0.022*
Marin	0.021	0.023	0.020	0.020	*0.020*
(average)	*0.059*	*0.054*	*0.055*	*0.050*	*0.054*

Table 7: Average exposures (outdoor concentrations, weighted by residential population) to NO_x attributed to targeted emissions from space and water heating appliances.

	Asian	Hispanic	Black	White	(average)
NO_x (ppb)					
Santa Clara	0.852	0.876	0.890	0.833	*0.854*
San Francisco	1.086	1.228	1.198	1.194	*1.162*
Alameda	0.777	0.793	0.920	0.748	*0.788*
San Mateo	0.576	0.705	0.670	0.625	*0.632*
Contra Costa	0.377	0.390	0.384	0.358	*0.373*
Napa	0.300	0.425	0.301	0.343	*0.369*
Sonoma	0.305	0.320	0.331	0.272	*0.290*
Solano	0.279	0.318	0.309	0.273	*0.293*
Marin	0.292	0.320	0.286	0.273	*0.284*
(average)	*0.755*	*0.690*	*0.718*	*0.643*	*0.692*

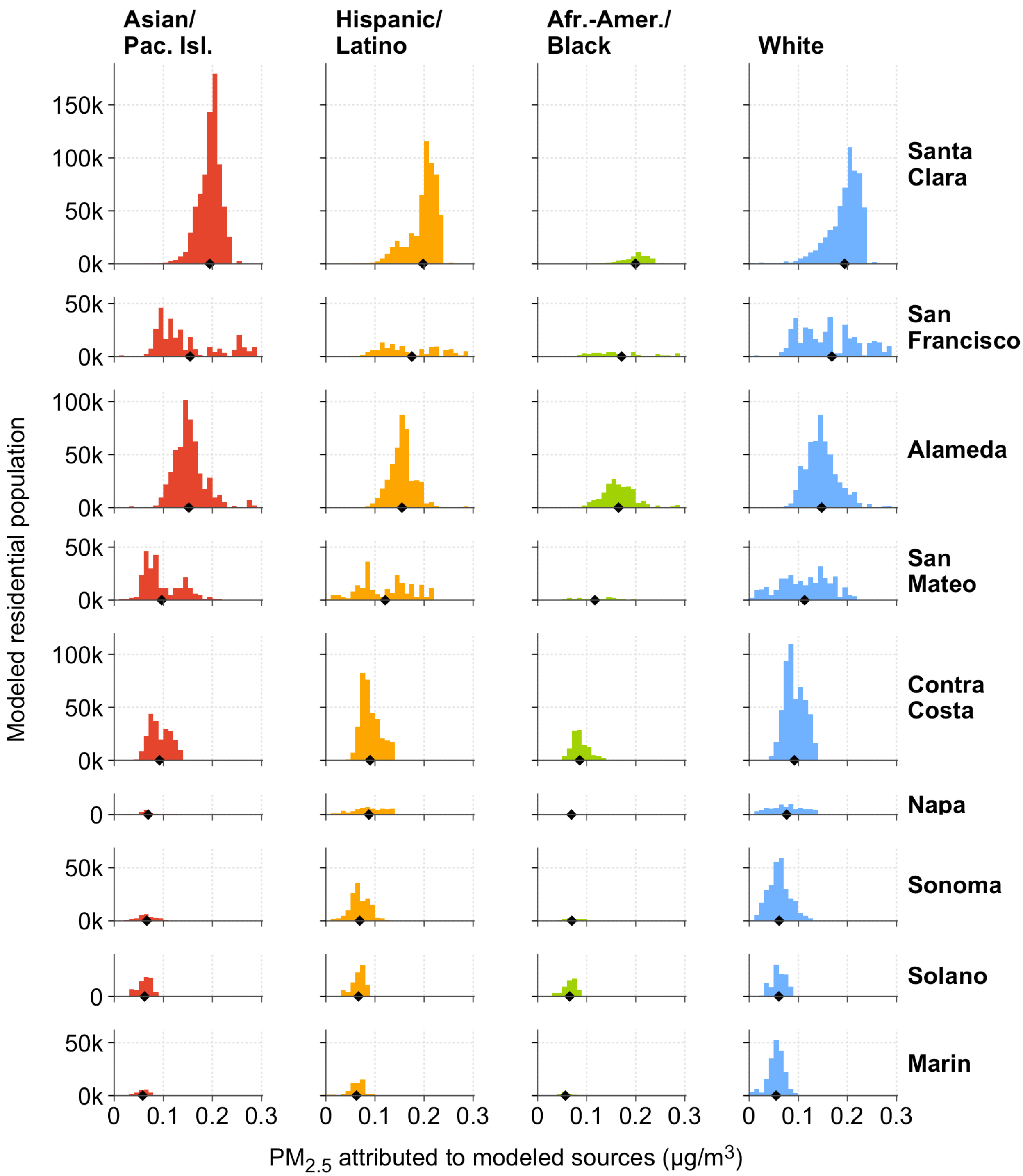

Figure 9: Distributions of exposure to total $PM_{2.5}$ attributed to targeted emissions from space and water heating appliances, by county and race/ethnicity. Diamonds on the x-axis indicate averages for each panel; exact values for these may be found in Table **4**. Histograms provide 0.01-µg/m^3 resolution detail. For clarity, a small number of exposures greater than 0.3 µg/m^3 are not shown.

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