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Article

Sociodemographic inequities in the burden of carcinogenic industrial air emissions in the United States

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Abstract

Background: Industrial facilities are not located uniformly across communities in the United States, but how the burden of exposure to carcinogenic air emissions may vary across population characteristics is unclear. We evaluated differences in carcinogenic industrial pollution among major sociodemographic groups in the United States and Puerto Rico.

Methods: We evaluated cross-sectional associations of population characteristics including race and ethnicity, educational attainment, and poverty at the census tract level with point-source industrial emissions of 21 known human carcinogens using regulatory data from the US Environmental Protection Agency. Odds ratios and 95% confidence intervals comparing the highest emissions (tertile or quintile) to the referent group (zero emissions [ie, nonexposed]) for all sociodemographic characteristics were estimated using multinomial, population density–adjusted logistic regression models.

Results: In 2018, approximately 7.4 million people lived in census tracts with nearly 12 million pounds of carcinogenic air releases. The odds of tracts having the greatest burden of benzene, 1,3-butadiene, ethylene oxide, formaldehyde, trichloroethylene, and nickel emissions compared with nonexposed were 10%-20% higher for African American populations, whereas White populations were up to 18% less likely to live in tracts with the highest emissions. Among Hispanic and Latino populations, odds were 16%-21% higher for benzene, 1,3-butadiene, and ethylene oxide. Populations experiencing poverty or with less than high school education were associated with up to 51% higher burden, irrespective of race and ethnicity.

Conclusions: Carcinogenic industrial emissions disproportionately impact African American and Hispanic and Latino populations and people with limited education or experiencing poverty thus representing a source of pollution that may contribute to observed cancer disparities.

Cancer disparities are well documented among African American, American Indian, Alaska Native, Asian, Pacific Islander, and Hispanic and Latino population groups, and those with low socioeconomic status (SES; ie, below the poverty line) (1,2). In the United States, people from these groups experience a disproportionate burden of exposure to environmental pollution, including criteria (eg, particulate matter, ozone) and hazardous (eg, acetaldehyde, formaldehyde) air pollutants from traffic, industry, and other sources (3-10). Industrial facilities are known sources of carcinogenic air pollutants, and similar patterns of unequal exposure burden have been shown among populations that live in proximity to these facilities (11-18), but few studies have evaluated specific chemicals emitted from industrial sources. Numerous national studies have illustrated racial, ethnic, and socioeconomic inequities in exposure to industrial pollution generally (19-24), most often using an aggregated air pollution estimate of burden, toxicity, or risk to reflect exposure. Although informative, these studies lack specificity and do not provide information on exposure patterns for specific carcinogenic chemicals emitted from industrial sources that may be associated with cancer risk, limiting their value for etiologic or translational research.

Small-area studies in California (25,26), Louisiana (27), Maryland (28), Missouri (29), Tennessee (30), and Texas (31,32), however, have examined population-level inequities in carcinogenic industrial pollution. These studies have shown disproportionate exposure among populations within urban areas and specific regions, including increased exposure to benzene and formaldehyde emissions among Black residents, and lower exposures to benzene, formaldehyde, and 1,3-butadiene exposures with increasing median household income (27). In Texas, the percentage of Hispanic populations in a census block group or tract was associated with higher estimated exposure to the total sum of carcinogenic air pollutants (31,32). However, it is unclear if these chemical-specific inequities persist across the United States. Nationally, little is known about the potential exposure to

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specific carcinogenic industrial air pollutants among the general population.

Industrial point source emissions may pose considerable environmental and public health burdens, especially when considering the cumulative impacts that some population groups may experience compared with others. Environmental racism is a recognized driver of inequality in the burden of environmental exposures to hazards, including industrial pollution and waste (33,34). A characterization of geographic and population patterns in exposure to carcinogenic industrial air emissions is a starting point for understanding their role in observed disparities in cancer outcomes. To address this critical research gap, we used a US regulatory database and data from the US census to estimate differences in census tract–level population exposure to emissions of carcinogens (eg, benzene, formaldehyde) released to air from industrial facilities in all 50 US states and Puerto Rico. We also examined emissions in the 4 other US territories (American Samoa, Guam, Northern Mariana Islands, and the US Virgin Islands) with permanent population.

Methods

Carcinogenic industrial air emissions

Carcinogenic industrial air emissions in US census tracts were based on 2018 data recorded in the US Environmental Protection Agency (EPA) Toxics Release Inventory (TRI) program (35). Briefly, the TRI program requires industrial facilities to annually report data on quantities and mode of chemical emissions if they meet certain regulatory requirements (eg, exceeding the minimum amount of allowed emissions; Supplementary Methods, available online). Of the 29 chemicals classified as carcinogenic to humans (group 1; Supplementary Table 1, available online) by the International Agency for Research on Cancer (36) that are tracked by the TRI program, 8 had no air emissions in 2018. Therefore, we identified air emissions (in pounds) for the 21 chemicals remaining. Bis(chloromethyl)ether, 4-aminobiphenyl, benzidine, and 2-Naphthylamine were emitted in less than 5 census tracts and therefore were excluded from carcinogen-specific analyses of population characteristics. We calculated the inverse distance-weighted sum of all the emissions within the tract for each carcinogen (Supplementary Methods, available online), weighting each facility's emissions by the linear distance between the facility and the population-based tract centroid. We evaluated 2 metrics of burden per tract: 1) chemical-specific inverse distance-weighted sums of air emissions and 2) total sum of inverse distance-weighted air emissions from all known carcinogens. To make comparisons after accounting for differences in toxicity among different chemicals, we obtained toxicity-weighted concentrations from the EPA's Risk-Screening Environmental Indicators (RSEI) model (Supplementary Methods, available online).

Population characteristics

Population data were obtained from the 2010 decennial US census and the 5-year 2006-2010 American Community Survey to characterize area-level sociodemographic characteristics (37). Tract-level characteristics included the percentage of population by self-reported race and ethnicity, educational attainment less than high school, unemployment, renter-occupied housing, and families below the poverty line, as well as median family income. We included tract-level persistent poverty and the Yost index (38,39), a composite of socioeconomic factors. Within each race and ethnicity group, we also assessed the percentage of adults with less than a high school education and families below the poverty line. We defined tracts as urban, suburban, or rural using the rural-urban commuting area codes from the 2010 US census (40) (Supplementary Methods, available online). We did not disaggregate population groups by ancestry because it is unclear that a nationwide analysis is ideal to describe inequities among groups that individually account for less than 10% of the US population.

Statistical analysis

We excluded 243 (0.3%) tracts that had zero population in the 2010 census (eg, airports, military installations). For all other tracts (n = 73 426), we estimated the air emissions for each carcinogen and determined the total carcinogenic air emissions by summing across all 21 chemicals. We excluded the 4 territories that do not have population data from subsequent analyses.

For the 9 carcinogens that were emitted in more than 5 but less than 50 tracts, the dependent variable for models was parameterized dichotomously to evaluate the presence or absence of carcinogen-specific emissions in the tract. For carcinogens emitted in a minimum of 50 tracts, we evaluated carcinogen-specific inverse distance-weighted emissions per tract (Supplementary Methods, available online). We categorized the pounds of inverse distance-weighted air emissions for the highly prevalent chemicals benzene, formaldehyde, and nickel (500 or more tracts with facilities) into their respective quintiles based on their distributions among all tracts with emissions of that carcinogen. We likewise created quintiles for the total sum of emissions based on the distribution among all tracts with emissions. We categorized arsenic, 1,3-butadiene, beryllium, ethylene oxide, and trichloroethylene (less than 200 tracts with facilities) into tertiles.

We used multinomial, population density–adjusted logistic regression models with robust variance estimation to estimate odds ratios (ORs) and 95% confidence intervals (CIs) comparing either the presence of emissions or the highest category of emissions (tertiles: T3 or quintiles: Q5) to the referent group of zero emissions (dependent variable), for continuous population characteristics (10%, $10 000, or 10-unit increases; Supplementary Methods, available online), and persistent poverty (categorical). For comparison with associations with inverse distance-weighted metrics, we also modeled RSEI concentrations (Supplementary Methods, available online). To evaluate if population patterns differed in urban and rural areas, we tested for interaction by urbanicity (Supplementary Methods, available online). All *P* values and 95% confidence intervals were 2-sided. Analyses were conducted using SAS version 9.4 and STATA/SE version 16.0.

Results

A total of 2196 facilities reported releases of 11 721 590 pounds of carcinogenic air emissions in 2018 and were located in 1763 (2.4%) tracts with an estimated population of 7 442 197 (Figure 1). Distributions of carcinogenic air emissions are presented in Supplementary Figure 1 and Supplementary Table 2 (available online). Carcinogens with the highest air emissions included formaldehyde, benzene, trichloroethylene, 1,3-butadiene, and vinyl chlorine (Table 1). When the carcinogens were ranked by their toxicity-weighted concentrations, the top 5 carcinogens were similar (eg, formaldehyde, benzene, and 1,3-butadiene) except for ethylene oxide and nickel, which had the 2 highest toxicity-weighted concentrations. Industrial facilities in the permanently inhabited island areas reported air releases of several carcinogenic compounds, including benzene (6594 pounds) and

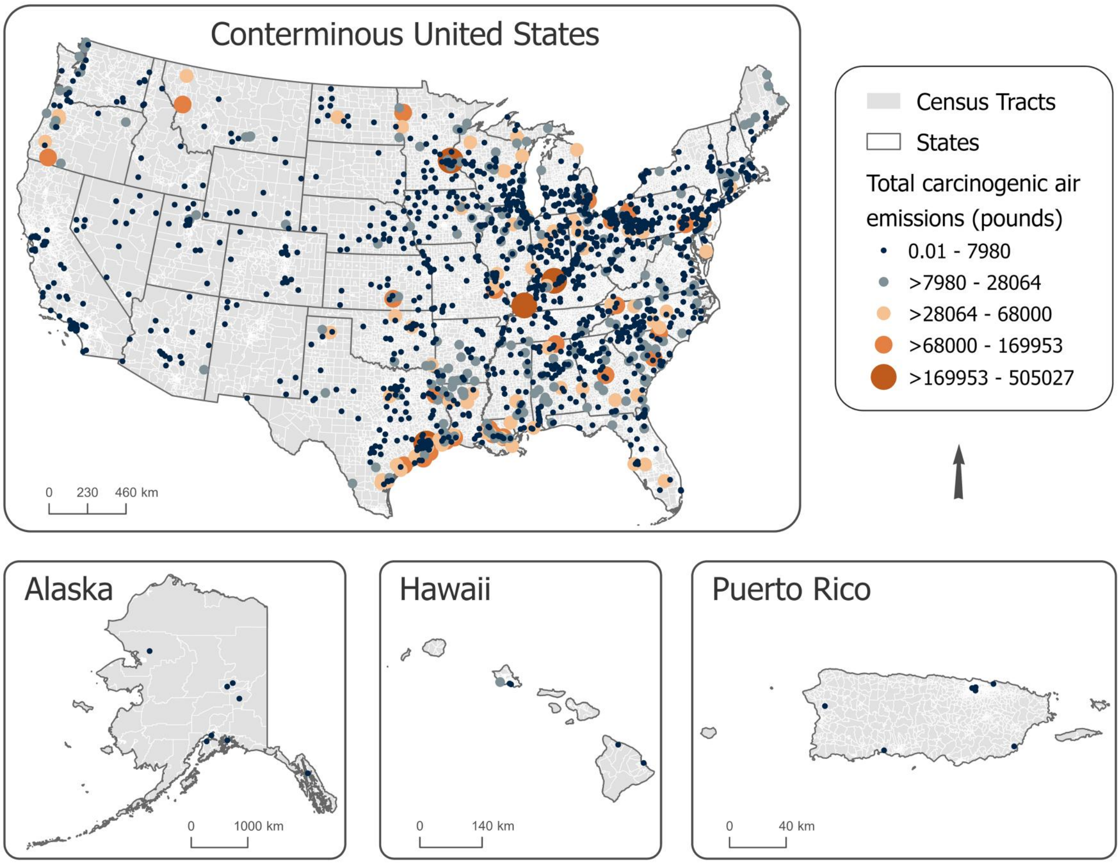

Figure 1. Locations of industrial facilities reporting air emissions of 21 chemicals classified as carcinogens by the International Agency for Research on Cancer across the conterminous United States, Alaska, Hawaii, and Puerto Rico by quintiles of pounds of air emissions per census tract.

Table 1. Summary of carcinogenic air emissions and affected population in the conterminous United States, Alaska, Hawaii, and Puerto Rico for 21 known carcinogens

Chemical	No. census tracts	% Urban or suburban	Population	Air releases,[a] pounds	Toxicity-weighted concentrations,[b] μg/m³
Formaldehyde	578	89	2 481 998	4 628 367	453 175
Benzene	524	93	2 086 814	3 011 602	678 623
Trichloroethylene	121	95	531 979	1 934 609	407 214
1,3-Butadiene	138	95	574 015	1 079 350	1 007 273
Vinyl chloride	26	88	103 058	549 035	76 426
Ethylene oxide	84	100	386 957	245 989	9 749 240
Nickel compounds	703	93	2 923 178	215 469	1 282 977
Arsenic and inorganic arsenic compounds	165	85	686 957	32 527	172 035
1,2-Dichloropropane	9	100	46 179	16 725	497.23
ortho-Toluidine	8	100	41 819	5541	22 312
Beryllium and beryllium compounds	52	86	222 698	917	8209
Bis(chloromethyl)ether	2	100	4482	663	998.1
Cadmium and cadmium compounds	18	88	84 467	211	1525
Polychlorinated biphenyls	25	84	111 003	181	61.2
Pentachlorophenol	16	93	61 532	178	43.2
Asbestos	12	83	44 466	171	26 993
Lindane	6	100	24 685	23	3.3
4-Aminobiphenyl	1	100	2537	10	0
4,4′-Methylenebis (2-chloroaniline)	6	83	18 468	8	401.2
Benzidine	1	100	2064	7	891.4
2-Naphthylamine	1	100	2064	7	0

[a] Emissions amounts self-reported by industrial facilities to the US Environmental Protection Agency Toxics Release Inventory Program in 2018.
[b] Toxicity-weighted concentrations of reported emissions derived using the US Environmental Protection Agency Risk-Screening Environmental Indicators model.

ethylene oxide (580 pounds) in Puerto Rico (Supplementary Results, available online).

Models showed that a 10% increase in the proportion of African American populations was associated with significantly greater odds (ranging from 10% to 20%) of living in a tract with the highest air emissions (T3 or Q5) of 1,3 butadiene, benzene, ethylene oxide, formaldehyde, nickel, and trichloroethylene compared with nonexposed (Table 2). The pattern for 1,3 butadiene, benzene, ethylene oxide, and formaldehyde was inverse for White populations (from -6% to -18%) and inverse for arsenic, benzene, and formaldehyde among Asian populations (−16% to -36% per 1% increase in the Asian population). Increases in Hispanic populations were associated with 16% to 21% higher odds of living in tracts with the highest air emissions of 1,3-butadiene, benzene, and ethylene oxide but with 17% and 22% lower odds for formaldehyde and trichloroethylene, respectively. For most of the carcinogens, except for beryllium, nearly all indicators of SES were associated with burden. The odds of the highest air emissions of these carcinogens were 19%-51% greater for populations with less than a high school education overall, and 19%-39% higher odds were observed for most carcinogens among White populations with less than a high school education. The odds of the highest air emissions were 24%-41% greater for families experiencing poverty overall and, by race and ethnicity, remained 11%-29% greater for White and African American families. Persistent poverty was significantly associated with 167%-228% higher odds of living in tracts with the highest air emissions of 1,3-butadiene, benzene, nickel, and trichloroethylene. Increases in the proportion of Asian families experiencing poverty were associated with high burden of arsenic exposure, as was the proportion of White adults with less than a high school education. Associations using toxicity-weighted emissions were most consistent among African American and White population groups and for some indicators of SES (Supplementary Table 3, available online).

For the 9 carcinogens with emissions in less than 50 tracts, patterns generally showed higher emissions burdens for African American, Hispanic, and low SES populations and lower emissions burdens for White and Asian populations, but most associations were not statistically significant (Supplementary Results and Supplementary Table 4, available online).

Models evaluating the total sum of emissions yielded patterns of association similar to those for individual carcinogens (Table 3). For example, a 10% increase in the proportion of African American populations in the tract was associated with 18% higher odds of living in a tract with the highest air emissions compared with nonexposed, whereas the pattern was inverse for White and Asian populations (11% and 62% lower odds, respectively). Low educational attainment was associated with greater odds of having the highest air emissions, overall and by race and ethnicity, mainly among White, African American, and Hispanic populations. The same was true for families experiencing poverty, mainly for White ($OR_{Q5\ vs\ nonexposed} = 1.22$, 95% CI = 1.15 to 1.28) and African American ($OR_{Q5\ vs\ nonexposed} = 1.10$, 95% CI = 1.06 to 1.13) families. Persistent poverty within a tract was associated with greater odds of having the highest air emissions ($OR_{Q5\ vs\ nonexposed} = 2.42$, 95% CI = 1.61 to 3.65). Patterns of association did not substantively change when race and ethnicity models were adjusted for SES, and vice versa, except that the association with persistent poverty was attenuated and no longer statistically significant.

More than 90% of tracts in the highest quintile of air emissions were in urban or suburban areas. Patterns of association limited to urban areas were like the nonstratified results (Supplementary Results and Supplementary Table 5, available online).

Discussion

Our novel evaluation showed that there are millions of pounds of carcinogens emitted to air from industrial sources across the United States and US territories and that notable population differences are apparent between those who do and do not live near high levels of these emissions. Prior to this work, there had been limited characterization of population patterns of exposure to emissions of specific carcinogenic industrial air pollutants on a national scale. Specifically, our findings illustrate inequitable emissions among African American populations that are independent of low educational attainment or family poverty, including in rural areas. In contrast, it wasn't until we accounted for educational attainment and poverty among White populations that we saw an increase in emissions burden in this group. Although we did not observe a statistically significant overall association with the sum of carcinogenic air emissions for Hispanic populations, when we stratified by urbanicity, the proportion of Hispanic populations in urban areas was associated with higher emissions burden. Importantly, SES was a critical predictor of exposure burden; multiple indicators of low SES were associated with high emissions.

Our investigation extends a limited body of previous work on a national scale (19-24), none of which evaluated specific carcinogens. One study that used census and TRI data from 1990 showed that African American, Asian and Pacific Islander, Hispanic, and other racial groups tended to live in counties with higher industrial emissions amounts relative to counties where White populations lived (18). In our analysis, Asian populations had lower emissions burden, consistent with another national study of 2010 census data that found tract-level Asian populations had one of the lower estimated cancer risk scores from hazardous air pollution from point sources but did not evaluate SES (41). Other studies of Asian populations have found increased exposure to particulate matter in metropolitan areas (42) and hazardous air pollutants from a mix of sources, including industry, both nationally (10) and in 4 US cities (43). However, our findings highlight the importance of simultaneously accounting for measures of SES; we no longer observed reduced odds of exposure among the Asian population with low SES in our analysis.

We evaluated emissions burden for 21 individual carcinogens, with emphasis on 8 carcinogens emitted in at least 50 tracts. Comparable investigation of specific carcinogenic exposure patterns has only been evaluated in small-area studies, like those conducted in California (25), Louisiana (27), Maryland (28), Missouri (29), Tennessee (30), and Texas (31,32). Similar to studies in Louisiana (27) and Tennessee (30), we observed disproportionate amounts of benzene and formaldehyde emissions among African American populations and benzene, formaldehyde, and 1,3-butadiene emissions among low SES populations, showing that disparities in these emissions are not limited to the smaller geographic areas included in previous studies. In our study, population-level indicators of low SES were associated with higher airborne emissions of benzene, formaldehyde, 1,3-butadiene, and nickel. For these carcinogens, low educational attainment and family poverty among White populations were associated a with greater emissions burden compared with being a White individual overall.

Table 2. Carcinogen-specific associations of tract-level sociodemographic characteristics with odds a tract having the highest[a] inverse-distance weighted carcinogenic air emissions compared with zero air emissions (nonexposed)

Tract characteristics	Arsenic OR_{T3} (95% CI)[b]	1,3-Butadiene OR_{T3} (95% CI)[b]	Benzene OR_{Q5} (95% CI)[b]	Beryllium OR_{T3} (95% CI)[b]	Ethylene oxide OR_{T3} (95% CI)[b]	Formaldehyde OR_{Q5} (95% CI)[b]	Nickel OR_{Q5} (95% CI)[b]	Trichloroethylene OR_{T3} (95% CI)[b]
Race and ethnicity, %								
African American	0.99 (0.83 to 1.18)	1.18 (1.04 to 1.33)	1.20 (1.11 to 1.29)	1.06 (0.78 to 1.45)	1.20 (1.05 to 1.37)	1.19 (1.12 to 1.28)	1.10 (1.03 to 1.17)	1.12 (1.01 to 1.25)
American Indian and Alaska Native	0.97 (0.92 to 1.02)[c]	0.96 (0.87 to 1.06)[c]	0.99 (0.97 to 1.01)[c]	0.94 (0.80 to 1.11)[c]	0.71 (0.48 to 1.05)[c]	0.99 (0.98 to 1.00)[c]	0.97 (0.94 to 1.01)[c]	0.76 (0.54 to 1.07)[c]
Asian	0.64 (0.41 to 0.99)[c]	0.86 (0.70 to 1.06)[c]	0.70 (0.56 to 0.89)[c]	0.83 (0.43 to 1.59)[c]	0.86 (0.72 to 1.03)[c]	0.84 (0.73 to 0.97)[c]	0.65 (0.36 to 1.19)	0.89 (0.53 to 1.49)
Hispanic	0.96 (0.78 to 1.19)	1.21 (1.10 to 1.32)	1.16 (1.09 to 1.24)	0.70 (0.42 to 1.17)	1.18 (1.06 to 1.32)	0.83 (0.72 to 0.96)	0.97 (0.88 to 1.07)	0.78 (0.63 to 0.97)
Multiracial	0.96 (0.85 to 1.10)[c]	0.65 (0.46 to 0.93)[c]	0.99 (0.89 to 1.09)	0.90 (0.68 to 1.19)[c]	1.02 (0.97 to 1.07)[c]	1.03 (1.01 to 1.05)[c]	1.05 (1.02 to 1.08)[c]	1.01 (0.94 to 1.09)
Native Hawaiian and Other Pacific Islander	0.98 (0.88 to 1.09)[c]	—	0.95 (0.74 to 1.21)[c]	—	0.01 (0.001 to 1.69)[c]	0.85 (0.50 to 1.42)[c]	0.92 (0.70 to 1.22)[c]	0.30 (0.03 to 2.31)[c]
Other	0.96 (0.52 to 1.75)[c]	0.04 (0.01 to 0.63)[c]	0.73 (0.25 to 2.12)[c]	—	0.10 (0.002 to 4.75)[c]	1.04 (0.59 to 1.82)[c]	0.91 (0.43 to 1.85)[c]	1.06 (0.83 to 1.35)[c]
White	1.05 (0.91 to 1.20)	0.82 (0.75 to 0.90)	0.83 (0.78 to 0.88)	1.09 (0.80 to 1.49)	0.82 (0.74 to 0.90)	0.94 (0.88 to 0.99)	0.95 (0.89 to 1.01)	0.99 (0.89 to 1.11)
Socioeconomic status, %								
Less than high school education	1.19 (1.01 to 1.40)	1.37 (1.14 to 1.65)	1.46 (1.31 to 1.64)	1.17 (0.83 to 1.64)	1.51 (1.30 to 1.75)	1.29 (1.16 to 1.43)	1.30 (1.18 to 1.42)	1.04 (0.84 to 1.27)
Rented housing units[d]	1.08 (0.90 to 1.31)	1.18 (1.05 to 1.33)	1.23 (1.14 to 1.33)	1.08 (0.77 to 1.53)	1.24 (1.09 to 1.41)	1.29 (1.22 to 1.37)	1.26 (1.17 to 1.36)	1.30 (1.16 to 1.47)
Unemployed	1.19 (0.78 to 1.81)	1.35 (1.05 to 1.75)	1.63 (1.44 to 1.84)	0.76 (0.30 to 1.93)	1.46 (1.20 to 1.78)	1.43 (1.22 to 1.68)	1.52 (1.33 to 1.75)	1.25 (0.90 to 1.74)
Families below poverty threshold	1.18 (0.99 to 1.41)	1.41 (1.24 to 1.61)	1.41 (1.29 to 1.55)	1.17 (0.65 to 2.10)	1.28 (1.10 to 1.49)	1.35 (1.24 to 1.48)	1.41 (1.28 to 1.54)	1.24 (1.04 to 1.47)
Persistent poverty	5.61 (1.93 to 16.24)	3.25 (1.26 to 8.39)	3.28 (1.68 to 6.42)	3.57 (0.46 to 27.5)	2.02 (0.44 to 9.23)	2.61 (1.17 to 5.80)	2.89 (1.67 to 4.99)	2.67 (1.18 to 6.02)
Family income, per $10k[e]	0.83 (0.72 to 0.94)	0.83 (0.74 to 0.93)	0.75 (0.69 to 0.83)	0.90 (0.71 to 1.14)	0.78 (0.68 to 0.89)	0.77 (0.70 to 0.85)	0.81 (0.74 to 0.89)	0.83 (0.75 to 0.93)
Yost Index, per 10 unit[f]	1.14 (1.03 to 1.26)	1.14 (1.03 to 1.25)	1.27 (1.18 to 1.37)	1.07 (0.89 to 1.29)	1.27 (1.13 to 1.43)	1.28 (1.18 to 1.38)	1.22 (1.15 to 1.30)	1.15 (1.04 to 1.26)
Families below poverty, %								
African American	1.07 (0.97 to 1.18)	1.15 (1.06 to 1.25)	1.11 (1.05 to 1.17)	1.05 (0.85 to 1.29)	1.12 (1.03 to 1.22)	1.12 (1.06 to 1.18)	1.12 (1.07 to 1.18)	1.08 (0.99 to 1.18)
American Indian and Alaska Native	0.93 (0.78 to 1.12)	0.99 (0.85 to 1.14)	1.06 (0.97 to 1.14)	—	1.04 (0.89 to 1.22)	1.05 (0.97 to 1.13)	1.01 (0.93 to 1.11)	0.81 (0.59 to 1.10)
Asian	1.17 (1.07 to 1.27)	0.87 (0.69 to 1.10)	0.97 (0.84 to 1.13)	—	1.04 (0.85 to 1.26)	0.91 (0.75 to 1.10)	0.96 (0.84 to 1.09)	1.12 (1.01 to 1.23)
Hispanic	1.02 (0.92 to 1.12)	0.96 (0.88 to 1.05)	0.93 (0.87 to 1.01)	0.92 (0.78 to 1.09)	0.97 (0.88 to 1.07)	1.08 (1.02 to 1.15)	0.99 (0.92 to 1.06)	0.98 (0.86 to 1.11)
Multiracial	1.00 (0.89 to 1.12)	1.02 (0.92 to 1.13)	0.99 (0.91 to 1.08)	1.06 (0.90 to 1.26)	0.97 (0.83 to 1.14)	1.06 (0.99 to 1.13)	1.06 (1.00 to 1.13)	1.06 (0.95 to 1.17)
Native Hawaiian and Other Pacific Islander	1.16 (0.94 to 1.42)	—	1.08 (0.87 to 1.33)	—	—	0.96 (0.77 to 1.19)	—	—
Other	0.99 (0.89 to 1.11)	1.00 (0.88 to 1.13)	1.04 (0.97 to 1.11)	0.88 (0.69 to 1.12)	1.02 (0.93 to 1.12)	1.03 (0.96 to 1.11)	1.01 (0.94 to 1.08)	0.90 (0.77 to 1.05)
White	1.23 (1.08 to 1.40)	1.29 (1.13 to 1.47)	1.25 (1.15 to 1.37)	1.03 (0.58 to 1.84)	1.15 (0.97 to 1.37)	1.26 (1.18 to 1.35)	1.23 (1.15 to 1.32)	1.15 (0.95 to 1.40)
Less than high school education, %								
African American	1.01 (0.91 to 1.11)	1.07 (0.96 to 1.20)	1.09 (1.02 to 1.16)	1.07 (0.92 to 1.25)	1.08 (0.95 to 1.23)	1.07 (1.01 to 1.14)	1.09 (1.03 to 1.15)	0.98 (0.87 to 1.11)
American Indian and Alaska Native	1.00 (0.90 to 1.11)	1.00 (0.89 to 1.12)	1.02 (0.95 to 1.09)	0.84 (0.57 to 1.23)	1.05 (0.93 to 1.20)	1.03 (0.97 to 1.10)	1.03 (0.96 to 1.09)	1.05 (0.94 to 1.17)
Asian	0.97 (0.84 to 1.12)	0.95 (0.80 to 1.12)	0.92 (0.81 to 1.05)	0.83 (0.62 to 1.11)	1.10 (0.97 to 1.26)	0.97 (0.88 to 1.07)	0.83 (0.73 to 0.95)	1.10 (0.99 to 1.22)
Hispanic	0.96 (0.88 to 1.06)	1.04 (0.96 to 1.13)	1.01 (0.95 to 1.07)	0.97 (0.83 to 1.14)	1.05 (0.95 to 1.16)	1.04 (0.98 to 1.11)	1.02 (0.95 to 1.08)	0.99 (0.89 to 1.10)
Multiracial	0.96 (0.86 to 1.08)	1.03 (0.92 to 1.16)	1.01 (0.93 to 1.09)	0.92 (0.74 to 1.13)	1.09 (0.98 to 1.22)	1.02 (0.94 to 1.09)	0.93 (0.86 to 1.01)	1.07 (0.97 to 1.17)
Native Hawaiian and Other Pacific Islander	1.13 (0.97 to 1.32)	—	0.75 (0.53 to 1.06)	—	—	0.82 (0.61 to 1.10)	0.95 (0.74 to 1.22)	—
Other	0.97 (0.89 to 1.05)	1.10 (1.02 to 1.17)	1.05 (1.00 to 1.11)	0.93 (0.81 to 1.07)	1.06 (0.97 to 1.15)	1.02 (0.96 to 1.07)	0.98 (0.93 to 1.04)	0.94 (0.83 to 1.05)
White	1.39 (1.23 to 1.56)	1.19 (1.04 to 1.37)	1.29 (1.19 to 1.41)	1.31 (1.03 to 1.67)	1.36 (1.23 to 1.50)	1.30 (1.21 to 1.40)	1.30 (1.22 to 1.40)	0.90 (0.72 to 1.14)

[a] For chemicals emitted in more than 50 but less than 200 tracts (arsenic, 1,3-butadiene, beryllium, ethylene oxide, and trichloroethylene), the distribution was categorized into tertiles (T), with estimates for the highest tertile (T3) compared with nonexposed presented. For chemicals emitted in more than 200 tracts (benzene, formaldehyde, and nickel), the distribution was categorized into quintiles, with estimates for the highest quintile (Q5) compared with nonexposed presented. "—" indicate odds ratios not presented due to unstable estimate. CI = confidence interval; OR = odds ratio.

[b] Odds ratios are adjusted for population density (population per km^2 land area of the tract) and reflect a 10% increase in the characteristic of the tract population (ie, a 10% increase in the percentage of the tract population with less than a high school education) unless otherwise noted; estimates for persistent poverty compare the odds of being in the highest emissions category among tracts experiencing persistent poverty with tracts that do not.

[c] Odds ratios for 1% increase in population characteristic substituted when 10% increase was not able to be estimated.

[d] Percentage of rented housing units missing for 214 tracts.

[e] Median family income missing for 493 tracts.

[f] Yost Index missing for 1469 tracts.

Table 3. Associations of tract-level sociodemographic characteristics with odds a tract having the highest quintile of total sum of inverse-distance weighted carcinogenic air emissions (quintile 5) compared with zero air emissions (nonexposed)

Tract characteristics	Inverse-distance weighted sum of air emissions OR_{Q5} vs nonexposed (95% CI)[a]
Race and ethnicity, %	
African American	1.18 (1.13 to 1.23)
American Indian and Alaska Native	0.86 (0.74 to 0.99)
Asian	0.38 (0.19 to 0.74)
Hispanic	1.04 (0.98 to 1.09)
Multiracial	1.19 (0.81 to 1.74)
Native Hawaiian and Other Pacific Islander	0.83 (0.55 to 1.24)[b]
Other	0.87 (0.37 to 2.02)[b]
White	0.89 (0.86 to 0.92)
Socioeconomic status, %	
Less than high school education	1.34 (1.26 to 1.43)
Rented housing units[c]	1.24 (1.18 to 1.29)
Unemployed	1.49 (1.34 to 1.65)
Families below poverty threshold	1.34 (1.27 to 1.42)
Persistent poverty	2.42 (1.61 to 3.65)
Family income, per $10k[d]	0.79 (0.75 to 0.83)
Yost Index, per 10 unit[e]	1.23 (1.18 to 1.28)
Families below poverty, %	
African American	1.10 (1.06 to 1.13)
American Indian and Alaska Native	1.03 (0.98 to 1.08)
Asian	1.00 (0.94 to 1.07)
Hispanic	1.01 (0.97 to 1.05)
Multiracial	1.03 (0.99 to 1.07)
Native Hawaiian and Other Pacific Islander	0.98 (0.82 to 1.15)
Other	1.02 (0.97 to 1.06)
White	1.22 (1.15 to 1.28)
Less than high school education, %	
African American	1.07 (1.03 to 1.11)
American Indian and Alaska Native	1.01 (0.97 to 1.06)
Asian	0.99 (0.94 to 1.05)
Hispanic	1.04 (1.01 to 1.08)
Multiracial	1.02 (0.98 to 1.06)
Native Hawaiian and Other Pacific Islander	0.73 (0.56 to 0.96)
Other	1.03 (1.00 to 1.06)
White	1.26 (1.20 to 1.32)

[a] Odds ratios are adjusted for population density (population per km^2 land area of the tract) and reflect a 10% increase in the characteristic of the tract population (ie, a 10% increase in the percentage of the tract population with less than a high school education) unless otherwise noted; estimates for persistent poverty compare the odds of being in the highest emissions category among tracts experiencing persistent poverty to tracts that do not. CI = confidence interval; OR = odds ratio.
[b] Odds ratios for 1% increase in population characteristic substituted when 10% increase was not able to be estimated.
[c] Percentage of rented housing units missing for 214 tracts (nonexposed n = 218; Q 1 n = 4; Q2 n = 3; Q3 n = 9; Q4 n = 4; Q5 n = 3).
[d] Median family income missing for 493 tracts (nonexposed n = 468; Q1 n = 3; Q2 n = 4; Q3 n = 10; Q4 n = 6; Q5 n = 2).
[e] Yost Index missing for 1469 tracts (nonexposed n = 1412; Q1 n = 10; Q2 n = 13; Q3 n = 17; Q4 n = 10; Q5 n = 7).

Our evaluation contributes a needed national characterization of levels of carcinogenic air emissions that has largely been lacking from the literature and is useful to guide etiologic investigation of cancer associations with specific chemicals in the environment, the study of which remains limited for many carcinogens. We acknowledge that the emissions are self-reported by each facility, may be subject to errors, and are difficult to verify, however, for some chemicals the TRI is the only routinely collected estimate of environmental emissions. These data have been leveraged in several ecologic and cohort studies (44-46) including a prospective cohort in multiple US states that observed an increased risk of incident intraductal breast cancer in association with relatively high estimated exposure to ethylene oxide emissions near the home (47). In 2018, regulated industries reported emissions of more than 1 million pounds each of benzene, formaldehyde, butadiene, and trichloroethylene, but we know very little about exposure levels and related cancer risks among the general US population. Identification of specific carcinogens with unequal exposure potential is informative not only to community members and policy makers but also to researchers planning environmental studies of cancer risk and disparities.

Major strengths of our study include use of emissions data for the United States, including the territories, and of census data that account for the diversity of the US population. To our knowledge, this is the first characterization of carcinogenic air emissions on the island territories. Our distance- and population-weighted emissions metrics provided a more detailed quantitative characterization than the simpler metrics (eg, counts of emission sources) that have been used in other national studies. Often, census tract–level estimates of environmental exposure rely on the geometric center of the tract, which assumes population is evenly distributed throughout the tract. Instead, we used the population-weighted centroid, which better reflects the actual areas where population reside and their exposure potential. Estimating exposure burden for these point source carcinogenic emissions is challenging given the limited measurement of these chemicals in the ambient environment. Studies in industrial areas in New York State (48) and Houston, Texas, have demonstrated associations between ambient benzene concentrations and industrial sources (49). In a monitoring study of Ohio homes within 2 km of a natural gas compressor station, indoor benzene levels were 2-17 times greater than the state's indoor standard (50). Nonsmokers living approximately 0.8 km from an ethylene oxide–emitting facility had statistically significantly higher levels of hemoglobin adduct levels compared with those farther away, and median levels among all residents of the general area were higher than levels measured in the US general population (51). However, we acknowledge that residing near an emitting facility does not necessarily confer exposure to the carcinogen, and likewise, emissions cross administrative boundaries like census tracts. Our exposure metrics are also different from studies that have used toxicity concentrations or cancer risk scores, such as data from the EPA's National Air Toxics Assessment or RSEI models that are based on TRI emissions. Although these datasets are created using sophisticated methods that incorporate important geospatial features and other factors influencing environmental fate and transport (eg, meteorological conditions), we did not use RSEI estimates in our main analyses because they are modeled using distances out to 50 km and subsequently would define large proportions of the US population as exposed at very low concentrations. In contrast, our goal was to characterize population patterns among highly exposed groups. We therefore limited our definition of exposure to populations within the tract where a facility is located to conservatively include populations with the greatest potential for exposure. Emissions quantities are one way to describe population burden, however, we acknowledge that each chemical has a different toxicity and that the toxicity may be relevant to subsequent cancer risk.

Although we present data from all racial and ethnic population groups in the 2010 census, there were small numbers for some (eg, American Indian, Alaska Native, Native Hawaiian) that sometimes resulted in wide confidence intervals and limited our ability to evaluate associations by educational attainment or family poverty. We presented results from models evaluating each population characteristic individually, but estimates did not substantively change when racial and ethnic characteristics were co-adjusted for SES or vice versa. We did not disaggregate population groups by ancestry. To evaluate patterns of emissions among disaggregated groups, a different approach would be better. For example, comparisons could be made of geographically distinct areas with and without relatively high proportions of residents of similar racial and ethnic ancestry. Additionally, we acknowledge that associations for Hispanics may have been underestimated because of their known underrepresentation in the US census (52). We used available data on persistent poverty but acknowledge the challenges of creating this construct for census tracts that may change boundaries over time. The placement of facilities that emit the carcinogens in our study are related to local land use and zoning rules, and we did not explore this in our analyses.

In this assessment, we demonstrated inequities in the burden of airborne carcinogenic emissions across the general population. These results highlight the influence of socioeconomic factors on living near industrial sources with the highest levels of carcinogenic emissions and underscore the importance of taking an intersectional approach that evaluates population characteristics jointly to elucidate environmental exposure disparities. Given ongoing concerns about socio-environmental drivers of health inequities, this work offers a timely characterization and is informative for environmental exposure assessments and studies of cancer risk.

Data availability

The data used in this study are publicly available from the US EPA (https://www.epa.gov/toxics-release-inventory-tri-program) and the US Census Bureau (https://www.census.gov/).

Author contributions

Jessica Madrigal, PhD, MS (Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Supervision; Visualization; Writing - original draft; Writing - review & editing), Abigail Flory, MS (Data curation; Methodology; Software; Visualization; Writing—review & editing), Jared Fisher, PhD (Data curation; Investigation; Methodology; Validation; Writing—review & editing), Elizabeth Sharp, BA (Writing—review & editing), Barry Graubard, PhD (Methodology; Writing—review & editing) Mary Ward, PhD (Methodology; Writing—review & editing), and Rena Jones, PhD, MS (Conceptualization; Data curation; Methodology; Funding acquisition; Investigation; Resources; Supervision; Writing—review & editing).

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Conflicts of interest

The authors declare no conflict of interest.

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