

UC Berkeley

UC Berkeley Previously Published Works

Title

An Index for Assessing Demographic Inequalities in Cumulative Environmental Hazards with Application to Los Angeles, California

Permalink

<https://escholarship.org/uc/item/99v7j0vq>

Journal

Environmental Science and Technology, 43(20)

ISSN

0013-936X

Authors

Su, Jason G
Morello-Frosch, Rachel
Jesdale, Bill M
et al.

Publication Date

2009-10-15

DOI

10.1021/es901041p

Peer reviewed

An Index for Assessing Demographic Inequalities in Cumulative Environmental Hazards with Application to Los Angeles, California

JASON G. SU,[†]
 RACHEL MORELLO-FROSCH,^{*,§}
 BILL M. JESDALE,[‡] AMY D. KYLE,[†]
 BHAVNA SHAMASUNDER,[‡] AND
 MICHAEL JERRETT^{*,†}

50 University Hall, Division of Environmental Health Sciences, School of Public Health, University of California, Berkeley, California 94720-7360, Department of Environmental Science, Policy and Management, University of California, Berkeley, California 94720, and Community Health and Human Development, School of Public Health, University of California, Berkeley, California 94720

Received April 6, 2009. Revised manuscript received August 21, 2009. Accepted August 27, 2009.

Researchers in environmental justice contend that low-income communities and communities of color face greater impacts from environmental hazards. This is also of concern for policy makers. In this context, our paper has two principal objectives. First, we propose a method for creating an index capable of summarizing racial–ethnic and socioeconomic inequalities from the impact of cumulative environmental hazards. Second, we apply the index to Los Angeles County to illustrate the potential applications and complexities of its implementation. Individual environmental inequality indices are calculated based on unequal shares of environmental hazards for racial–ethnic groups and socioeconomic positions. The illustrated hazards include ambient concentrations of particulate matter, nitrogen dioxide, and estimates of cancer risk associated with modeled estimates for diesel particulate matter. The cumulative environmental hazard inequality index (CEHII) then combines individual environmental hazards, using either a multiplicative or an additive model. Significant but modest inequalities exist for both individual and cumulative environmental hazards in Los Angeles. The highest level of inequality among racial–ethnic and socioeconomic groups occurs when a multiplicative model is used to estimate cumulative hazard. The CEHII provides a generalized framework that incorporates environmental hazards and socioeconomic characteristics to assess inequalities in cumulative environmental risks.

* Corresponding author phone: (510) 642-3960; fax: (510) 642-5815; e-mail: jerrett@berkeley.edu.

[†] Division of Environmental Health Sciences, School of Public Health.

[‡] Department of Environmental Science, Policy and Management.

[§] Community Health and Human Development, School of Public Health.

Introduction

Objectives. Researchers and policy-makers concerned about environmental justice argue that low-income communities and communities of color face a higher frequency and magnitude of impact from environmental hazards as well as psychosocial stressors (1–3). These disparities are increasingly recognized as potential determinants of health inequalities (4, 5) and additional research is needed to assess the cumulative impact of multiple environmental hazards and their toxic effects on these vulnerable communities (6). The potential interaction of elevated environmental hazards and socioeconomic stressors have been described as a form of “double jeopardy” (2, 7). As a result, environmental justice advocates have urged the regulatory and scientific communities to integrate cumulative impacts in their decision-making and enforcement activities. Regulatory agencies are beginning to grapple with the methodological challenge of developing transparent, yet scientifically valid, indicators of cumulative impacts and to examine and address environmental health inequities (7, 8). Recent reports from the National Research Council have also advocated “cumulative risk frameworks” (9).

This paper proposes an index to assess the cumulative environmental hazard inequalities in socially disadvantaged groups and neighborhoods. There are two principal objectives: (1) to develop an index capable of summarizing inequalities of impact from cumulative environmental hazards; and (2) to apply the index to the Los Angeles region of California, the case of ambient environmental pollution, to illustrate the potential applications and complexities in implementing the index.

Cumulative Environmental Hazard Inequality Index. Derivation of an index capable of characterizing inequalities in cumulative environmental hazards has two major components: (1) a measure to characterize inequality, and (2) an estimate of cumulative environmental hazards. To measure inequality related to racial–ethnic or socioeconomic measures, we modify a “concentration index” measure that is commonly used in the fields of social science and health planning (10). The concentration index was developed to assess inequality of health distributions across socioeconomic groups, with the term “concentration” in this context referring to the concentration of health (compared to poor health) in a small number of people (11, 12). The concentration index can also be used to assess inequalities in impact from environmental hazards between different social groups. To our knowledge, concentration indices have only been used in one study to assess inequalities in exposure to individual environmental hazards (13), and no index has attempted to characterize inequalities to cumulative environmental hazard.

In this paper we extend the concentration index to summarize the inequality in the distribution of multiple pollutants across socioeconomic and racial–ethnic groups. Because the term “concentration” has a different meaning in environmental health science, we refer to our extension of the concentration index as the “cumulative environmental hazard inequality index (CEHII)”. Specifically, the CEHII measures socioeconomic and racial–ethnic inequalities in exposure to cumulative environmental hazard. The index uses the cumulative proportion of the population, ranked by area-based racial, ethnic or socioeconomic composition, starting from the most disadvantaged—against the cumulative environmental hazard aggregated with the aid of various weighting functions. This methodological approach for

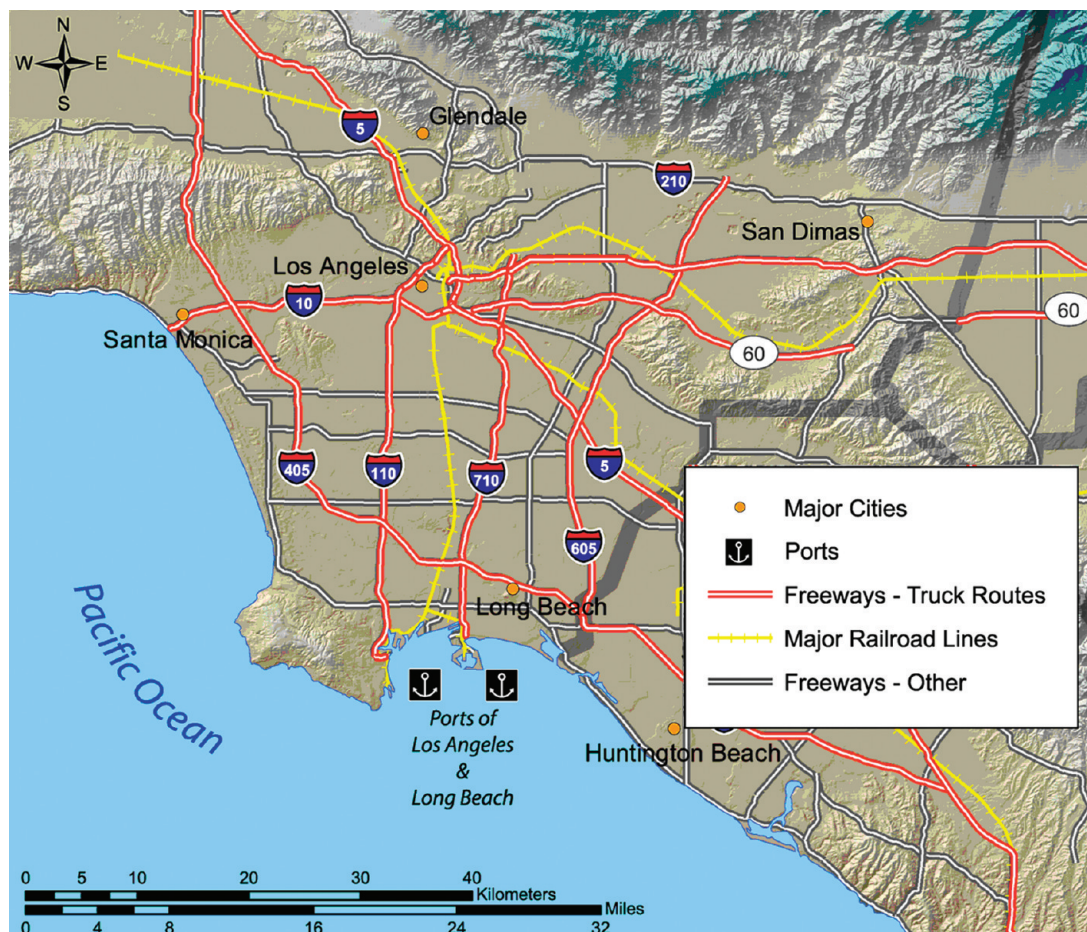


FIGURE 1. The Los Angeles study area, covering central and southern Los Angeles County areas south of the Angeles National Forest Park, with major roads and ports shown.

deriving a CEHII is the first attempt to characterize cumulative impact in a way that integrates environmental hazard and social data.

Materials and Methods

This section describes the study site of Los Angeles, the data used to demonstrate the CEHII, and the algorithms used to estimate cumulative environmental hazards.

Study Site. With a population of 16.7 million in 2006, the Los Angeles metropolitan area is the largest urban area in the state of California and the second-largest in the United States. Los Angeles is consistently ranked as one of the most polluted metropolitan areas in the U.S., partially due to heavy reliance on automobiles for transportation. It is these features plus the region's diverse racial composition, which includes Hispanic, non-Hispanic black, and Asian populations that place Los Angeles in a unique position for research on environmental justice issues. Figure 1 shows the site map of Los Angeles County, south of Angeles National Forest. A previous environmental injustice study in Los Angeles (14) demonstrated that concentrations of benzene, butadiene, chromium particles, and diesel particles were higher than average for people who are nonwhite, are from lower-income households, and live in high population density areas. Hazmat spills during transport were also found to disproportionately occur in Hispanic neighborhoods in Los Angeles (15). Other ambient pollutants investigated elsewhere in the environmental justice literature include total suspended particulates (16), toxic chemicals (17), and criteria pollutants such as nitrogen oxides and carbon monoxide (18). The one exception

is ozone, which is usually higher in suburban areas and in wealthier neighborhoods (14).

Selecting and Modeling Environmental Hazards. Selection of the air pollutants used for this study was aimed at examining the potential cumulative and unequal impacts of important air pollutants in the region, while also illustrating how the CEHII metric can incorporate various pollution measures with different spatial, reactive and health risk characteristics. In this case we combined pollutants with a National Ambient Air Quality Standard (NAAQS) (i.e., NO₂, nitrogen dioxide and PM_{2.5}, particles less than or equal to 2.5 μm in aerodynamic diameter) or a widely accepted regulatory benchmark (i.e., 1 per million cancer risk for the diesel particulates). NO₂ is a marker of traffic pollution (19) with high spatial variation. PM_{2.5} in Los Angeles is emitted directly from incomplete combustion of fossil fuels from transportation, heating/cooling and industry. PM_{2.5} is also formed through secondary atmospheric reactions, and in Los Angeles this secondary formation leads to regional patterns over large areas. EPA has concluded that diesel exhaust poses the greatest health risks such as increased lung cancer and respiratory effects. We applied these criteria and toxic air pollutants to demonstrate the flexibility in the derivation of the CEHII, but other environmental hazards can be incorporated into this index as well.

We used land use regression modeling (20, 21), a technique for estimating spatial variation in traffic pollutants, to estimate exposures to NO₂ using pollution data from an earlier study (22). Because there are a limited number of government monitoring sites available (23) and PM_{2.5} varies over larger

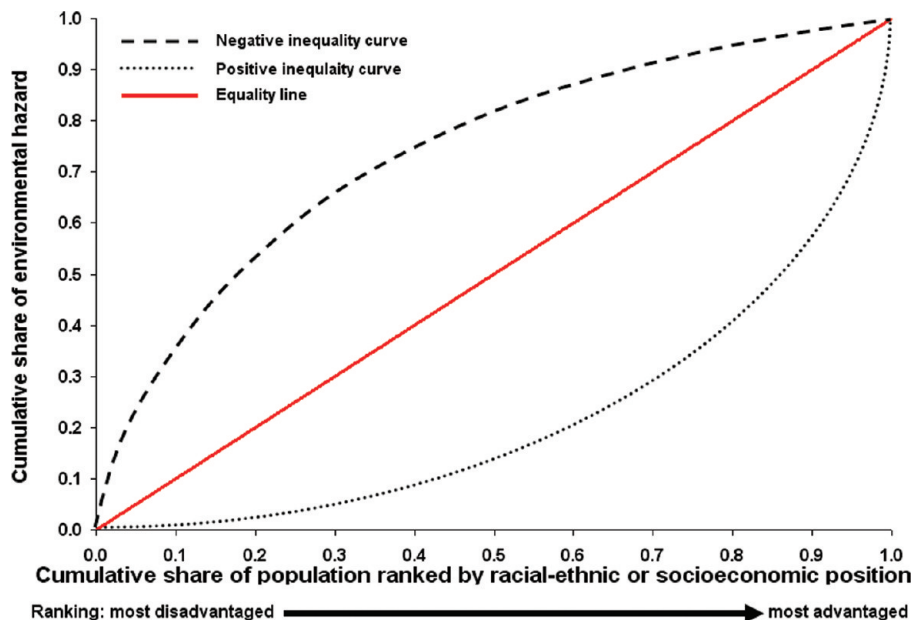


FIGURE 2. Positive and negative inequality curves. Note: Modified from Kakwani et al. (11). On these hypothetical graphs, a positive curve indicates census tracts with a higher percentage of a specific racial-ethnic group or lower socioeconomic position have lower shares of environmental hazard. The negative curve portrays the opposite case. The equality line indicates that there is no environmental inequality related to the racial-ethnic or socioeconomic composition measures.

areas, geostatistical interpolation was used to estimate exposure to this more regionally distributed pollutant. Census tract level NO_2 and $\text{PM}_{2.5}$ mean concentrations were extracted from corresponding modeled surfaces. We then calculated ratios by dividing each census tract concentration estimates by the NAAQS, respectively, of 53 ppb for NO_2 and of $15 \mu\text{g m}^{-3}$ for $\text{PM}_{2.5}$ (24). Diesel PM data were acquired from the U.S. Environmental Protection Agency for 1999. The tract-level diesel PM-related cancer risks were compared to the regulatory benchmark concentration of 1 in a million lifetime cancer risk (25). More information on the methods used to estimate NO_2 , $\text{PM}_{2.5}$, and diesel PM cancer risk surfaces is included in Supporting Information no. 1.

Defining Individual Inequality Index. To estimate the unequal distribution of an environmental hazard, for each census tract we plotted the cumulative proportion of the population, ordered by area-based percentage racial-ethnic or socioeconomic composition, from the most disadvantaged—against the cumulative share of the environmental hazard (See Figure 2). In the case for which each population group has the same share of the cumulative impact of environmental hazards, the curve coincides with the equality (i.e., 45 degree or diagonal) line. If the curve lies above the equality line (inequality index is negative), then the most disadvantaged groups experience higher cumulative environmental hazard burdens. A curve below the equality line (inequality index is positive) implies that the least disadvantaged groups carry a higher proportion of cumulative environmental hazard burdens. A summary measure of inequality is defined as twice the area between the curve and the equality line:

$$I = 1 - 2 \int_1^n e(s) ds \quad (1)$$

This measure gives a quantitative summary of inequality among groups, in which 0 is the lowest level of inequality where all groups have equal exposure to an environmental hazard and 1 is the highest level of inequality, where one group bears the burden of all of the exposures.

Characterizing Cumulative Environmental Impact. There are many aggregation methods available for constructing

cumulative environmental impact (26–30), including additive, multiplicative, and mixture approaches.

The multiplicative approach, also known as the geometric mean method, is one of the most commonly used aggregating methods for constructing the cumulative environmental impact measure (29). It can be represented as follows:

$$C_j = \prod_{i=1}^N (w_i x_{i,j}) \quad (2)$$

where $x_{i,j}$ is environmental hazard x_i at community/region j , and w_i a weight attached to x_i . To construct a multiplicative index of cumulative environmental impact, the variables are usually normalized to allow comparison without scale effect; however, this is not always the case. The individual variables do not need to be in the same scale and the CEHII remains unchanged if multiplied or divided by a constant.

The additive approach, also known as the weighted-sum method, can also be used to derive an estimate of cumulative impact (29). It is built as follows:

$$C_j = \sum_{i=1}^N w_i x_{i,j} \quad (3)$$

where $x_{i,j}$ is a normalized variable at community/region j , and w_i also a weight attached to x_i with $\sum_{i=1}^N w_i = 1$ and $0 \leq w_i \leq 1$, $i = 1, 2, \dots, N$. w_i is weighted by experts or estimated through regression coefficients. The additive approach entails a weighted linear aggregation rule applied to a set of variables. The main technical steps needed for its construction are (a) standardization of the variables to allow comparison without scale effect, and (b) weighted summation of these variables (27).

Measuring Race–Ethnicity and Socioeconomic Position.

Although there are numerous ways to measure social disadvantage, we selected two widely used metrics for illustrative purposes. The first metric, based on the 2000 U.S. Census, is tract-level racial-ethnic composition and is defined as the percentage of nonwhites. This measure includes the proportion of Hispanic, non-Hispanic Asian, and non-Hispanic African American population. The second

TABLE 1. Descriptive Statistics for Census Tracts Included in the Analysis for the Los Angeles Area

measures	minimum	mean	maximum	SD
% of population that is nonwhite	0.00	32.18	99.96	28.51
% of population under twice the poverty level	0.00	40.28	96.20	22.37
NO ₂ (ppb)	1.50	22.30	47.69	5.03
PM _{2.5} (μg m ⁻³)	13.35	20.22	24.25	2.85
diesel PM (cancer risk per million)	37	344	2463	169

metric is poverty. It estimates the proportion of the population with an income less than 200% of the federal poverty level (FPL). The reason for using household income less than 200% of the federal poverty level was because the poverty measure (single household income = \$21 000) the U.S. government uses today was established in the 1960s, and on average, families need an income of about twice the federal poverty level to meet their basic needs (31). Though other metrics such as deprivation indices could also be applied, only racial–ethnic and socioeconomic composition are used as an example.

Constructing Cumulative Environmental Impact. The cumulative environmental impact of the multiplicative approach entailed multiplying the ratios for the two criteria air pollutants and diesel PM cancer risk for each census tract. The cumulative environmental impact (r_j) to the criteria pollutants and diesel PM cancer risk at census tract j was modified from eq 2 and estimated as follows:

$$r_j = p_j \times \left(\prod_{k=1}^s r_{k,j} \right) \quad (4)$$

$r_{k,j}$ is the normalized (ratio or rate) environmental impact at census tract j of hazard k . p_j is the population at census tract j , and s is the total number of environmental hazards being considered, where in this research $s = 3$. We assumed that a census tract of greater population of the same cumulative effect would have higher environmental risk; therefore eq 4 is population weighted.

The second illustration assumed an additive effect and entailed adding the ratios for each air pollutant and diesel PM cancer risk at the census tract level. The additive approach requires each individual environmental hazard to be on the same scale (e.g., all values between 0 and 1 or with a mean of 1). Therefore, the ratios were further normalized to have a mean of 1 using formula 5:

$$r_{k,j}^{\text{norm}} = \frac{r_{k,j}}{\sum_{j=1}^N (r_{k,j} \times p_j) / \sum_{j=1}^N p_j} \quad (5)$$

N is the total number of census tracts for the region of interest. The metric for cumulative environmental impact (r_j) to the criteria pollutants and diesel PM cancer risk at census tract j in an additive scenario in eq 3 was modified and estimated as shown below:

$$r_j = p_j \times \left(\sum_{k=1}^s r_{k,j}^{\text{norm}} \right) \quad (6)$$

Similar to the multiplicative scenario, the additive approach was also population weighted. The variables in eqs 5 and 6 have the same definitions as in eq 4. The population data for each census tract were drawn from the U.S. Census Bureau for year 2000.

Computing Environmental Inequality Indices. We calculated individual inequality indices for NO₂, PM_{2.5} and the diesel PM cancer risk, and then the CEHII to the two criteria

pollutants and the diesel PM cancer risk by the multiplicative and additive approaches described above. We derived the following measures: (1) individual inequality indices based on proportion of nonwhite residents for NO₂, PM_{2.5}, and diesel PM cancer risk and (2) CEHII based on the proportion of nonwhite residents for NO₂, PM_{2.5}, and diesel PM cancer risk combined using both the multiplicative and additive methods. We also calculated the same metrics for the individual pollutants and for the cumulative environmental impact using proportion of residents living below twice the federal poverty level.

Standard errors and significance tests (available in Supporting Information no. 2) were calculated to assess whether inequalities by the single and cumulative metrics significantly differed from the equal distribution (where no inequality exists). Other tests of difference were performed to assess whether differences in inequality existed between various pollutants and social measures.

Results

This section first describes census tract level characteristics of racial–ethnic and socioeconomic measures, followed by NO₂ and PM_{2.5} levels, and diesel PM cancer risk. The individual and cumulative environmental hazard inequalities by race/ethnicity were then summarized and followed by poverty. Finally, t tests for difference in inequality between the racial–ethnic and socioeconomic measures were applied, followed by the inequality difference test between the three environmental hazards and the cumulative hazard.

For racial–ethnic population composition, the highest census tract had 99.96% nonwhites, whereas the lowest census tract had 0.00% nonwhites with a standard deviation of 28.51% (Table 1). Figure 3a shows that nonwhite residents are mainly populated in the downtown area and along the major traffic corridors. For poverty, the highest census tract had 96.20% of the population living at less than 200% of the federal poverty level and the lowest being 0.00% with a standard deviation of 22.37% (Table 1). Figure 3b shows that populations living at less than 200% federal poverty level have a similar geographic pattern to the nonwhite population composition (higher percentage in downtown area and the two ports) but are less clustered.

NO₂ and PM_{2.5} levels and diesel PM cancer risk for Los Angeles are also listed in Table 1. The annual mean of NO₂ concentration for the metropolitan area was 22.30 ppb, with census tract level annual concentrations ranging from 1.50 (minimum) to 47.69 ppb (maximum) and a standard deviation of 5.03 ppb. The NO₂ concentrations were high in the downtown area and most traffic corridors, suggesting that traffic was a major source of NO₂. The minimum, mean, maximum, and standard deviation for PM_{2.5} were 13.35, 20.22, 24.25, and 2.85 μg m⁻³, respectively. For diesel PM cancer risk, the corresponding values were 37, 344, 2463, and 168 cases per million. The spatial distribution of PM_{2.5} showed a general trend of areas between downtown Los Angeles and San Bernardino corridor having the highest concentrations, reflecting the influence of traffic, topography and meteorology. Diesel PM was similar to NO₂, but also showed high cancer risks at the Los Angeles/Long Beach port complex

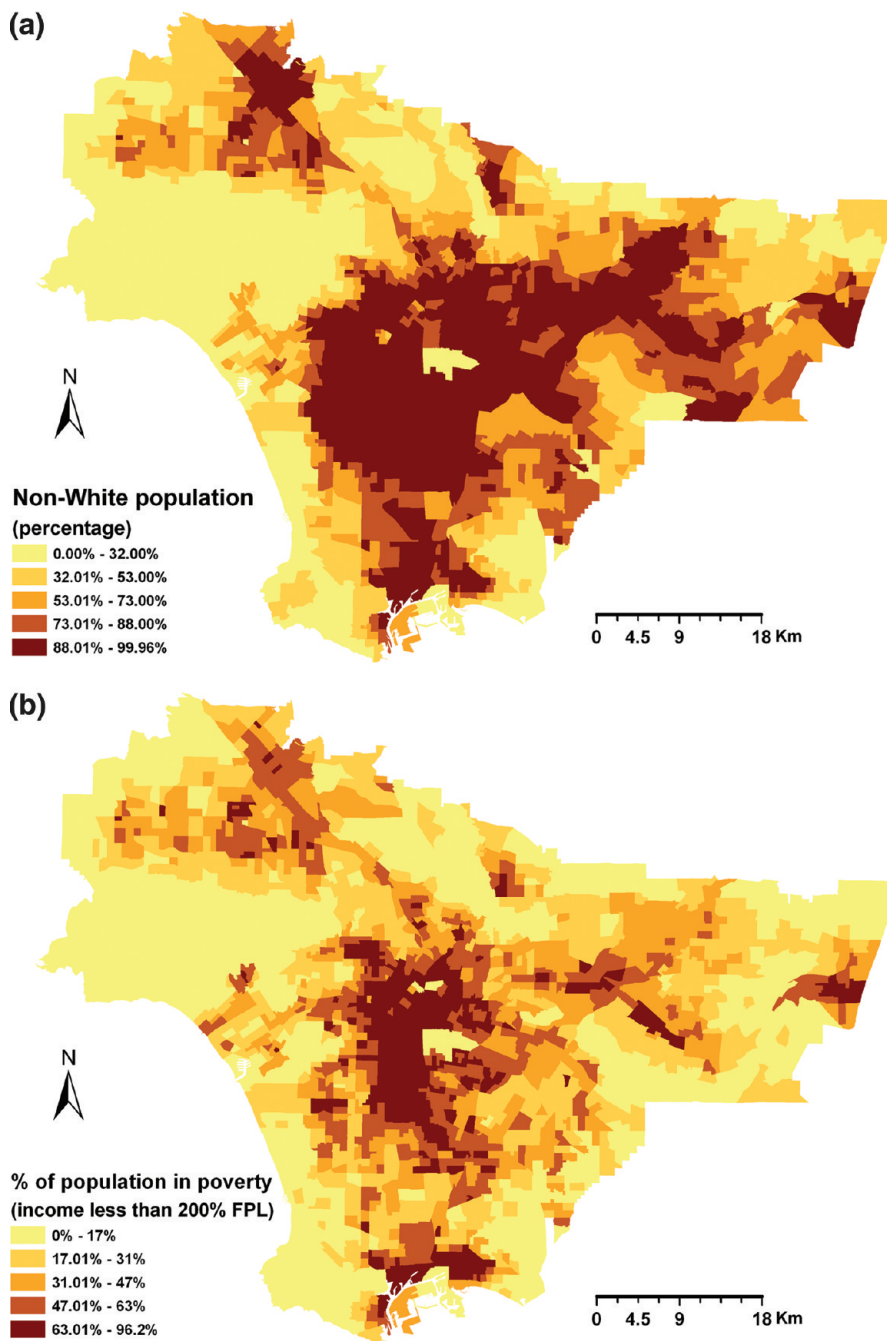


FIGURE 3. Census tract level nonwhite population composition (3a) and percent of population at less than 200% of the federal poverty level (3b).

and the Los Angeles International Airport. If we consider the cumulative environmental hazard, the multiplicative approach showed that high cumulative impacts were clustered in the downtown area, followed by the Los Angeles/Long Beach port complex (Figure 4).

Inequality curves for each of the three individual environmental hazards and for the cumulative environmental hazard, using the multiplicative approach are displayed in Figure 5a–d, showing differences with regard to racial–ethnic composition. Their corresponding individual and cumulative environmental hazard inequality indices and significance test results are listed in the top portion of Table 2. We saw the greatest environmental inequalities from diesel PM cancer risk ($C = -0.085$), followed by NO_2 ($C = -0.067$) and then $\text{PM}_{2.5}$ ($C = -0.031$). Although different in size, all three indices demonstrated inequality that is significantly different from equality. The cumulative environmental hazard inequality

index using the multiplicative approach (CEHII-A1 = -0.167) had the highest value. By contrast, the CEHII using the additive approach (CEHII-A2 = -0.061) fell between the highest and lowest inequality values for the individual pollutants. As a methodological matter, it is generally expected that the multiplicative method produces greater differences than the additive approach. The individual and cumulative environmental hazard inequalities related to socioeconomic position as well as the results for their statistical significance using both the multiplicative and additive approaches are shown in the lower portion of Table 2. These findings are similar to the racial–ethnic composition results as all the individual and cumulative environmental inequalities were significant. The CEHII using the multiplicative approach for the three environmental hazards (CEHII-A1 = -0.167) was greater than environmental inequalities for each individual pollutant for the poverty strata. Similar

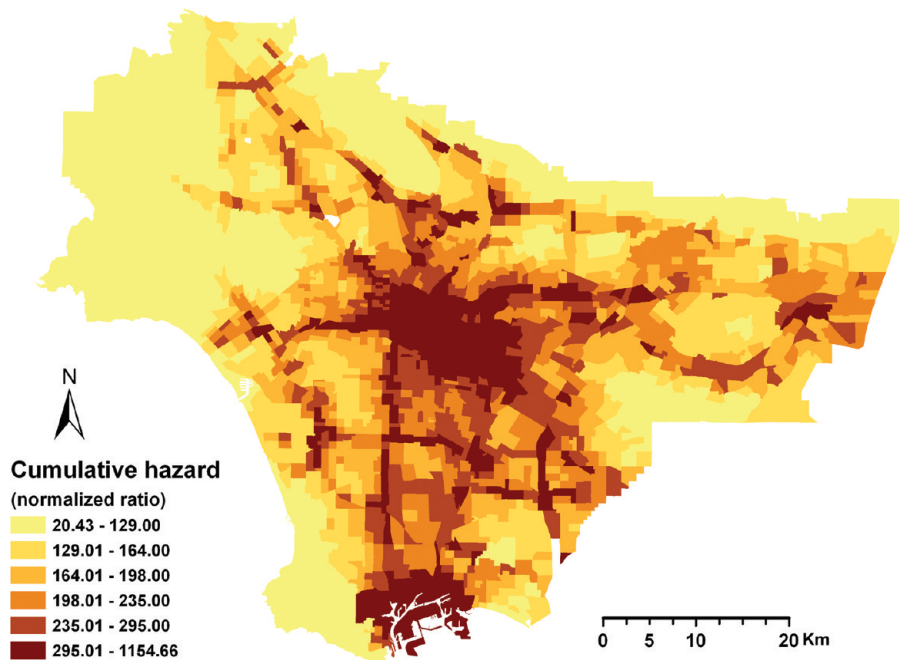


FIGURE 4. The cumulative environmental hazard using the multiplicative approach. Census tract level cumulative environmental hazard = $(NO_2)/(53) \times (PM_{2.5})/(15) \times (DPM)/(1)$.

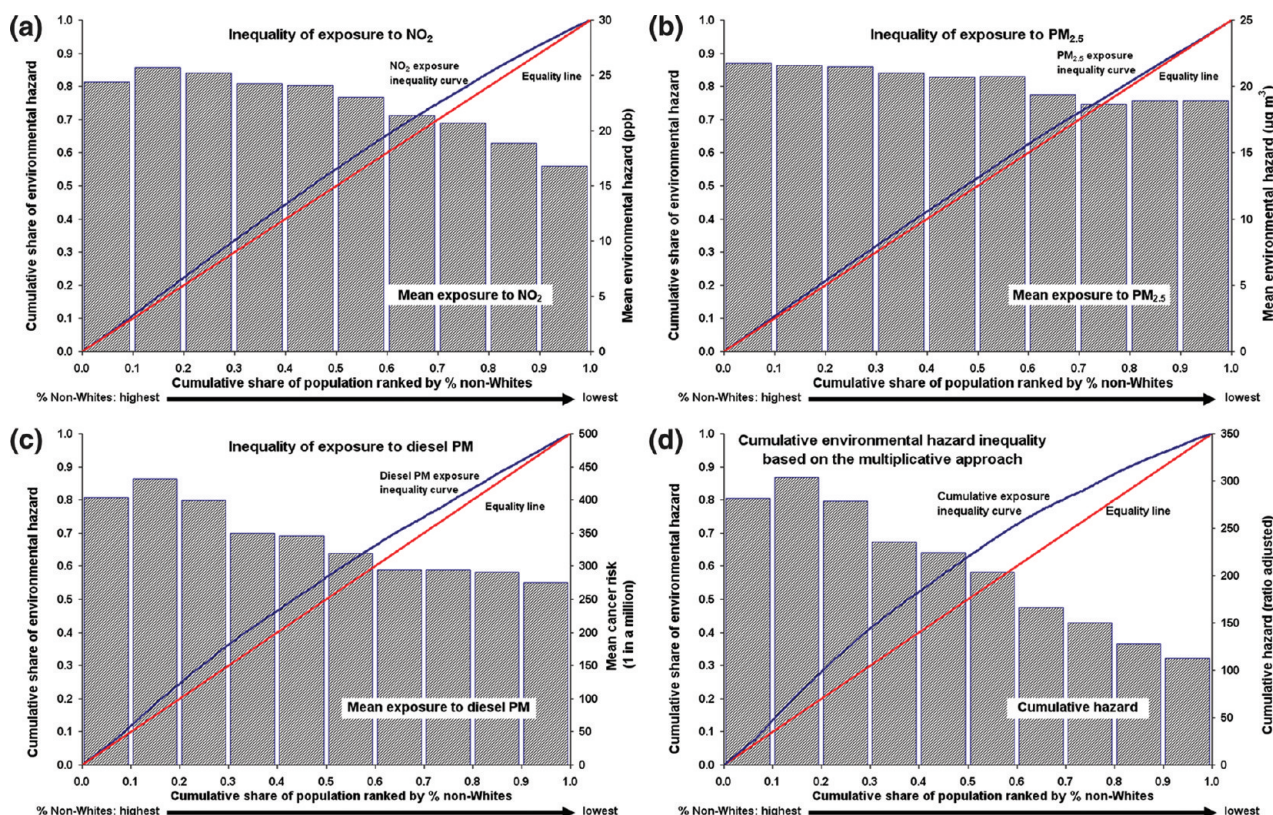


FIGURE 5. The environmental inequality of individual and cumulative impact to three environmental factors using the multiplicative approach based on the nonwhite population composition. Note: The x-axis represents the cumulative proportion of the population ranked by a specific demographic measure (e.g., % of tract residents living below the poverty line or % of nonwhite residents) from the highest percentage on the left to the lowest percentage on the right. The y-axis on the left represents the cumulative proportion of environmental hazard. For example the curve in Figure 5a shows the inequality in NO_2 exposure based on the proportion of nonwhite residents. On the x-axis where the cumulative proportion of the population is 10%, those census tracts with the highest percentage of nonwhites bear a disproportionate share of NO_2 exposure of 11%; when the cumulative proportion of the total tract population is 50%, those census tracts have a cumulative proportion of environmental hazard of 55.5%. The y-axis on the right is for the bar charts and represents the average pollutant concentration for each 10% of the population. For example the first bar on the left in Figure 5a indicates that 10% of the population living in tracts with the highest percentage of nonwhites has an average NO_2 concentration of 24 ppb. Similarly, the last bar on the right indicates that 10% of the population living in tracts with lowest percentage of nonwhite residents has an average NO_2 concentration of 17 ppb.

TABLE 2. Significance Tests of Inequality in Racial–Ethnic and Socioeconomic Measures for Both Individual and Cumulative Environmental Hazards

category of inequality		t test result on environmental inequality index	
		environmental inequality index	95% CI ^a
proportion of nonwhite residents	NO ₂	–0.067	(–0.072, –0.062)
	PM _{2.5}	–0.031	(–0.034, –0.028)
	DPM ^b cancer risk	–0.085	(–0.095, –0.075)
	CEHII-A1 ^c	–0.167	(–0.178, –0.156)
	CEHII-A2 ^d	–0.061	(–0.065, –0.057)
proportion of residents living two times below poverty	NO ₂	–0.066	(–0.072, –0.061)
	PM _{2.5}	–0.020	(–0.023, –0.017)
	DPM ^b cancer risk	–0.090	(–0.102, –0.079)
	CEHII-A1 ^c	–0.167	(–0.179, –0.154)
	CEHII-A2 ^d	–0.059	(–0.064, –0.054)

^a 95% CI = 95% confidence interval. ^b DPM = diesel particular matter. ^c Cumulative environmental hazard inequality using the multiplicative approach (CEHII-A1). ^d Cumulative environmental hazard inequality using the additive approach (CEHII-A2).

to the results by the racial–ethnic composition, the cumulative environmental hazard inequality index for socioeconomic position using the additive approach (CEHII-A2 = –0.059) was between the highest and lowest environmental inequality indices for the individual pollutants.

While *t* tests for inequality between the racial–ethnic and socioeconomic measures were statistically insignificant (*p* < 0.05) for each of the three environmental hazards, the inequalities between the three environmental hazards for racial–ethnic or socioeconomic measures were statistically significant. The CEHII using the multiplicative approach were greater and significantly different from its individual environmental hazard inequalities for racial–ethnic and socioeconomic composition. The CEHII using the additive approach were, by contrast, statistically insignificant compared to individual inequalities in exposure to NO₂.

Discussion

We sought to derive an index for assessing racial/ethnic and socioeconomic disparities in cumulative environmental hazards. After deriving the method, we analyzed single and cumulative environmental inequalities in exposure to NO₂, PM_{2.5} and diesel PM cancer risk for the poverty measure and racial/ethnic population composition in Los Angeles County. All environmental inequality curves for individual and cumulative environmental hazards are significantly different from the equality line. This demonstrates that modest environmental inequalities exist for nonwhite populations and for poorer populations in Los Angeles, and more importantly that the new CEHII may supply useful information to environmental justice debates.

Individual and cumulative exposure indices are presented in the literature on environmental health and justice; however, these indices generally do not address inequality and cumulative effects together. Their application for environmental justice analysis relies on further analysis of socioeconomic or racial–ethnic data. For example, Bolin et al. (32) used the cumulative hazard density index (CHDI) to reveal disproportionate distribution of risk burdens in urban census tracts. The resulting CHDI provides an aggregate hazard score for each tract, which was then correlated statistically with demographic data in order to measure levels of environmental inequity. Here we present a novel framework that quantitatively assesses inequality and cumulative exposures in an integrated manner. This approach can estimate inequalities across regions and by different demographic groupings. This offers new opportunities to understand sources of inequalities and to develop strategies to address them.

Los Angeles was used as an illustrative example for application of the index. Though NO₂, PM_{2.5}, and diesel PM cancer risk were used to demonstrate the application of the CEHII, this metric is also capable of incorporating additional environmental hazard measures, such as water pollution, traffic density, noise, proximity to large emission sources, and other potentially hazardous land uses such as agricultural operations. In addition, positive amenities such as green spaces and access to supermarkets or other fresh food sources could be incorporated into the CEHII and provide an integrated way of assessing cumulative environmental inequality for a region of interest.

While inequities in cumulative impact have important implications for distributional patterns at local scales, the index developed in this paper is not conducive to this application. Rather the index characterizes inequities in cumulative impacts of environmental hazards at the regional level and allows for comparisons across large geographic scales. The index can be applied at the regional scale (or counties, metropolitan areas or other large jurisdictional areas) that is of regulatory concern for social inequities in cumulative environmental hazard burdens. Such an application could then identify regions for more detailed analysis of localized patterns and drivers of those inequities. Other indices, such as Theil's Entropy Index (33), could be used to further decompose regional inequality into more localized scales. This latter analysis requires a different methodological approach, which is beyond the purview of this paper, but will be the subject of our future research.

An assumption implied by the multiplicative and additive approaches is that environmental variables are preferentially independent. Due to the potential correlation or chemical reaction between individual environmental factors, the potential for double-counting or mixture/interaction of cumulative hazards should be considered. For example, air toxics from diesel PM are likely to be correlated with the traffic marker NO₂, and precursors to nitrogen oxides may contribute to formation of secondary PM_{2.5}. If the mixture involves interactions of chemical and physical agents, the primary and secondary hazards should be investigated at the same time. At present, there is no widely accepted method of aggregating environmental hazards with potentially overlapping components. The index could help analysts to confront these issues more transparently.

The inequality index is sensitive to change in several factors. The index depends on the distribution of the individual or cumulative environmental hazard, the distribution of the socioeconomic or racial–ethnic metric used to

describe the population, and their joint covariation (for cumulative indices). The index is also sensitive to the level of aggregation used to describe the population and the number of population-based units, in this case census tracts, especially if there are not a large number of aggregation units. In constructing the cumulative impact index using the additive approach, environmental hazards were standardized to allow comparison without scale effect. However, the normalization loses the magnitude of exceedances, which is a potential indicator of impact. A remedy to this is to have a weighting scheme applied for the environmental hazards after adjustment made by the benchmark standard; no further normalization is then needed. To simplify our analysis, we assumed that each environmental hazard had an equal contribution to the cumulative impact, so a mean value of 1 was used to normalize each environmental hazard for the additive approach. For policy making, the weighting scheme might need to be modified by expert opinions or through a deliberative process (1).

For the cumulative impact through the multiplicative approach, even though no normalization is required to the environmental hazards after adjusted by the benchmark standard, special attention should be paid to areas of very low levels of environmental hazards or of an environmental hazard not present while other environmental hazard levels are high. The multiplicative approach may inadvertently indicate the cumulative impact in this area is lower, which in fact may not be the case.

Overall, our index allows for analysis of cumulative environmental inequality from multiple hazard exposures, which provides a regional screening assessment that incorporates cumulative impact and social data into one indicator. This type of indicator can be useful for informing regulatory decision-making that seeks to assess geographic and demographic patterns of social inequities in exposures to multiple hazards.

Our research supports previous work in Los Angeles that points to patterns indicating that communities with high proportions of low income residents and populations of color bear significantly greater cumulative environmental burdens than predominantly white and more affluent communities (14). The utility of the CEHI highlights those vulnerable communities as a policy concern. Specifically the index can identify opportunities for addressing cumulative exposures in environmental regulation by, for example, integrated source reduction, forms of "cleaner" production, and even placement of more positive amenities such as playgrounds, parks, and green spaces within highly impacted neighborhoods. Future refinements and innovative applications of the index could also supply information critical to interpreting health effects findings from environmental epidemiologic investigations, including the identification of confounding effects ignored by single measures of air pollution. Although scientific evidence on the functional form of cumulative effects remains formative, the framework allows for investigations of scenarios that can be used to demonstrate the impacts of alternate assumptions about whether effects are additive, multiplicative, or both. These contributions may lead to policies that directly target communities of concern and lead to improvements in public health.

Acknowledgments

This work was supported by the California Office of Environmental Health Hazard Assessment (07-E0009, Understanding and Acting on Cumulative Impacts on California Communities) and the California Air Resources Board (06-332, Spatiotemporal Analysis of Air Pollution and Mortality in California Based on the American Cancer Society Cohort and 04-308 Air Pollution and Environmental

Justice, Integrating Indicators of Cumulative Impact and Socio-Economic Vulnerability into Regulatory Decision-Making).

Supporting Information Available

Details on modeling pollutant concentrations of NO₂, PM_{2.5} and diesel PM cancer risk can be found from SI no. 1 and the significance test for the cumulative environmental inequality index from SI no. 2. This material is available free of charge via the Internet at <http://pubs.acs.org>.

Literature Cited

- (1) Morello-Frosch, R.; Shenassa, E. The environmental 'riskscape' and social inequality: implications for explaining maternal and child health disparities. *Environ. Health Perspect.* **2006**, *114*, 1150–1153.
- (2) Institute of Medicine (IOM). *Toward Environmental Justice: Research, Education, and Health Policy Needs*; Institute of Medicine, Committee on Environmental Justice, Health Sciences Policy Program, Health Sciences Section: Washington, DC, 1999.
- (3) 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.
- (4) Finkelstein, M. M.; Jerrett, M. A study of the relationships between Parkinson's disease and markers of traffic-derived and environmental manganese air pollution in two Canadian cities. *Environ. Res.* **2007**, *104*, 420–432.
- (5) Morello-Frosch, R.; Jesdale, B. Separate and unequal: residential segregation and air quality in the metropolitan U.S. *Environ. Health Perspect.* **2006**, *113*, 386–393.
- (6) National Environmental Justice Advisory Council (NEJAC). *Ensuring Risk Reduction in Communities with Multiple Stressors: Environmental Justice and Cumulative Risks/Impacts - Draft Report*; National Environmental Justice Advisory Council: New Orleans, 2004.
- (7) Cal-EPA Environmental Justice Action Plan. Available at: <http://www.calepa.ca.gov/EnvJustice/ActionPlan/Documents/October2004/ActionPlan.pdf> (Accessed July 20, 2008).
- (8) DeFur, P. L.; Evans, G. W.; Hubal, E. A.; Kyle, A. D.; Morello-Frosch, R. A.; Williams, D. A. Vulnerability as a function of individual and group resources in cumulative risk assessment. *Environ. Health Perspect.* **2007**, *115*, 817–824.
- (9) National Research Council. *Science and Decisions: Advancing Risk Assessment*; National Academy Press: Washington, DC, 2008.
- (10) O'Donnell, O.; van Doorslaer, E.; Wagstaff, A.; Lindelow, M. *Analyzing Health Equity Using Household Survey Data: A Guide to Techniques and Their Implementation*; The International Bank for Reconstruction and Development/The World Bank: Washington, DC, 2008.
- (11) Kakwani, N.; Wagstaff, A.; van Doorslaer, E. Socioeconomic inequalities in health: Measurement, computation, and statistical inference. *J. Econ.* **1997**, *77*, 87–103.
- (12) Kawachi, I.; Kennedy, B. P. The relationship of income inequality to mortality: Does the choice of indicator matter. *Soc. Sci. Med.* **1997**, *45*, 1121–1127.
- (13) Walker, G.; Mitchell, G.; Fairburn, J.; Smith, G. Industrial pollution and social deprivation: Evidence and complexity in evaluating and responding to environmental inequality. *Local Environ.* **2005**, *10*, 361–377.
- (14) Marshall, J. D. Environmental inequality: Air pollution exposures in California's South Coast Air Basin. *Atmos. Environ.* **2008**, *42*, 5499–5503.
- (15) Schweitzer, L. Environmental justice and hazmat transport: A spatial analysis in southern California. *Transp. Res., D: Transp. Environ.* **2006**, *11*, 408–421.
- (16) Buzzelli, M.; Jerrett, M.; Burnett, R.; Finkelstein, N. Spatiotemporal perspectives on air pollution and environmental justice in Hamilton, Canada, 1985–1996. *Ann. Assoc. Am. Geogr.* **2003**, *93.3*, 557–573.
- (17) Bolin, B.; Matranga, E.; Hackett, E. J.; Saddalla, E. K.; Pijawka, K. D.; Brewer, D.; Scotte, D. Environmental equality in a Sunbelt city: the spatial distribution of toxic hazards in Phoenix, Arizona. *Environ. Hazards* **2000**, *2*, 11–24.
- (18) Grineski, S.; Bolin, B.; Boone, C. Criteria air pollution and marginalized populations: Environmental inequality in metropolitan Phoenix, Arizona. *Social Sci. Q.* **2007**, *88*, 535–554.

- (19) Emenius, G.; Pershagen, G.; Berglind, N.; Kwon, H.; Lewne, M.; Nordvall, S.; Wickman, M. NO₂, as a marker of air pollution, and recurrent wheezing in children: a nested case-control study within the BAMSE birth cohort. *Occup. Environ. Med.* **2003**, *60*, 876–881.
- (20) Jerrett, M.; Arain, A.; Kanaroglou, P.; Beckerman, B.; Potoglou, D.; Sahuvaroglu, T.; Morrison, J.; Giovis, C. A review and evaluation of intraurban air pollution exposure models. *J. Exposure Anal. Environ. Epidemiol.* **2005**, *15*, 185–204.
- (21) Su, J. G.; Jerrett, M.; Beckerman, B.; Wilhelm, M.; Ghosh, J. K.; Ritz, B. Optimized land use regression models for predicting traffic-related air pollution in Los Angeles basin. *Environ. Res.* **2009**, *109*, 657–670.
- (22) Su, J. G.; Jerrett, M.; Beckerman, B. A distance decay model selection strategy for optimized land use regression modeling. *Sci. Total Environ.* **2009**, *407*, 3890–3898.
- (23) Hricko, A. Global trade comes home: Community impacts of goods movement. *Environ. Health Perspect.* **2008**, *116*, A78–A81.
- (24) Kyle, A. D.; Wright, C. C.; Caldwell, J. C.; Buffler, P. A.; Woodruff, T. J. Evaluating the health significance of hazardous air pollutants using monitoring data. *Public Health Reports.* **2001**, *116*, 32–44.
- (25) Clean Air Act. Clean Air Act Amendments of 1990. Public Law, 1990, 101–549.
- (26) Kang, S. M.; Kim, M. S.; Lee, M. The trends of composite environmental indices in Korea. *J. Environ. Manage.* **2002**, *64*, 199–206.
- (27) Munda, G. “Measuring sustainability”: A multi-criterion framework. *Environ., Dev. Sustainability* **2005**, *7*, 117–134.
- (28) Esty, D. C. ; Levy, M. A. ; Srebotnjak, T.; de Sherbinin, A. *2005 Environmental Sustainability Index: Benchmarking National Environmental Stewardship*. Yale Center for Environmental Law and Policy: New Haven, CT, 2005.
- (29) Zhou, P.; Ang, B. W.; Poh, K. L. Comparing aggregating methods for constructing the composite environmental index: An objective measure. *Ecol. Econ.* **2006**, *59*, 305–311.
- (30) Ott, W. R. *Environmental Indices: Theory and Practice*; Ann Arbor Science Press: Ann Arbor, MI, 1978.
- (31) National Centre for Children in Poverty. <http://www.nccp.org/> (Accessed March 20, 2009).
- (32) Bolin, B.; Nelson, A.; Hackett, E. J. The ecology of technological risk in a Sunbelt city. *Environ. Plan. A* **2002**, *34*, 317–339.
- (33) Shorrocks, A. F. The class of additively decomposable inequality measures. *Econometrica* **1980**, *48*, 613–625.

ES901041P