Cumulative Cancer Risk from Air Pollution in Houston: Disparities in Risk Burden and Social Disadvantage

ARTICLE *in* ENVIRONMENTAL SCIENCE AND TECHNOLOGY · JULY 2008

Impact Factor: 5.33 · DOI: 10.1021/es072042u · Source: PubMed

Stephen H Linder
University of Texas Health Science Center …

Dritana Marko
University of Texas Health Science Center …

Cumulative Cancer Risk from Air Pollution in Houston: Disparities in Risk Burden and Social Disadvantage

STEPHEN H. LINDER,*,† DRITANA MARKO,† AND KEN SEXTON‡

Institute for Health Policy, E-1023, and Division of Environmental and Occupational Health Sciences, E-1033, The University of Texas School of Public Health, 1200 Herman Pressler Street, Houston, Texas 77030

Received August 15, 2007. Revised manuscript received March 19, 2008. Accepted March 24, 2008.

Air toxics are of particular concern in Greater Houston, home to one of the world's largest petrochemical complexes and a quarter of the nation's refining capacity. Much of this complex lies along a navigable ship channel that flows 50 miles from east of the central business district through Galveston Bay and into the Gulf of Mexico. Numerous communities, including both poor and affluent neighborhoods, are located in close proximity to the 200 facilities along this channel. Our aim is to examine the spatial distribution of cumulative, air-pollution-related cancer risks in Houston and Harris County, with particular emphasis on identifying ethnic, economic, and social disparities. We employ exposure estimates from NATA-1999 and census data to assess whether the cumulative cancer risks from air toxics in Houston (and Harris County) fall disproportionately on certain ethnicities and on the socially and economically disadvantaged. The cancer risk burden across Harris County census tracts increases with the proportion of residents who are Hispanic and with key indicators of relative social disadvantage. Aggregate disadvantage grows at each higher level of cancer risk. The highest cancer risk in Harris County is concentrated along a corridor flanking the ship channel. These high-risk neighborhoods, however, vary markedly in relative disadvantage, as well as in emission source mix. Much of the risk they face appears to be driven by only a few hazardous air pollutants. Results provide evidence of risk disparities from hazardous air pollution based on ethnicity and social disadvantage. At the highest levels of risk the pattern is more complex, arguing for a neighborhood level of analysis, especially when proximity to high-emissions industries is a substantial contributor to cumulative cancer risk.

Introduction

Hazardous air pollutants or HAPs (also know as "air toxics") pose a problem for many cities in the U.S., and each has its own unique mix of emissions from a variety of sources, including urban traffic, heavy industry, air, rail, and sea transport, construction activities, and a plethora of dispersed facilities, such as dry cleaners and service stations. Air toxics are of particular concern in Houston because it is home to one of the world's largest petrochemical complexes, with over a quarter of the nation's refining capacity (*1*). Much of this sprawling complex lies along a man-made, 50-mile-long ship channel that runs from just east of the central business district through Galveston Bay and ultimately into the Gulf of Mexico. Numerous communities are located in close proximity to the Houston ship channel, including a combination of poor and affluent neighborhoods. Our aim is to examine the spatial distribution of cumulative, air-pollution-related cancer risks in Harris County, with particular emphasis on identifying economic and social disparities.

The study of risk disparities associated with community exposure to air toxics has progressed significantly over the past decade. The U.S. Environmental Protection Agency's (EPA's) Cumulative Exposure Project (*2*) estimated ambient air concentrations of air toxics and assayed social and geographical variation in the distribution of exposures (*3*) and health risks (*4, 5*). Data from this project were also applied to community-level risk screening (*6*) and to regional assessments of environmental justice (*7*). Based on a 1996 national emissions inventory of 32 HAPs, the first National-Scale Air Toxics Assessment (NATA-1996) used the air dispersion model from the Cumulative Risk Project and an inhalation exposure model to provide more reliable estimates of relative health risk (*8*). The NATA-1996 allowed HAPs-related risk to be assessed either separately or cumulatively (*9*), provided for the apportionment of source contributions, and permitted risk estimates to be linked with measures of social demographics from the U.S. Census.

Recently, Apelberg et al. (*10*) used NATA-1996 to assess racial and socioeconomic factors underlying the statewide distribution of risk from air toxics in Maryland, finding that, "cancer risk associated with air toxics exposure, particularly from on-road and area sources, disproportionately falls onto socio-economically disadvantaged and African American communities." In February 2006, EPA released NATA-1999 with an updated, more complete emissions inventory, coverage of 176 HAPs (plus diesel), and improved versions of exposure-related models. We employ exposure estimates from NATA-1999 and an approach similar to Apelberg et al. (*10*) to assess whether the cumulative cancer risks from air toxics in Houston (Harris County) fall disproportionately on racial minorities and on the socially and economically disadvantaged.

Methods

To analyze risk disparities, we first estimate excess lifetime, cumulative cancer risks from exposure to HAPs in Harris County census tracts in 1999 and then link these risks to the socioeconomic characteristics of the tracts. The contribution of each component emission source (major, area, on-road mobile, off-road mobile, and background) to the pollutant-specific risk in the census tract is calculated for each HAP, and then values are aggregated across carcinogens in the census tract. Thus, the cumulative cancer risk for a particular census tract is the sum of combined risks across all five emission categories for 91 carcinogenic HAPs evaluated. The analysis is done for all 649 census tracts in Harris County. The details of this process have been described previously (*11*). Basically, the exposure concentration (in $\mu g/m^3$) for each pollutant in a given census tract, is converted to a risk

* Corresponding author phone: (713) 500-9494; fax: (713) 500-9493; e-mail: stephen.h.linder@uth.tmc.edu.
† Institute for Health Policy.
‡ Division of Environmental and Occupational Health Sciences.

10.1021/es072042u CCC: $40.75
Published on Web 05/08/2008

estimate by applying the corresponding unit risk factor. Inhalation exposure concentrations from EPA's NATA-1999 Hazardous Air Pollutant Exposure Model, version 5 (HAPEM5) were downloaded from the NATA Web site. An extended description of these models appears in our Supporting Information. These estimates take into account differences in population demographics, such as age and gender, activity and commuting patterns, climate data, and indoor-to-outdoor variability. Unit risk factors are drawn principally from EPA's Integrated Risk Information System (IRIS). When unavailable from IRIS, values were obtained from the California OEHHA; when more than one estimate was available, the more protective value was chosen. A complete listing of the chemical names, unit risks, and sources for the 91 carcinogenic HAPs modeled in NATA-1999 appears in the Supporting Information.

The sociodemographic variables for our analysis are drawn mainly from the U.S. Census 2000 Summary File 3, downloaded from the Census Bureau's Web site (*12*). These are sample data from about 1 in 6 households designated by the Census Bureau to complete the more-thorough, long form; they are then weighted to represent similar households that had completed the short form instead. Population density figures were drawn from Summary File 1 and represent exact counts. Our measure of the proportion of residents who are working class is a composite indicator computed from employment data from Summary File 3 for eight different occupational groups. (For a listing of the occupational groups, see our Supporting Information.) We include a measure, based on the proportion of residents in each census tract who have no health insurance, as an indicator of relative vulnerability to the risks of untreated disease. Small area estimates of the uninsured, drawn from the Census Bureau's American Community Survey (2005) and geocoded to census tracts, were obtained from a local, research-based, health philanthropy (*13*). The variable, "percent of new mothers with less than high school education," came from this same source and is based on information gathered by the Bureau of Vital Statistics of the Texas Department of Health. To be consistent with the spatial scale of NATA-1999 risk estimates, the census tract serves as the unit of analysis. Hence, all sociodemographic variables, except density (which is based on square miles), are computed as the proportion of households, housing units, or residents having a particular characteristic of interest relative to the total number within a given census tract. For ease of interpretation, all proportions have been converted to percentages.

We employ several measures of socioeconomic standing, based mainly on Krieger (*14*) and intended to capture relative material differences at the census tract level; these are supplemented with other indicators related to vulnerable populations, such as young mothers and children. To measure individual poverty, we use the percent of each census tract's residents living below the Federal poverty level, the percent living below 50% of this level, and the percent of children (aged 1−17 years) living below this level. For individual employment, we include the percent of residents over age 16 years and unemployed. As a measure of social class, we use the percent in a blue-collar occupation, drawing on 8 of the 13 census-defined job categories. We use the percent over 25 years old with less than a high school education and the percent of new mothers with less than high school education, as surrogates for educational disadvantage. A final pair of individual measures relate more directly to health risk and access to care: the percent of new mothers less than 18 years old and the percent of all ages without health insurance. As indicators of household poverty, we use the percent of female-headed households, the percent of households on public assistance, and, for crowding, the percent of housing units with more than 1 person per room. As the inverse of poverty, we use several measures of household assets, including the percent of housing units that are owner-occupied, the percent of households with 1 or more cars, and the percent of households with income of $50000 or greater.

We also include measures of the racial and ethnic composition of each census tract as a way to capture how the relative size of historically subordinated groups in an area can reflect past patterns of discrimination and vulnerability. As Bell et al. pointed out recently (*15*), the social context matters in determining which groups to consider. In Houston's case, being self-identified as Hispanic of any race is chosen as the ethnicity variable of importance, as this group still faces barriers to full inclusion. The second largest, historically subordinated group in Houston is African-Americans, so the percent of those self-identified as Black, non-Hispanic is selected to account for race.

The main analysis is conducted in three phases. In the first phase, following a strategy developed by Apelberg et al. (*10*), we evaluate the statistical significance of differences in the proportion of relatively high-risk census tracts (above the 90th percentile cumulative cancer risk) across quartiles of our socioeconomic indicators using Pearson's χ^2 test. The presence of risk disparities appears as a statistically significant increase in the proportion of "high-risk" census tracts going from the lowest to highest quartile. To evaluate the change in this proportion relative to that occurring at the lowest quartile, we compute relative risks (RR) and their 95% confidence intervals. We also examine how the more dramatic differences across quartiles vary by emission source category. In the second phase we create neighborhood profiles across risk categories, characterizing the social and economic differences between high- and low-risk census tracts. The third phase combines analysis of high-risk census tracts with location, neighborhood profiles, and emission source categories. When it comes to using the mean values of our indicators in the second and third phases, we correct for skewness through log transformations. *P*-values for trends across risk levels are computed using linear regression with the quintiles of cancer risk as a categorical variable. We also map the putative high-risk census tracts with ArcGIS from the Environmental Systems Research Institute, Inc. (ESRI) and then consider the relevant, contextual features that emerge. Finally, we assess differences in the social and economic profiles of the affected communities and compare their mix of emission sources.

Results

The distribution of cumulative cancer risk estimates among census tracts for Harris County, broken down by source category, appears in Table 1. There are two aspects of these data that stand out. First, the relative magnitudes of the source contributions vary substantially. Nonroad mobile sources contribute the largest share of risk to the average tract, with on-road mobile sources falling close behind. The contribution of major and background sources appear similar with area sources the smallest of the five categories. We will return later to this issue of relative contribution. The second aspect is the dramatic increase in the level of cumulative risk as we move to the higher percentiles. Since this disproportionate increase is linked to our notion of risk disparity, it is useful to consider it in more detail.

The cumulative frequency distribution of risk levels across census tracks is shown in Figure 1. Note that the 90th percentile closely corresponds to the inflection point in this distribution, indicating a sharp increase in risk above the 90th percentile. This provides empirical support for selecting the 90th percentile as our cutoff defining high-risk census tracts for closer scrutiny. There are 64 census tracts falling

TABLE 1. Distribution of Cumulative Cancer Risk by Emission Source Category among Census Tracts in Harris County, 1999 (n = 649 Census Tracts)

		percentiles				
cancer risk[a]	mean	5th	25th	50th	75th	95th
all sources	6.76×10^{-4}	3.79×10^{-4}	4.58×10^{-4}	5.66×10^{-4}	7.31×10^{-4}	1.31×10^{-3}
major	8.47×10^{-5}	3.88×10^{-6}	1.32×10^{-5}	4.83×10^{-5}	9.20×10^{-5}	2.56×10^{-4}
area	3.02×10^{-5}	1.14×10^{-5}	1.69×10^{-5}	2.26×10^{-5}	3.15×10^{-5}	5.11×10^{-5}
on-road	2.14×10^{-4}	1.14×10^{-4}	1.46×10^{-4}	1.79×10^{-4}	2.43×10^{-4}	4.59×10^{-4}
nonroad	2.81×10^{-4}	1.46×10^{-4}	1.77×10^{-4}	1.77×10^{-4}	2.74×10^{-4}	5.72×10^{-4}
background	6.62×10^{-5}	6.51×10^{-5}	6.60×10^{-5}	6.64×10^{-5}	6.68×10^{-5}	6.75×10^{-5}

[a] Cancer risk is measured as an upper bound probability that a person would have of contracting cancer due to inhaling air containing these particular pollutant concentrations for 70 years.

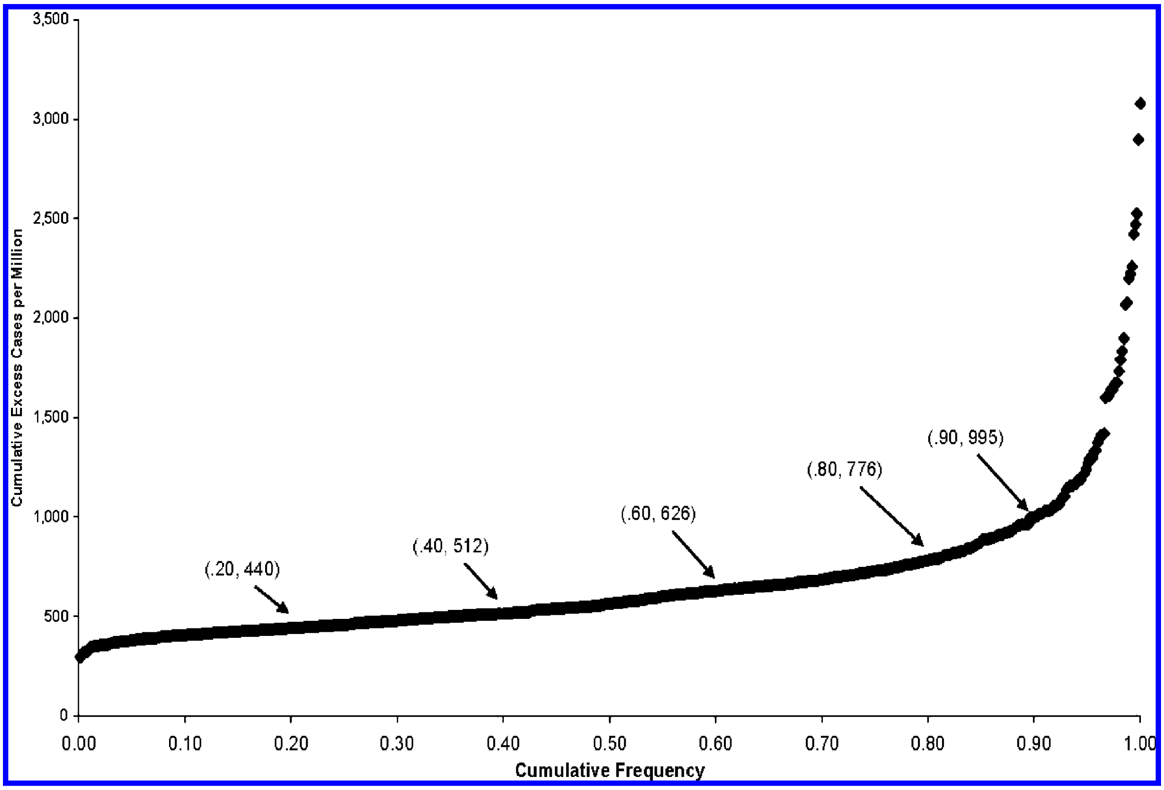

FIGURE 1. Cumulative frequency distribution of risk levels across census tracts in Harris County, 1999 (n = 649).

above the 90th percentile in cumulative risk. Two of these tracts are in isolated locations west of the city, while the remaining 62 are contiguous and extend eastward; we omit these two as anomalies for purposes of our analysis. Findings from an examination of selected social indicators by quartile for these 62 census tracts are summarized in Table 2.

Risk Disparities. Consider the first set of quartiles associated with percent Hispanic at the top of the table. Each quartile includes roughly 162 census tracts. The lowest quartile represents tracts that are 0 to 11% Hispanic, while the highest quartile includes tracts that range from 47 to 100% Hispanic. A proportional distribution of high-risk tracts means that about 16 of these tracts should appear in each quartile. However, high-risk tracts are concentrated in the upper quartiles of Hispanic population. Census tracts with the highest proportion of Hispanics are more than 6 times as likely to be among the high-risk tracts as those with the fewest Hispanics ($p < 0.001$). Moreover, the relative risk varies from 2.6 (Q2) to 6.4 (Q4). The situation is different for Black, non-Hispanic residents, the next group appearing in Table 2. Here, we come closer to proportionality, with the highest and lowest quartiles having about the same share of high-risk tracts. Most of the relative risks are also close to 1.

Among the poorest neighborhoods—where the proportion of people living below the poverty line approaches 25% and children living in poverty exceeds 30%—the chances of living with relatively high cumulative cancer risk are 4 to 10 times as great as in those neighborhoods with the fewest poor residents ($p < 0.001$). With regard to education levels, neighborhoods with the highest proportion of residents who did not finish high school (42% and higher) are over 18 times as likely to be located in high cumulative risk areas as those where over 90% of the residents have a high school diploma (95% CI, 4.53−75.55). The inverse relationship between a neighborhood's overall level of education and its chances of having high cumulative cancer risk levels is one of the strongest statistical associations observed across all of our social and economic indicators.

We use percent mothers under 18 years old as an indicator of health care needs and percent uninsured as an indicator of barriers to access to health care. In both instances, the chances of being in a high-risk neighborhood are about 4 times as great for areas in the highest quartile (most needy and least access) as compared to the lowest (respective 95% CI, 1.89−9.30 and 1.97−8.66). A similar pattern of risk disparity was observed for indicators of relative deprivation.

TABLE 2. Percent of Census Tracts Exceeding 90th Percentile of Cumulative Cancer Risk (n = 64) and Relative Risk (RR) by Quartile of Social Indicators, Harris County, 1999−2000

census tract social indicators	no. of CT > 90% of risk	percent CT > 90% of risk	RR	95% CI	p
percent Hispanic					
Q1 (lowest)	5	3.11	-		
Q2	13	8.07	2.60	0.95−7.13	0.063
Q3	12	7.45	2.40	0.86−6.66	0.093
Q4 (highest)	32	19.88	6.40	2.56−16.02	<0.001
percent Black, non-Hispanic					
Q1	18	11.18	-		
Q2	18	11.11	0.99	0.54−1.84	0.984
Q3	7	4.38	0.39	0.17−0.91	0.030
Q4	19	11.80	1.06	0.58−1.94	0.861
percent below poverty line					
Q1	3	1.86	-		
Q2	16	9.94	5.33	1.58−17.97	0.007
Q3	12	7.45	4.00	1.15−13.92	0.029
Q4	31	19.38	10.40	3.24−33.36	<0.001
percent children 1−17 years old under poverty					
Q1	4	2.50	-		
Q2	17	10.63	4.25	1.46−12.36	0.008
Q3	14	8.75	3.50	1.18−10.41	0.024
Q4	26	16.25	6.50	2.32−18.21	<0.001
percent below 50% poverty line					
Q1	6	3.73	-		
Q2	10	6.21	1.67	0.62−4.48	0.311
Q3	15	9.32	2.50	0.99−6.29	0.051
Q4	31	19.38	5.20	2.23−12.13	<0.001
percent over 16 years old unemployed					
Q1	7	4.35	-		
Q2	13	8.07	1.86	0.76−4.54	0.174
Q3	16	9.94	2.29	0.97−5.41	0.060
Q4	26	16.15	3.71	1.66−8.32	0.001
percent working class					
Q1	6	3.73	-		
Q2	11	6.83	1.83	0.69−4.84	0.221
Q3	20	12.42	3.33	1.37−8.09	0.008
Q4	25	15.63	4.19	1.77−9.95	0.001
percent over 25 years old with less than high school education					
Q1	2	1.24	-		
Q2	8	4.97	4.00	0.86−18.57	0.077
Q3	15	9.32	7.50	1.74−32.30	0.007
Q4	37	22.98	18.50	4.53−75.55	<0.001
percent new[a] mothers with less than high school education					
Q1	2	1.24	-		
Q2	11	6.88	5.53	1.25−24.60	0.025
Q3	14	8.70	7.00	1.62−30.34	0.009
Q4	34	21.25	17.11	4.18−70.09	<0.001
percent new[a] mothers under 18 years old					
Q1	7	4.32	-		
Q2	9	5.66	1.31	0.50−3.43	0.583
Q3	16	9.94	2.30	0.97−5.44	0.058
Q4	29	18.13	4.19	1.89−9.30	<0.001
percent all ages uninsured					
Q1	8	4.97	-		
Q2	13	8.07	1.62	0.69−3.82	0.265
Q3	8	4.97	1.00	0.38−2.60	1.000
Q4	33	20.50	4.12	1.97−8.66	<0.001
percent households on public assistance					
Q1	8	4.97	-		
Q2	6	3.73	0.75	0.27−2.11	0.586
Q3	22	13.66	2.75	1.26−6.00	0.011
Q4	26	16.25	3.27	1.53−7.01	0.002
percent housing units with more than 1 person/room					
Q1	7	4.35	-		
Q2	13	8.07	1.86	0.76−4.54	0.174
Q3	13	8.07	1.86	0.76−4.54	0.174
Q4	29	18.13	4.17	1.88−9.25	<0.001
percent female-headed households					
Q1	11	6.83	-		
Q2	10	6.21	0.91	0.40−2.08	0.822
Q3	22	13.66	2.00	1.00−3.99	0.049

TABLE 2. Continued

census tract social indicators	no. of CT > 90% of risk	percent CT > 90% of risk	RR	95% CI	p
Q4	19	11.88	1.74	0.85−3.54	0.127
percent owner occupied housing units					
Q1	15	9.32	-		
Q2	19	11.80	1.27	0.67−2.41	0.470
Q3	20	12.42	1.33	0.71−2.51	0.373
Q4	8	5.00	0.54	0.23−1.23	0.142
percent households with income equal/above 50000 (US$)					
Q1	29	18.01	-		
Q2	18	11.18	0.62	0.36−1.07	0.087
Q3	11	6.83	0.38	0.20−0.73	0.004
Q4	4	2.50	0.14	0.05−0.39	<0.001
percent housing units with 1 or more cars					
Q1	28	17.39	-		
Q2	19	11.80	0.68	0.40−1.16	0.160
Q3	6	3.73	0.21	0.09−0.50	<0.001
Q4	9	5.63	0.32	0.16−0.66	0.002
density per square mile of land area					
Q1	27	16.56	-		
Q2	15	9.26	0.56	0.31−1.01	0.055
Q3	8	4.94	0.30	0.14−0.64	0.002
Q4	14	8.64	0.52	0.28−0.96	0.036
percent residents under 18 years old per square mile					
Q1	22	13.66	-		
Q2	12	7.45	0.55	0.28−1.06	0.076
Q3	15	9.32	0.68	0.37−1.27	0.226
Q4	13	8.07	0.59	0.31−1.13	0.113

[a] Mothers with newborns in 2000.

Neighborhoods with the highest proportion of residents on public assistance or living in the most crowded conditions are, respectively, 3 and 4 times more likely to also live in relatively high cumulative risk areas (respective 95% CI, 1.53−7.01 and 1.88−9.25). When it comes to asset indicators, the meaning of the higher quartiles is reversed; meaning that higher quartiles represent neighborhoods that are relatively better off, economically. For example, the percent of owner-occupied homes in a neighborhood is unrelated to risk disparity between the highest and lowest quartiles. Percent of moderate income residents, in contrast, mirrors the disparity observed in neighborhoods below the poverty line.

To assess whether disparities vary across categories of emission sources, we looked at the four variables from Table 2 (percent over 25 years old with less than a high school education; percent new mothers with less than a high school education; percent below the poverty line; percent Hispanic) that exhibited the most pronounced disparities. We expect that the number of high-risk tracts will be substantially greater in the highest quartiles of these indicators. The question is, will this pattern vary across source categories? As shown in Figure 2, for all four indicators, the nonroad and on-road mobile source categories represent the largest differences between the highest quartiles and the rest; they most closely parallel the pattern shown for the total across sources. Note that HAPEM background source concentrations, unlike ASPEN estimates, vary across census tracts; this accounts in part for the significant variation across quartiles of "percent residents under poverty level" shown in Figure 2. In contrast, for major point sources, the highest quartile has fewer high-risk tracts than do the middle quartiles; for area sources, the highest quartile matches the second or third quartiles. Clearly, this is an anomaly that will need to be taken up later. One key factor is that the high-risk census tracts are not uniformly distributed across the county and neither are the source contributions to cumulative risk.

Gradient in Social Disadvantage. There are 11 social and economic indicators most clearly associated with a disproportionate burden of high risk—that is, having at least 4 times the number of high-risk tracts in the highest quartile compared to the lowest quartile. We modeled social disadvantage for each census tract as a profile composed of the expected values of these nine indicators and then assessed how social disadvantage profiles vary by level of risk. The profiles of relative social disadvantage across quintiles of cumulative cancer risk are displayed in Table 3. Note that the indicator values appearing in the first column on the left of Table 3, corresponding to the lowest quintile of risk, consistently show the least social disadvantage. As we move across the columns, each of the expected values for these indicators increase in concert; the last column on the right represents the conditions of greatest relative disadvantage. The pattern of increasing profiles from lowest to highest risk quintile indicates a positive association between social disadvantage and higher levels of cumulative cancer risk. As shown in Table 3, p-values for linear trends across the five levels of risk are statistically significant.

To examine the connection between risk, neighborhood location, and relative social disadvantage, we return to the subset of high-risk neighborhoods identified earlier as exceeding the 90th percentile in cumulative risk. The gradient we identified in Table 3 predicts that these high-risk locations will also represent the greatest relative social disadvantage.

Location and Social Disadvantage. Most of the petrochemical complex in the Houston area lies east of the city along the ship channel, which begins at the turning basin just east of downtown and follows a southeasterly course through Galveston Bay to the Gulf of Mexico. As shown in Figure 3, the red areas, which denote the high-risk census tracts (above the 90th percentile), are located almost exclusively along this corridor. The only two high-risk census tracts (shown in orange) that do not fit this pattern are located to the northwest and west of the ship channel area.

From the west, the first grouping of high-risk census tracts (North Central City) is near the center of the map, and spans the central business district extending northward to include the North Loop 610, a major traffic artery. To the east the

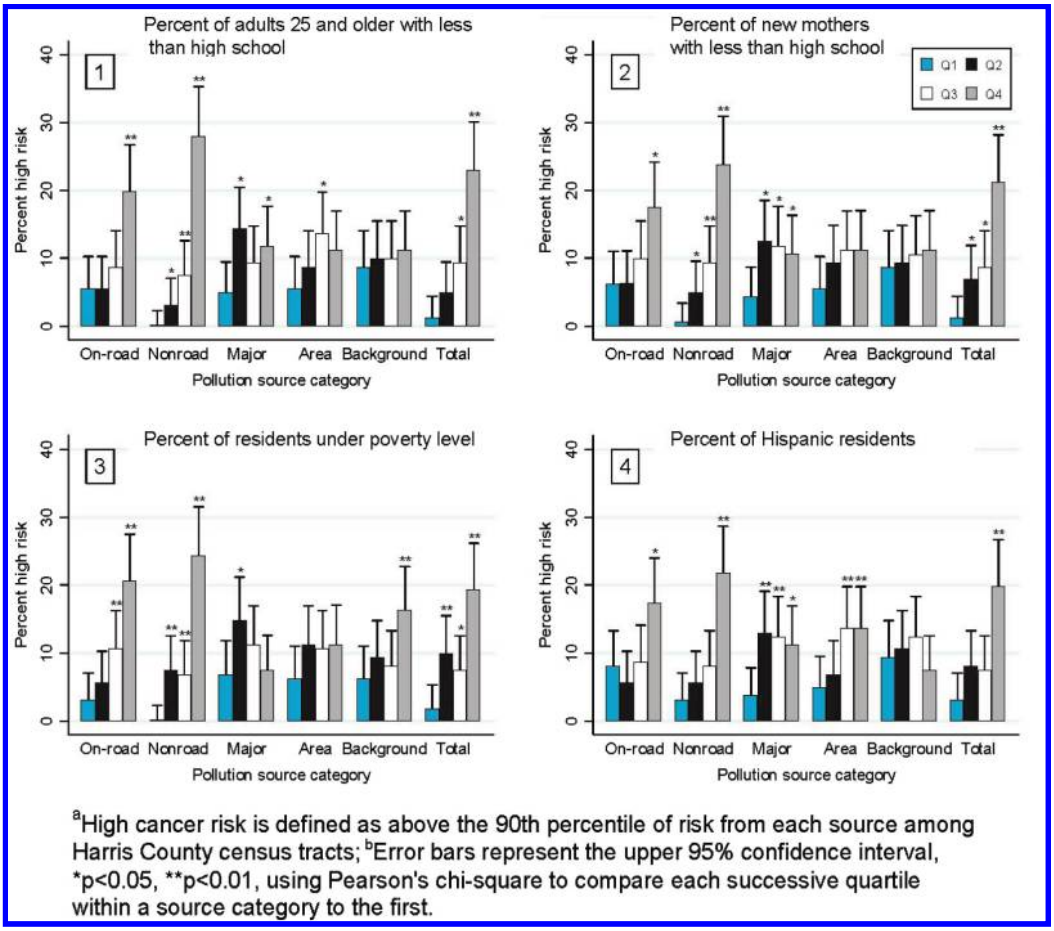

FIGURE 2. Percent of high cancer risk[a] census tracts by social indicator quartiles[b] by source category.

TABLE 3. Means[a] of Social Indicators by Quintiles of Total Cancer Risk, Harris County, 1999−2000 (n = 649 Census Tracts)

sociodemographic characteristic	cancer risk					
	1st quintile[b]	2nd quintile	3rd quintile	4th quintile	5th quintile[c]	p for trend[d]
percent Hispanic	14.8	17.4	19.6	25.5	38.5	<0.001
percent below poverty line	6.2	8.3	8.7	16.3	20.1	<0.001
percent below 50% poverty	2.50	3.65	3.96	7.66	8.92	<0.001
percent children 1−17 years old under poverty	7.1	8.0	10.5	18.7	20.3	<0.001
percent working class	47.2	48.5	47.1	50.3	55.0	<0.001
percent above 25 years old with less than HS[e]	9.7	14.5	13.5	24.7	36.1	<0.001
percent new[f] mothers with less than HS[e]	10.7	13.7	12.8	28.3	36.2	<0.001
percent housing units with more than 1 person/room	4.2	5.7	5.9	10.5	14.6	<0.001
percent households with income equal/above 50000 (US$)	46.0	42.4	37.4	30.7	22.9	<0.001
percent new[f] mothers under 18 years old	0.7	1.2	0.7	2.5	3.4	<0.001
percent all ages uninsured	23.4	25.1	24.1	29.1	32.7	<0.001

[a] Social indicator variables were log-transformed given their skewed distribution, and geometric mean was estimated. [b] 1st quintile is the lowest. [c] 5th quintile is the highest. [d] Tests for trend based on linear regression with quintiles of risk as a categorical variable [e] HS = high school education. [f] Mothers with newborns in 2000.

next grouping of high-risk tracts (East Houston) includes the neighborhoods in the East End and extends to the turning basin at the western terminus of the ship channel. Moving further to the east and south, the next grouping of high-risk census tracts includes neighborhoods in the area immediately north and south of the ship channel (Channelview). The next grouping of high-risk census tracts (San Jacinto) is to the north of Channelview and extends northward from the channel itself to include several tributaries of the San Jacinto River that feed the ship channel. To the south of Channelview, the final grouping of high-risk tracts (Bay Shores) is to the southeast of the ship channel area and includes the Port of Houston's main container facility at Barbour's Cut and the new facility further south at Bayport.

As summarized in Table 4, we examine the profiles of social disadvantage corresponding to the five high-risk

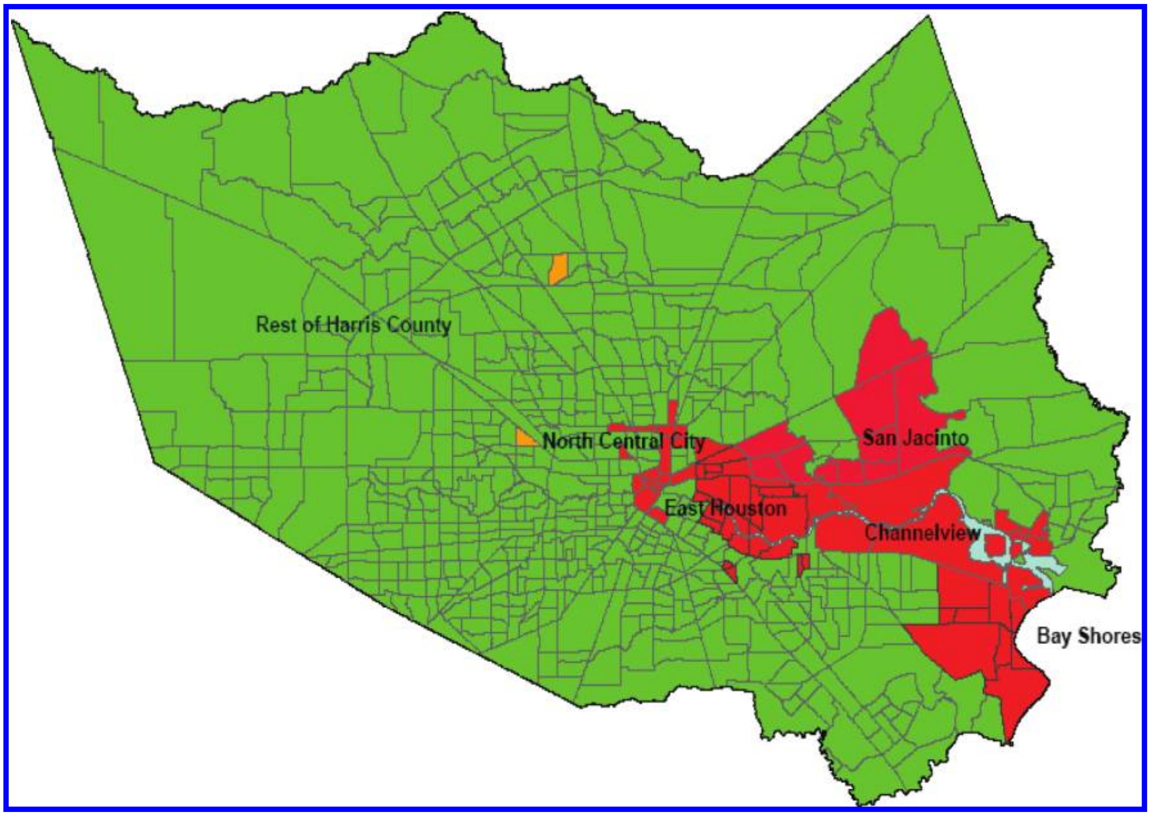

FIGURE 3. Individual cancer risk > 90th percentile by area, Harris County, 1999.

TABLE 4. Means[a] of Social Indicators across High Risk Designated Areas in Harris County, 1999-2000

sociodemographic characteristic	cancer risk equal to/below 90th percentilerest of Harris County ($n = 585$)	cancer risk above 90th percentile ($n = 62$)[b] North Central City ($n = 16$)	East Houston ($n = 21$)	Channel View ($n = 6$)	San Jacinto ($n = 10$)	Bay Shore ($n = 9$)
percent Hispanic	20.4	30.8	63.3	52.8	40.4	16.0
percent below poverty line	10.2	33.2	25.3	20.7	9.7	7.3
percent below 50% poverty	4.5	17.7	10.8	7.7	4.9	1.7
percent children 1−17 years old under poverty	11.2	25.2	28.5	24.2	8.0	8.9
percent working class	48.9	58.6	57.9	54.3	56.8	49.5
percent above 25 years old with less than HS[c]	16.1	47.7	59.2	44.4	35.6	15.0
percent new[d] mothers with less than HS[c]	16.6	54.2	35.5	43.7	44.1	20.5
percent housing units with more than 1 person/room	6.9	16.0	17.5	17.1	14.0	4.2
percent households with income equal/above 50000 (US$)	36.2	15.5	18.9	29.8	35.8	50.3
percent new[d] mothers under 18 years old	1.3	3.0	6.1	6.0	0.7	4.1
percent all ages uninsured	26.2	32.8	38.8	33.0	29.2	20.7

[a] Sociodemographic variables were log-transformed given their skewed distribution and geometric mean was estimated. [b] Total number of census with cancer risk exceeding 90th percentile of risk = 64 (two census tracts are not included as they are not part of the designated areas). [c] HS = high school education. [d] Mothers with newborns in 2000.

geographical areas and provide a comparison to the other 585 census tracts in Harris County. Each of the high-risk areas manifests a distinctive pattern and profile of relative social disadvantage. Areas on the eastern side of the high-risk corridor (San Jacinto and Bay Shores) represent neighborhoods with relatively few socioeconomically disadvantaged residents, despite their predicted levels of high cumulative cancer risk. San Jacinto typically ranks second, behind Bay Shores on our economic indicators and falls closer to the rest of the county than to the other three high-risk areas; it has a substantially higher Hispanic population than either Bay Shores or the rest of the county, however, and falls closer to Channelview or North Central City on several of our social indicators. East Houston scores the highest in relative disadvantage on 6 of the 11 mean values in our profile, followed by North Central City, which scores highest on the remaining 5. East Houston neighborhoods tend to be proportionately more Hispanic (about 3 times the rest of the county average), have more children in poverty, more adult residents without a high school education, more crowding,

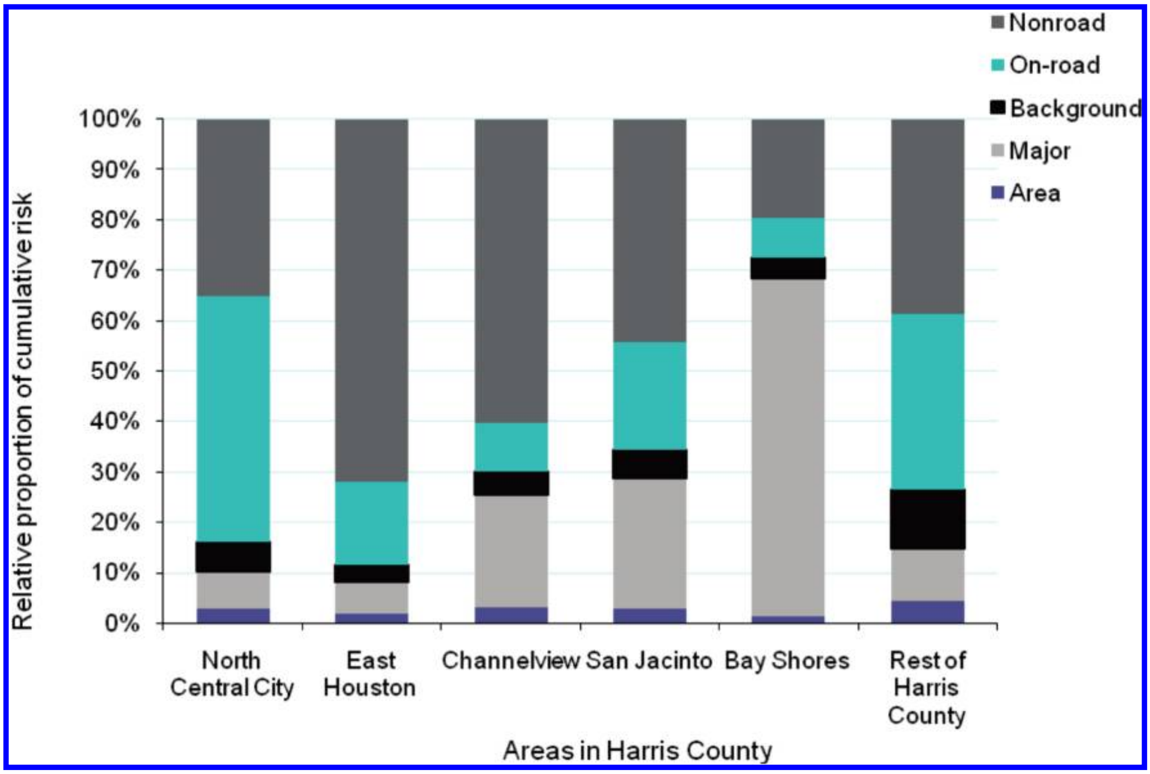

FIGURE 4. Relative contribution of emission source categories to cumulative cancer risk across areas in Harris County, 1999.

more new mothers under 18 years old, and more uninsured. The profile for North Central City is similar, with about a third of the residents living in poverty (3 times the rest of the county average), more than half of the new mothers have not completed high school, and the proportion of households with at least a moderate income is 15%—half of the county level and about a third of the proportion in Bay Shores.

Location and Source Apportionment. The relative contribution of emission source categories to cumulative cancer risk is displayed in Figure 4 for each of the five high-risk areas. Note that the largest proportional contributions from area and background sources in Harris County are outside the high-risk locations. As we will see below, this is a reflection of the fact that the average census tract in this lower-risk area carries about half the overall risk compared to the tracts in our high-risk areas. The role of major point sources (e.g., refineries, chemical plants) tends to increase as we move eastward from the North Central City area to Bay Shores. For neighborhoods in the Bay Shores area, almost 70% of their cumulative cancer risk burden comes from local point sources, or about 7 times the county average. Despite a few exceptions, the trends are in the opposite direction for mobile sources, with contributions from on-road sources generally increasing from east to west as we move from Bay Shores to North Central City, where mobile source contribution exceeds the county level by about a third. The off-road mobile contribution increases in the same east-to-west direction but reaches its maximum in the East Houston area, where it accounts for over 70% of the cumulative cancer risk burden.

The absolute contribution of each source category, averaged by the number of census tracts in each area, is shown in Figure 5. Here, Bay Shores and East Houston residents bear the highest cumulative risk of any area. Off-road mobile sources contribute the largest amount in relative and absolute terms to the risk in East Houston. Similarly, major sources contribute the most in relative and absolute terms to the risks borne by Bay Shores residents. The only area where on-road sources dominate is in North Central City; in the four remaining areas, either off-road mobile or major sources account for the largest portion of the risk. The contributions of background and area sources appear relatively minor.

Although the mix of emission sources varies across the five high-risk locations, relatively few pollutants account for most of the high cumulative risk burden, and the same three or four compounds (diesel particulate matter, chromium(VI), ethylene dibromide, and benzene) account for the majority of the cumulative risk in all five locations. In fact, as shown in Table 5, the situation is much the same throughout the rest of Harris County in areas with lower average levels of cumulative risk. Diesel particulate matter contributes about two-thirds of the cancer risk attributed to on-road sources and over 95% of the risk to off-road sources. For major point sources, chromium(VI) is responsible for about three-quarters of the cancer risk whether inside or outside the high-risk ship-channel corridor. Chromium(VI) is a combustion waste product that is also released in plating operations. Before its use was banned in 1998, it was present in anticorrosive compounds widely used for cooling towers at refineries and chemical plants. Cancer risk from background sources are mainly attributed to ethylene dibromide. The nation's largest industrial source is located about 200 miles southwest of Houston.

Discussion

Our aim in using HAPEM estimates as the basis for computing cumulative cancer risks is to increase the accuracy of our assumptions about the connection between personal exposures and ambient concentrations. The HAPEM model takes into account a number of factors that affect the exposure levels of particular residents to outdoor air. Rather than assuming that people have uniform and constant exposure to a particular ambient concentration, HAPEM considers data on how different demographic groups spend their time, where they spend it, for example, outdoors, in their cars, at work, and inside their homes, and on how much time they spend there. The result is a time-weighted average concentration that summarizes group exposures across different activities and locations, bringing us a step closer to a more accurate

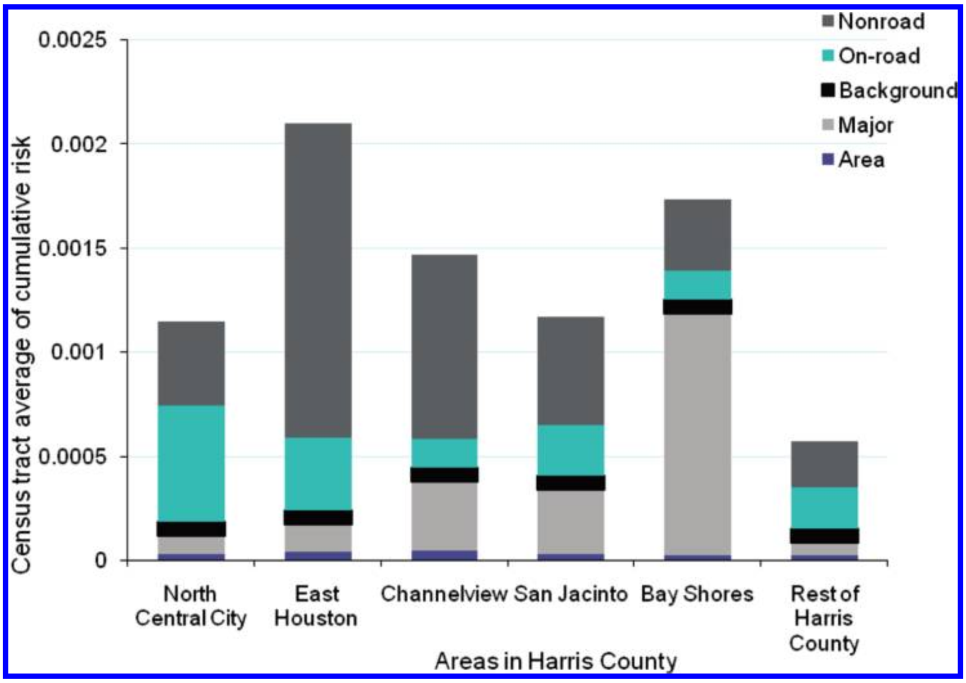

FIGURE 5. Contribution of emission source categories to average cumulative cancer risk probabilities for census tracts across areas in Harris County, 1999.

proxy for personal exposure. In effect, the exposure concentration is assigned to the residents of a particular location and not to the location itself. So when we compare locations relative to cumulative risk and social disadvantage, we are more accurately comparing aggregate characteristics of the people who live there and not physical features of the area where they live.

With these adjustments in place, the exposure concentrations for any particular census tract are likely to be less than the corresponding ASPEN ambient concentrations; for Harris County, the cumulative exposure concentrations from HAPEM are less than the cumulative ambient concentrations from ASPEN for residents in every census tract. Nevertheless, the difference between the ASPEN and HAPEM estimates is not sufficient to change our results (see Table SI-1 in the Supporting Information for the ASPEN-based version of our Table 2). An unanswered question is whether the difference is also small enough to permit the use of HAPEM estimates for prioritizing sources for emission controls, even though its estimates include sources in both the resident and the commuter-destination census tracts. We cannot resolve that from these comparisons.

Our results drawn from NATA-1999 and the 2000 Census provide further evidence for risk disparities for minority and socially disadvantaged neighborhoods from hazardous air pollution. Consistent with earlier studies, our analysis shows that ethnicity matters, as does poverty and inadequate education, when considering the distribution of cumulative cancer risk. Results suggest that cumulative cancer risk increases in direct proportion to a neighborhood's social disadvantage profile. Relative disadvantage across neighborhoods reflects disproportionate minority status, shown in Houston by a high percentage of Hispanic residents, along with high percentages on eight other social and economic indicators: residents living in poverty; unemployed; less than high school education; living in crowded environments; uninsured; children living in poverty; mothers without high school diploma; and mothers less than 18 years old. Conversely, fewer high-risk census tracts were seen within more affluent neighborhoods measured by their household income at or more than $50000, home ownership, or number of cars available in a household. Although racial (African American) and ethnic (Hispanic) composition has been associated with risk disparities in other cities (*15*), when it comes to cumulative, air pollution-related risks for Houston residents, ethnicity rather than race is the key variable. Part of the reason that a high percentage of Hispanic residents in a given neighborhood (and not Black non-Hispanic residents) is associated with high cumulative cancer risk in Houston is the fact that there are far fewer Black-majority as opposed to Hispanic-majority neighborhoods in Harris County.

The strongest statistical associations between high-risk and socioeconomic indicators were observed for educational attainment, ethnicity, and poverty level. These relationships were robust not only for the cumulative risk from all source categories but also for on-road and nonroad sources of pollution in particular. Though there is little doubt that poor people, a disproportionate fraction of whom are ethnic minorities, bear more than their fair share of environmental risks, a closer look reveals that the picture is more complicated than these indicators would initially suggest. While it is generally true that people who share similar characteristics tend to settle in similar neighborhoods, the sharing is only partial, and these neighborhoods are neither homogeneous nor free of social change. It is also true that the characteristics of socially disadvantaged neighborhoods do not necessarily mirror all the attributes of any one resident and vice versa. In short, community context matters (*14*), and the social disadvantage profile of a particular community used here represents a rough (but hopefully helpful) picture of the aggregate characteristics that can affect the health and well-being of people who live there, whatever their individual disadvantages. Among neighborhoods where the disadvantaged are concentrated, social disadvantage can be viewed more as a structural condition than as an individual trait, since it is likely to be self-reinforcing and resistant to change. This concept goes beyond variables describing, for example, income or level of education, to encompass a wide range of exclusionary mechanisms and experiences. We employ a collection of values from multiple indicators—a numerical profile—to characterize neighborhoods and empirically approximate their relative social disadvantage.

TABLE 5. Principal Contributors to Cumulative Cancer Risk Across High Risk Designated Areas in Harris County, 1999

cancer risk	cancer risk equal to/below 90th percentilerest of Harris County (n = 585)	cancer risk above 90th percentile (n = 62)[a]				
		North Central City (n = 16)	East Houston (n = 21)	Channel View (n = 6)	San Jacinto (n = 10)	Bay Shore (n = 9)
major	chromium(VI) (75%)	chromium(VI) (79%)	chromium(VI) (60%)	chromium(VI) (72%)	chromium(VI) (69%)	chromium(VI) (88%)
area	chromium(VI) (54%)	chromium(VI) (41%)	benzene (55%)	chromium(VI) (38%)	chromium(VI) (37%)	ethylene oxide (34%)
on-road	diesel PM (68%)	diesel PM (65%)	diesel PM (66%)	diesel PM (72%)	diesel PM (68%)	diesel PM (72%)
nonroad	diesel PM (92%)	diesel PM (92%)	diesel PM (97%)	diesel PM (97%)	diesel PM (96%)	diesel PM (95%)
background	ethylene dibromide (25%)	ethylene dibromide (26%)	ethylene dibromide (25%)	ethylene dibromide (25%)	ethylene dibromide (25%)	ethylene dibromide (25%)

[a] Total number of census with cancer risk above 90th percentile = 64 (two census tracts are not included as they are not part of the designated areas).

Clearly, certain kinds of neighborhood-level disadvantage, such as low income and low educational attainment, are associated with high levels of cumulative cancer risk in Houston. However, the data also indicate that this kind of disadvantage is a sufficient but not a necessary condition for a high cumulative risk burden. As we looked more closely at high cumulative risk areas in Houston, we found that neighborhoods varied considerably according to their degree of relative disadvantage. Along and around the Houston ship channel corridor, there were neighborhoods at both ends of the advantage−disadvantage spectrum. Although a full account of the reasons behind the occurrence of high air pollution-related cancer risk in some of the least disadvantaged areas is beyond the scope of this article, we can still advance some suppositions. The petrochemical industries and port terminals along the corridor provide substantial employment opportunities and host a specialized work force, whose better education and income puts them well above the poverty line. Some nearby municipalities, such as Baytown, were built by refiners in the 1930s to draw skilled employees. Locations along the shore of the bay were once major summer resort areas and still provide summer homes for the affluent. The Bay Shores area, generally, has benefited from the growth brought by new port construction, by tourism, and by the presence of the Lyndon B. Johnson Space Center. While these areas experience levels of cumulative cancer risk that are among the highest in the county, our profile data suggest that they have very different capacities and resources to cope with, and perhaps recover from, the effects of air pollution.

It is also noteworthy that the sources of HAP emissions vary in significant ways. For example, major point sources made a substantially larger contribution than suggested by previous analyses based on NATA-1996 (*10*). Part of this difference can be attributed to the relatively unique concentration of petrochemical point sources in Houston, and part, to the fact that NATA-1999 expanded 5-fold the set of air toxics under consideration, including many more volatile organic compounds emitted by industrial sources. Moreover, the cumulative cancer risks from point source emissions appear to be at their highest among the least disadvantaged neighborhoods, while mobile sources continue to predominate, relative to other sources, in more disadvantaged areas. A large part of this anomaly can be accounted for by considering local context. In Houston's case, high HAPs emitters were not drawn to poor neighborhoods, they were drawn to the cheap transport and proximity to oil provided by the ship channel. These differences in disadvantage and source mix across location became apparent because we used a level of aggregation larger than a census tract but smaller than a county.

Finally, our analysis points to the dominance of a few HAPs regardless of the source category or where these emission sources are located. This is plausible given the high relative toxicity of these few pollutants. However, if we exclude diesel particulate matter and chromium(VI), since they dominate the mobile and point source contributions, respectively, the remaining contributors to risk might be subject to greater variability across location, possibly altering the details of mitigation plans.

Executive Order 12898 (*16*) directed federal agencies to include low income as well as minority status as part of their effort to identify and rectify environmental injustices, including risk disparities. Research over the past decade on the social determinants of health (*17, 18*) has documented the significant effect of relative socio-economic status on the risk of premature death. Disparities in exposure to pollutants, to the extent that they parallel differing levels of social disadvantage, can be expected to compound vulnerabilities to illness and injury that track these status differences.

Adding cumulative cancer risk to the other sources of vulnerability facing disadvantaged neighborhoods compounds the disproportional burdens assumed by those least able to bear them. Typically, however, the association of disproportional risk from pollutant exposure with environmental injustice follows the legal framework of civil rights, which emphasizes equal protection and individual harms. An alternative view, implicit in our analysis, is a concern with cumulative risk to whole neighborhoods and for the collective aspects of social disadvantage. Additive or interactive regression models cannot capture this situation adequately. The profiles of characteristics that we use are only rough approximations of the real-world features of disadvantage that multiply health risks from a wide range of sources, including air toxics. Mitigating overall risk disparities in disadvantaged neighborhoods will likely entail a variety of measures to reinforce the health gains from reducing hazardous pollutant levels.

Acknowledgments

Support was provided by the Institute for Health Policy and the Division of Environmental and Occupational Health Sciences at the University of Texas School of Public Health.

Appendix A

ABBREVIATIONS

ASPEN	Assessment system for population exposure nationwide
EPA	U.S. Environmental Protection Agency
HAPs	Hazardous air pollutants
HAPEM	Hazardous Air Pollution Exposure Model
NATA	National-Scale Air Toxics Assessment
OEHHA	Office of Environmental Health Hazard Assessment (California)
URE	Unit risk estimate

Supporting Information Available

This information is available free of charge via the Internet at http://pubs.acs.org.

Literature Cited

(1) Sexton, K.; Linder, S. H.; Marko, D.; Bethel, H.; Lupo, P. J. Comparative assessment of air pollution-related health risks in Houston. *Environ. Health Perspect.* **2007**, *115* (10), 1388–93.

(2) Rosenbaum, A. S.; Axelrad, D. A.; Woodruff, T. J.; Wei, Y. H.; Ligocki, M. P.; Cohen, J. P. National estimates of outdoor air toxics concentrations. *J. Air Waste Manage. Assoc.* **1999**, *49* (10), 1138–52.

(3) Woodruff, T. J.; Axelrad, D. A.; Caldwell, J.; Morello-Frosch, R.; Rosenbaum, A. Public health implications of 1990 air toxics concentrations across the United States. *Environ. Health Perspect.* **1998**, *106* (5), 245–51.

(4) Caldwell, J. C.; Woodruff, T. J.; Morello-Frosch, R.; Axelrad, D. A. Application of health information to hazardous air pollutants modeled in EPA's Cumulative Exposure Project. *Toxicol. Ind. Health* **1998**, *14* (3), 429–54.

(5) Morello-Frosch, R. A.; Pastor, M.; Sadd, J. Environmental justice and Southern California's 'riskscape': The distribution of air toxics exposures and health risks among diverse communities. *Urban Affairs Rev.* **2001**, *36*, 551–78.

(6) Fox, M. A. Evaluating cumulative risk assessment for environmental justice: A community case study. *Environ. Health Perspect.* **2002**, *110* (Suppl. 2), 203–9.

(7) Morello-Frosch, R.; Pastor, M., Jr.; Porras, C.; Sadd, J. Environmental justice and regional inequality in southern California: Implications for future research. *Environ. Health Perspect.* **2002**, *110* (Suppl. 2), 149–54.

(8) U.S. EPA. National-Scale Air Toxics Assessment, 1996. http://www.epa.gov/ttn/atw/nata/ (accessed 04/14/06).

(9) Tam, B. N.; Neumann, C. M. A human health assessment of hazardous air pollutants in Portland, OR. *J. Environ. Manage.* **2004**, *73* (2), 131–45.

(10) Apelberg, B. J.; Buckley, T. J.; White, R. H. Socioeconomic and racial disparities in cancer risk from air toxics in Maryland. *Environ. Health Perspect.* **2005**, *113* (6), 693–9.

(11) U.S. EPA. National-Scale Air Toxics Assessment, 1999. http://www.epa.gov/ttn/atw/nata1999/index.html (accessed 03/14/06).

(12) U.S. Census Bureau. Census 2000 Summary File 3 (SF 3)−Sample Data, 2000. http://www.census.gov/ (accessed 11/07/06).

(13) St. Luke's Episcopal Health Charities, Community Health Information System (CHIS). http://www.slehc.org/ (accessed 12/19/06).

(14) Krieger, N.; Williams, D. R.; Moss, N. E. Measuring social class in US public health research: Concepts, methodologies, and guidelines. *Annu. Rev. Public Health* **1997**, *18*, 341–78.

(15) Bell, M. L.; Dominici, F.; Samet, J. M. A meta-analysis of time-series studies of ozone and mortality with comparison to the national morbidity, mortality, and air pollution study. *Epidemiology* **2005**, *16* (4), 436–45.

(16) Executive order 12898. Federal actions to address environmental justice in minority populations and low income populations *Fed. Reg.* **1994**, *59* (32), 7629−7633.

(17) Marmot, M., Wilkinson, R. G., Eds. *Social Determinants of Health*; Oxford University Press: New York, 2005.

(18) O'Neill, M. S.; Jerrett, M.; Kawachi, I.; Levy, J. I.; Cohen, A. J.; Gouveia, N.; Wilkinson, P.; Fletcher, T.; Cifuentes, L.; Schwartz, J. Health, wealth, and air pollution: Advancing theory and methods. *Environ. Health Perspect.* **2003**, *111*, 1861–1870.

ES072042U