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Black carbon exposure and extreme concentrations of residential economic and racial/ethnic privilege and deprivation

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Abstract

Background—Scant data quantify associations between economic and racial/ethnic spatial polarization and individual's exposure to pollution.

Methods—We linked data on the socioeconomic position (SEP) of 1757 urban working class white, black, and Latino adults (age 25–64; Boston, MA: 2003–2004–2008–2010) to: (1) spatiotemporal model-based estimates of cumulative black carbon exposure at their exact residential address, and (2) their census tract values for the Index of Concentration at the Extremes (ICE) for SEP and race/ethnicity.

Results—ICE measures, but not individual- and household-SEP, remained independently associated with black carbon exposure.

Conclusions—The ICE may be useful for environmental health research.

Keywords

Black carbon; Income; Race/ethnicity; Residential segregation; Socioeconomic

1. Introduction

Links between the spatial patterning of social vulnerability and exposure to environmental pollution is a topic of growing concern (Kruize et al., 2014; Nweke et al., 2011). To date, most studies have primarily focused on either racial/ethnic segregation at the city or regional level (Downey et al., 2008; Lopez, 2002), or on within-city concentrations of groups adversely affected by racial discrimination or economic deprivation, such as census tract percent black or below poverty (Goodman et al., 2011; James et al., 2012; Hajat et al.,

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Conflicts of interest

The authors declare no conflicts of interest.

2013). Much less research, however, has investigated how exposure to pollution (Morello-Frosch and Lopez, 2006; Brulle and Pellow, 2006; Pulido, 2000; Smith, 2009), or other public health outcomes (Ludwig et al., 2012), is shaped by the joint influences of within-city extreme concentrations of social position that reflect inequitable social class and race relations (Krieger et al., 1997; Krieger, 2012; Winant, 2000; Shaw et al., 2007). Recent social science research, however, has underscored the need to investigate consequences of rising spatial economic segregation, above and beyond the impact of individual- and household-level income (Massey, 1996; Dwyer, 2010).

In this study, we build on prior research investigating the social-spatial patterning of airborne pollutants, which have primarily focused on urban areas and whose findings typically show that neighborhoods with higher concentrations of poverty and of populations of color have higher exposure to traffic-related pollutants (Lopez, 2002; Goodman et al., 2011; James et al., 2012; Hajat et al., 2013; Krieger et al., 2014). We accordingly sought to improve understanding of the social determination of these patterns by analyzing exposure to one spatially patterned traffic-related air pollutant – black carbon – in relation to the recently developed Index of Concentration at the Extremes (ICE) (Massey, 2001). First proposed by Massey (2001), a leading scholar on racial/ethnic and economic segregation (Massey, 1996, 2012), the ICE simultaneously measures concentration of privilege and deprivation and can be computed at multiple levels and scales, and in the social science literature, has been used solely in relation to socioeconomic measures, such as income and education (Massey, 2001; Kramer, 2013). To our knowledge, the ICE has been employed in only 7 public health studies, none of which focused on environmental exposures (Kramer, 2013; Doh et al., 2007; Carpiano et al., 2009; Finch et al., 2010; Casciano and Massey, 2012; Eastwood et al., 2013; Rudolph et al., 2013). All of these studies employed solely socioeconomic ICE measures and all found evidence of associations between the ICE and the outcomes they studied that were independent of individual or household social characteristics. Guiding our decision to focus on black carbon as an exposure with notable public health significance, substantial evidence indicates that, as summarized in a recent major review article, black carbon is “causally involved in all-cause, lung cancer, and cardiovascular mortality, morbidity, and perhaps adverse birth and nervous system effects” (Grahame et al. 2014, p. 620). In the US, the largest single source of black carbon is transportation (2010 estimate: 216 out of 321 Gg emitted) (Grahame et al., 2014), rendering black carbon an important indicator of ambient traffic-related fine particulate matter, especially for urban air pollution (Grahame et al., 2014; Gryparis et al., 2007).

Our hypothesis was that, after controlling for individual and household social characteristics, higher extreme concentrations, at the census tract level, of economic and racial/ethnic privilege would be associated with lower residential black carbon exposure, as measured by long-term averages of black carbon levels. Conversely, high concentrations of economic deprivation and lack of racial/ethnic privilege would be associated with higher exposure, even after controlling for individual and household characteristics. Possible mechanisms leading to these associations, as discussed in prior research on social variation in exposure to traffic-related pollutants, involve the disproportionate siting of traffic routes with high exposure to car and truck exhaust in neighborhoods that are more likely to be low-income, with relatively few white residents, and with less distance between residential homes and the

street curb, due to smaller (or no) sidewalks and smaller (or no) lawns or front-yards (Brulle and Pellow, 2006; Hajat et al., 2013; Lopez, 2002; Morello-Frosch and Lopez, 2006; Nweke et al., 2011; Pulido, 2000). To test our hypotheses, we conducted an epidemiological investigation using cross-sectional population-based observational data that linked rich individual- and household-level data of individual study participants to model-based spatiotemporal estimates of black carbon exposure at their residential address (exact latitude–longitude) and to diverse census tract ICE measures pertaining to income, education, and race/ethnicity, singly and combined.

2. Materials/subjects and methods

2.1. Study population

We used the same study base employed in our prior analysis of black carbon exposure and census tract poverty (Krieger et al., 2014), whereby study participants comprised all persons enrolled, after written informed consent, in two prior Boston-based studies that employed identical socioeconomic and sociodemographic variables. The *United for Health* (UFH) study (2003–2004) recruited 1202 employed working class adults, age 25–64, who worked in wholesale meat and meat production, retail grocery stores, lighting fixtures manufacturing, and school bus services; the study response rate was 72% (Barbeau et al., 2007). The *My Body, My Story* (MBMS) study (2008–2010) recruited 1005 black and white non-Hispanic US-born members, age 35–64, from a random sample of members of four Boston community health centers; the study response rate was 82% (Krieger et al., 2011). Use of these previously collected data and their linkage, via geocoding, to census-derived area based data and to the black carbon data, was approved as exempt by the Harvard School of Public Health Institutional Review Board (Protocol #23169-101), effective November 5, 2012.

2.2. Sociodemographic and socioeconomic data: individual- and household-level

In our study, we conceptualized race/ethnicity as a social construct arising from inequitable race relations that shape living and working conditions and hence population health (Krieger, 2012; Winant, 2000). To measure this construct and to enable our data to be readily compared to other studies, we used the pre-specified self-report categories employed in the US census, which likewise employ a social definition of race/ethnicity (US Census Bureau, 2014). Data on nativity (US-born vs. foreign-born) and gender were also based on self-report.

We measured diverse aspects of socioeconomic position (SEP) at the individual- and household-level over the lifecourse, per our conceptualization of socioeconomic position as an inherently multidimensional, multilevel, and dynamic relational construct (Krieger et al., 1997; Shaw et al., 2007). Table 1 details the validated self-report socioeconomic measures employed, pertaining to occupational class, educational attainment (of the participant and of her/his parents, as a measure of childhood socioeconomic position), annual household income, and poverty level.

2.3. Census tract data: geocoding, poverty level, and Index of Concentration at the Extremes

Informed by the methods and findings of our *Public Health Disparities Geocoding Project* (Krieger et al., 2005), we were able to geocode 93% of the UFH and 95% of the MBMS participants to latitude–longitude based on residential street address. We used these geocodes to link the study participant data to the census tract and black carbon data. We obtained the census tract data from 2006 to 2010 from the American Community Survey (ACS) (US Census Bureau, 2014), and computed the percent of persons below poverty and determined each tract's income, education, and racial/ethnic composition, needed to compute the ICE measures. We used the 2006–2010 ACS data because research shows that single-year estimates from the ACS at the census tract level are highly imprecise and vary across years (due both to sampling frames and sampling size) (Spielman et al., 2014), and the more stable 5-year estimate we employed encompasses the enrollment period for the MBMS study, which the earliest available 5-year ACS estimate (2005–2009) does not (US Census Bureau, 2014).

The ICE is defined as (Massey, 2001):

$$ICE_i = (A_i - P_i) / T_i$$

where, say, A_i = number of affluent persons in neighborhood i (e.g., in 80th income percentile), P_i = number of poor persons in neighborhood i (e.g., in 20th income percentile), and T_i = total population with known income level in neighborhood i . The ICE thus can range from -1 to 1 , thereby capturing simultaneously concentrated extremes of privilege and deprivation while avoiding problems of multi-collinearity arising when separate measures of deprivation and advantage are used (Massey, 2001). Moreover, unlike most measures of residential segregation that are calculated at the city-level or higher (e.g., the index of dissimilarity, which typically is computed by determining the number of persons who would have to move across census tracts to achieve an even racial/ethnic distribution) (Massey, 2012), the ICE can be meaningfully quantified at diverse geographic or administrative levels, whether block, census tract, city, or region (Massey, 2001; Kramer, 2013). Another useful feature is that it shows the directionality of the concentration (i.e., -1 to 1), as opposed to showing only that inequality in distribution exists (as per the index of dissimilarity and other residential segregation indices).

To generate the ICE socioeconomic measures, we set as the extremes: (a) for income, the ACS household income categories that most closely approximated cut-points for the US 20th and 80th household income percentiles for this time period (i.e., $< \$25,000$ and $\$100,000$; US Census Bureau, 2014), thereby using percentile cut-points routinely employed for analyzing income inequality (Shaw et al., 2007); and (b) for education among persons

25, persons with $<$ high school education and 4 years of college. We also created three novel ICEs. The first was for race/ethnicity, setting as the extreme groups persons who self-identified as white vs those who self-identified as black. The other two combined data on income and race/ethnicity: both set as most privileged white persons whose household income was 80th income percentile and set as least privileged persons in households below

the 20th income percentile and who additionally were classified as either black or as a person of color (i.e., inclusive of all persons other than white). We computed the ICEs for all CTs in which the study participants resided, and additionally computed them for all CTs within the air pollution monitoring catchment area, which encompasses the Greater Boston Area (Gryparis et al., 2007; Krieger et al., 2014).

2.4. Exposure to black carbon

We estimated each individual's 1-year cumulative average exposure to ambient black carbon exposure at the longitude–latitude of their residential address in the year prior to their study enrollment. The model is described in detail elsewhere (Gryparis et al., 2007), but briefly, it is informed by data collected over the period of 1999–2008, involving over 8700 daily observations obtained from 134 locations, most of which monitored black carbon continuously using aethalometers. Covariates in the prediction model included cumulative traffic density within 100 m, geographic information system (GIS) location (latitude, longitude), daily meteorological factors (apparent temperature, wind speed, and height of the planetary boundary layers), and other characteristics (day of week, day of season), and separate models were fit for warm and cold seasons. Using this model, a validation sample at an additional 30 monitoring sites found an average correlation of 0.59 between the predicted and observed black carbon levels, indicating the model is appropriate (Gryparis et al., 2007).

2.5. Analytic methods

The analytic dataset included the 1757 participants (UFH: 807; MBMS: 905) (Krieger et al. 2006, 2011) who resided in the air monitor catchment area (Gryparis et al., 2007) and whose records we were able to geocode to latitude-longitude. Building on our prior analyses (Krieger et al., 2014) we first analyzed the distribution of the study participants' residential black carbon exposure (mean and standard deviation (SD)) in relation, separately, to each category of their census tract ICE measures, their census tract poverty level, and their individual- and household-level social characteristics. We next analyzed the Pearson correlation value for associations between the ICE measures and also between each ICE measure and the census tract poverty level, for the census tracts in which the study participants resided. We then analyzed, for all census tracts in the air pollution monitoring catchment area, the proportion of the census tract population within the extreme groups defined for each ICE measure, so as to determine, empirically, what proportion of census tracts with ICE values equal to 0 belonged to which of the three hypothetically possible scenarios that could give rise to these values: (i) an equal number of persons in the top and bottom groups, with these two groups together comprising some proportion (>0%) of the total population; (ii) an equal number of persons in the top and bottom groups, with these two groups comprising the total population; and (iii) no persons in both the top and bottom group; we carried out analogous analyses for census tracts with ICE values close to 0.

We then conducted multivariable linear regression to quantify the association between the study participants' census tract ICE measures or poverty level and their residential annual average black carbon exposure, in models that controlled for their individual- and household-level SEP and other relevant covariates. The models were of the form: $Y = \beta_1 X_1 +$

$\beta_2 X_2 + \dots \beta_n X_n + \varepsilon$, where Y is the black carbon exposure, $X_1 \dots X_n$ refer to the exposure (ICE) and covariates included in the models, and ε is the error term. In all models, we examined the extent of variation (R^2) in the exposure explained by the included variables.

3. Results

Table 1 provides data on the distribution (mean and SD) of the study participants' residential black carbon exposure (i.e., average cumulative exposure for the year prior to their enrollment in their health study) in relation to: (1) quintile of their census tract ICE measures, and (2) their additional individual and household sociodemographic characteristics. We present these results for the total study population and by race/ethnicity. The participants' black carbon exposure exhibited positive associations with virtually all of their census tract ICE measures (more concentrated privilege, less exposure). Thus, for example, for ICEincome, the average annual black carbon exposure, among all study participants, ranged from 0.6725 $\mu\text{g}/\text{m}^3$ (SD=0.1368) in the lowest quintile to 0.4830 $\mu\text{g}/\text{m}^3$ (SD=0.1654) in the highest quintile (F test p value <0.0001), and the same pattern was observed among the white non-Hispanic, black non-Hispanic, and Hispanic/Latino participants (Table 1). The only exception, showing no variation, was the ICE for educational level among black non-Hispanic participants (Table 1). To provide context for these data, in Table 1 we also show that, as we have reported previously: (a) the black and Latino participants were, compared to white participants, more subjected to socioeconomic deprivation, as both children and as adults, at the individual, household, and census tract level (Krieger et al. 2006, 2011), and (b) the association of estimated black carbon exposure at the participants' residential address was greater for their census tract poverty level as compared to their individual and household SEP (Krieger et al., 2014).

The mean value for the ICEincome (Table 2) was notably highest among white participants in MBMS (mean=0.030, SD 0.272), intermediate and similar by race/ethnicity among UHF participants (mean -0.121, SD 0.243), and lowest among black MBMS participants (mean=-0.202, SD 0.249). For ICEwhite/black, among black participants, the mean value ranged from a low of -0.200 (SD 0.499) in MBMS to 0.116 (SD 0.483) in UHF, whereas among white participants, the mean value ranged from 0.057 (SD 0.530) in UHF to high of 0.486 (SD 0.403) in MBMS (Table 2). Additionally, correlations between the ICE measures and census tract poverty were high ($r>0.65$) in all racial/ethnic groups, except for ICEwhite/black ($r=0.5$) (Table 2). As further shown in Fig. 1, in the catchment area outside of Boston, the extreme concentration of white populations were located both in areas of extreme concentrations of high income and of low income. Within Boston, census tracts with extreme concentrations of high education and white populations did not necessarily have extreme high income, e.g., in areas known to have large student populations.

Table 3 provides empirical data regarding the meaning of an ICE value equal to 0 (or close to 0), analyzed in relation to all CTs included in the air pollution monitoring catchment area. In the case of an ICE value equal to 0, these occurred for only 0.1% to at most 0.6% of the 1069 census tracts in the catchment area, and for 4 of the 5 ICE measures, these 0s were because the extreme categories contained 0 persons, with the one exception being the ICE for income only (for which the top and bottom categories comprised 25% of the total

population). Census tracts with ICE values close to 0 (ranging from [-0.5 to 0.5]) in turn comprised anywhere from just under 2% of the 1609 census tracts (for the ICE for white vs. black) to just over 11% (for the ICE for income only), and for all 5 ICE measures, the proportion of persons in the top plus bottom extreme categories ranged from 10.6% (for the ICE for high income white population vs. low income black population) to 57.8% (for the ICE for white vs. black), with a mean value of 35.2% (SD 24.7%). Together, these data indicate that a value of 0 (or close to 0) does arise from population distributions in which most (and rarely all) of the population is not in the extreme categories.

Table 4 presents results of the linear regression analyses for the ICE measures and black carbon. The observed inverse associations between the participants' ICE measures with their residential black carbon exposure were greater (and more likely to have 95% CI that excluded 0) compared to those observed for their individual and household SEP (Models 1 and 2). The *R*-squared values (>0.10) for baseline models (Model 2) that included the ICE income-related measures along with study and exam date were also two to three times higher than those of the analogous baseline models with only ICEwhite/black ($R^2=0.036$).

Among models containing the baseline and sociodemographic variables (Model 3 and 4), those with the ICE and census tract poverty variables (Model 4) likewise accounted for a greater amount of the variance in black carbon exposure ($R^2>0.12$) compared to models including only the baseline and sociodemographic and household- and individual-level socioeconomic data (Model 3; $R^2=0.0433$). In these models, the ICE measures remained independently inversely associated with black carbon exposure, whereas the individual- and household-level SEP measures did not (Model 5), with the exception of household income and education in the ICE models for education and for race/ethnicity.

4. Discussion

Our results indicate that extreme concentrations of socioeconomic resources and racial/ethnic privilege, structured by social class and race relations, as manifested at the census tract level, are inversely associated with individuals' residential exposure to black carbon, an important airborne pollutant, even after controlling for individual and household social characteristics. Two additional noteworthy findings are that: (a) extreme concentrations of high and low income were more strongly associated with residential black carbon exposure than were extreme concentrations of race/ethnicity (e.g., black vs. white), and (b) ICE measures for both income and race/ethnicity were more strongly associated with black carbon exposure than were individual- and household-level socioeconomic and sociodemographic characteristics.

The plausibility of our findings rests in part on the study strengths and limitations. Strengths include reliance on two multiethnic working class population-based studies with high response rates (Krieger et al. 2006, 2011), and for whom a very high percent ($>95\%$) had residential addresses that could be geocoded to latitude-longitude and thus linked to validated model-based spatiotemporal estimates for residence-specific long-term ambient black carbon exposure (Gryparis et al., 2007). Two limitations pertain to measurement error. First, annual ACS estimates have been shown to have high uncertainty due to the small

number of persons sampled (Spielman et al., 2014); we accordingly used only the 5-year average ACS estimates. Second, the black carbon exposures estimates are model based, also potentially introducing imprecision of measurement (Gryparis et al., 2007; Krieger et al., 2014). Both of these limitations, each involving non-differential measurement error, would likely bias results to the null. Also potentially leading to conservative estimates of association was the largely working class composition of the study participants (Barbeau et al., 2007; Krieger et al., 2011); had the study base included more affluent and more highly educated professionals, greater associations might have been observed, given the likely wider range of black carbon exposure and also ICE values.

Our finding that the ICE measures remained associated with the specified outcome (in our case, black carbon), independent of individual- and household-level socioeconomic position, is consistent with the findings of both prior social science studies (e.g., Massey, 2001; Casciano and Massey, 2008; Kubrin and Stewart, 2006) and also the handful of public health studies that have used the ICE (Kramer, 2013; Doh et al., 2007; Carpiano et al., 2009; Finch et al., 2010; Casciano and Massey, 2012; Eastwood et al., 2013; Rudolph et al., 2013). None of these studies, however, used an ICE for race/ethnicity, alone or combined with income, nor did any investigate environmental pollution. Our findings further clarify, empirically, that, at least in the case of a major US city, values of or close to 0 for an ICE overwhelmingly occur because the numbers of persons in the top and bottom groups is equal or close to equal and typically comprise about 1/3 of the total population, as opposed to arising because 0 persons are in the top and bottom groups. To our knowledge, our results are the first empirical findings analyzing the population distributions that contribute to an observed ICE value of 0 (or close to 0).

Considered together, these prior studies and our results support the need for analysis of the inequitable health consequences of increasingly polarized concentrations of high and low income, as linked to high and low wealth (Piketty, 2014), in conjunction with present and past patterns of racial/ethnic residential segregation (Massey, 1996, 2012) and on-going evidence of racial discrimination in the housing market (Massey, 2012; Hanson and Hawley, 2011). These patterns of spatial social polarization are, as indicated by prior research, likely to shape risk of exposure to traffic-related air pollution, both because of siting of densely-trafficked streets and because neighborhoods with fewer economic and social resources are likely to have smaller (or no) sidewalks and residences with smaller (or no) front yards or lawns (Brulle and Pellow, 2006; Hajat et al., 2013; Lopez, 2002; Morello-Frosch and Lopez, 2006; Nweke et al., 2011; Pulido, 2000). A particular advantage of the novel ICEs we created that combine income and racial/ethnic data, moreover, is that in contrast to analytic approaches that treat these two variables separately (and, in some cases, attempt to model interaction effects) (Smith, 2009), the new ICEs we have deployed enable capturing, in a way that is socially meaningful and statistically tractable, the joint realities of spatial concentrations of economic and racial/ethnic privilege and lack of such privilege.

In conclusion, research on environmental exposures will likely benefit from using area-based measures, such as the ICE, that capture growing social extremes. As suggested by our results, a focus solely on individual- and household socioeconomic and sociodemographic characteristics does not suffice, and nor is it adequate to focus solely on

racial/ethnic segregation without also data on economic segregation. The larger implication is that research on health equity, including in environmental health, must reckon with the intertwining of economic and racial/ethnic polarization at multiple scales and political levels of geography (Polednak, 1997; Morello-Frosch, 2002; Krieger, 2012; Kruize et al. 2014). Such data are likely to be useful to the policy makers, scientists, and community advocates seeking to redress social inequalities in exposure to environmental pollution (Brulle and Pellow, 2006; Downey et al., 2008; Goodman et al., 2011; Hajat et al. 2013; James et al., 2012; Kruize et al., 2014; Morello-Frosch and Lopez, 2006; Morello-Frosch, 2002; Nweke et al., 2011; Pulido, 2000; Smith, 2009).

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at. doi: 10.1016/j.healthplace.2015.05.008

Fig. 1.

Map of census tract values for Index of Concentration at the Extremes for income and race/ethnicity and for poverty (most privileged: darkest green; least privileged: darkest brown): black carbon measurement catchment area and Boston, MA (2006–2010).

Social distribution of study participants’ residential black carbon exposure (cumulative 1-year exposure prior to study enrollment), overall and by race, ethnicity, for their census tract level Index of Concentration at the Extremes (ICE) and individual and household sociodemographic and economic characteristics: 1757 urban working class adults (age 25–64) enrolled in *United for Health (UFH)*, Greater Boston Area, MA, 2003–2004) and *My Body, My Story (MBMS)*, Boston, MA, 2008–2010).

Table 1

VARIABLE	Alta (N=1757; UFH=807; MBMS=950)				White (N=670; UFH=205; MBMS=465)				Black (N=787; UFH=302; MBMS=485)				Latino (N=195; UFH=195; MBMS=40)			
	N	% ^a	Black carbon ($\mu\text{g}/\text{m}^{-3}$); mean (SD)	F tes p value	N	%	Black carbon ($\mu\text{g}/\text{m}^{-3}$); mean (SD)	F test p value	N	%	Black carbon ($\mu\text{g}/\text{m}^{-3}$); mean (SD)	F test p value	N	%	Black carbon ($\mu\text{g}/\text{m}^{-3}$); mean (SD)	F test p value
ICE quintiles (cut-points) ^c																
ICEincome																
q1 (−0.12911) (lowest)	758	43.1	0.6725 (0.1358)	34.65 (<.0001)	174	26.0	0.7024 (0.1492)	25.44 (<.0001)	439	55.8	0.6546 (0.1255)	8.07 (<.0001)	89	45.6	0.7136 (0.1388)	3.75 (0.0058)
q2 (0.06702)	525	29.9	0.6786 (0.1371)		213	31.8	0.6997 (0.1466)		228	29.0	0.6502 (0.1174)		56	28.7	0.6882 (0.1376)	
q3 (0.21909)	285	16.2	0.6512 (0.1794)		163	24.3	0.6541 (0.1776)		80	10.2	0.6327 (0.1880)		31	15.9	0.6821 (0.1825)	
q4 (0.35443)	133	7.6	0.5729 (0.1822)		85	12.7	0.5522 (0.1597)		25	3.2	0.6206 (0.2726)		15	7.7	0.5941 (0.1344)	
q5 (0.76880) (highest)	56	3.2	0.4830 (0.1654)		35	5.2	0.4946 (0.1967)		15	1.9	0.4558 (0.1025)		4	2.0	0.5124 (0.0174)	
ICEeducation																
q1 (0.01299) (lowest)	708	40.3	0.6707 (0.1395)	8.15 (<.0001)	179	26.7	0.7225 (0.1531)	17.45 (<.0001)	391	49.7	0.6393 (0.1224)	0.70 (0.5887)	85	43.6	0.7118 (0.1395)	2.67 (0.0334)
q2 (0.20797)	446	25.4	0.6644 (0.1686)		151	22.5	0.6888 (0.1963)		208	26.4	0.6474 (0.1545)		61	31.3	0.6663 (0.1431)	
q3 (0.37484)	308	17.5	0.6247 (0.1389)		163	24.3	0.5961 (0.1337)		109	13.8	0.6612 (0.1354)		26	13.3	0.6307 (0.1448)	
q4 (0.57532)	198	11.3	0.6692 (0.1910)		115	17.2	0.6566 (0.1895)		54	6.9	0.6611 (0.1920)		17	8.7	0.7471 (0.1973)	
q5 (1.00000) (highest)	97	5.5	0.6055 (0.1312)		62	9.2	0.5827 (0.1128)		25	3.2	0.6470 (0.1564)		6	3.1	0.6517 (0.1132)	
ICEwhite/black																
q1 (0.45848) (lowest)	1206	68.6	0.6722 (0.1326)	28.60 (<.0001)	337	50.3	0.6969 (0.1392)	17.95 (<.0001)	656	83.4	0.6512 (0.1268)	12.48 (<.0001)	138	70.8	0.7044 (0.1209)	4.04 (0.0036)
q2 (0.72166)	304	17.3	0.6672 (0.1720)		168	25.1	0.6620 (0.1733)		85	10.8	0.6744 (0.1762)		33	16.9	0.6655 (0.1600)	
q3 (0.85726)	89	5.1	0.5493 (0.1550)		50	7.5	0.5411 (0.1515)		24	3.0	0.5667 (0.1837)		9	4.6	0.5307 (0.1288)	
q4 (0.92687)	97	5.5	0.6265 (0.2308)		67	10.0	0.6453 (0.2218)		15	1.9	0.5047 (0.1773)		12	6.2	0.7129 (0.3028)	
q5 (0.99444) (highest)	61	3.5	0.5204 (0.1822)		48	7.2	0.5369 (0.1941)		7	0.9	0.4114 (0.1160)		3	1.5	0.5546 (0.0465)	
ICEincome + white/black																
q1 (0.06553) (lowest)	1026	58.4	0.6720 (0.1241)	26.85 (<.0001)	262	39.1	0.7022 (0.1301)	23.52 (<.0001)	572	72.7	0.6488 (0.1129)	5.33 (0.0003)	122	62.6	0.7104 (0.1260)	2.82 (0.0265)
q2 (0.21017)	376	21.4	0.6775 (0.1755)		176	26.3	0.6993 (0.1805)		144	18.3	0.6624 (0.1752)		37	19.0	0.6446 (0.1576)	
q3 (0.31729)	153	8.7	0.6259 (0.1672)		89	13.3	0.6150 (0.1572)		36	4.6	0.6261 (0.1832)		20	10.3	0.6558 (0.1677)	
q4 (0.42648)	147	8.4	0.5930 (0.2015)		109	16.3	0.5791 (0.1810)		19	2.4	0.6017 (0.2870)		13	6.7	0.6904 (0.2439)	
q5 (0.79070) (highest)	55	3.1	0.5042 (0.1913)		34	5.1	0.5070 (0.1998)		16	2.0	0.5060 (0.2050)		3	1.5	0.5156 (0.0198)	
ICEincome + white/of color																

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VARIABLE	Alia (N=1757; UFH=807; MBMS=950)				White (N=670; UFH= 205; MBMS = 465)				Black (N=787; UFH= 302; MBMS=485)				Latino (N=195; UFH=195; MBMS=0)			
	N	% ^a	Black carbon (µg/m ⁻³); mean (SD)	F tes p value	N	%	Black carbon (µg/m ⁻³); mean (SD)	F test p value	N	%	Black carbon (µg/m ⁻³); mean (SD)	F test p value	N	%	Black carbon (µg/m ⁻³); mean (SD)	F test p value
q1 (0.00096) (lowest)	1060	60.3	0.6752 (0.1237)	38.53 (<.0001)	284	42.4	0.7010 (0.1293)	28.89 (<.0001)	588	74.7	0.6517 (0.1128)	12.05(<.0001)	117	60.0	0.7216 (0.1241)	7.04(<.0001)
q2 (0.18464)	352	20.0	0.6761 (0.1848)		158	23.6	0.7017 (0.1903)		133	16.9	0.6642 (0.1868)		43	22.0	0.6284 (0.1487)	
q3 (0.30584)	188	10.7	0.6258 (0.1581)		122	18.2	0.6285 (0.1520)		35	4.4	0.5766 (0.1350)		21	10.8	0.7129 (0.2072)	
q4 (0.42062)	102	5.8	0.5618 (0.2032)		70	10.4	0.5393 (0.1759)		16	2.0	0.6466 (0.3354)		12	6.2	0.5585 (0.1259)	
q5 (0.79070) (highest)	55	3.1	0.4760 (0.1660)		36	5.4	0.4929 (0.1953)		15	1.9	0.4361 (0.0818)		2	1.0	0.52025 (0.0255)	
SOCIODEMOGRAPHIC																
Age (years)																
25–34 years	170	9.7	0.7379 (0.1751)	21.28 (<.0001)	34	5.1	0.7933 (0.1794)	8.68 (<.0001)	52	6.6	0.7340 (0.2086)	8.53 (<.0001)	56	28.7	0.7298 (0.1437)	4.41 (0.005)
35–44 years	561	32.0	0.6629 (0.1452)		208	31.1	0.6680 (0.1493)		248	31.6	0.6495 (0.1372)		73	37.4	0.6864 (0.1519)	
45–54 years	649	37.0	0.6469 (0.1606)		258	38.6	0.6508 (0.1866)		309	39.4	0.6405 (0.1400)		52	26.7	0.6749 (0.1355)	
55–64 years	373	21.3	0.6298 (0.1344)		168	25.2	0.6358 (0.1584)		176	22.4	0.6257 (0.1061)		14	7.2	0.5772 (0.1499)	
(missing: N, %)	4	0.00			2	0.00			2	0.00						
Nativity																
US-born	1358	78.9	0.6617 (0.1520)	3.75 (0.053)	649	97.0	0.6601 (0.1714)	0.0 (0.952)	619	79.5	0.6584 (0.1298)	21.95 (<.0001)	50	28.7	0.6980 (0.1393)	0.02 (0.8793)
Not US-born	364	21.1	0.6440 (0.1635)		20	3.0	0.6624 (0.1656)		160	20.5	0.6013 (0.1641)		124	71.3	0.6941 (0.1569)	
(missing: N, %)	35	0.02			1	0.00			8	0.01			21	0.11		
Gender																
Women	929	53.3	0.6575 (0.1469)	0.05 (0.8281)	367	54.9	0.6439 (0.1573)	7.34 (0.0069)	443	56.9	0.6596 (0.1390)	7.85 (0.0052)	80	58.3	0.6775 (0.1386)	0.88 (0.3502)
Men	813	46.7	0.6591 (0.1628)		302	45.1	0.6798 (0.1848)		335	43.1	0.6314 (0.1389)		112	58.3	0.6980 (0.1565)	
(missing: N, %)	15	0.01			1	0.00			9	0.01			3	0.02		
ECONOMIC																
Individual-level: current																
Occupational class																
Working class: non-supervisory employee	753	48.3	0.6566 (0.1589)	1.2 (0.309)	262	43.0	0.6679 (0.1785)	0.66 (0.6203)	343	49.8	0.6362 (0.1411)	1.03(0.3916)	91	56.2	0.6954 (0.1523)	1.11 (0.3487)
Not working class:																
supervisory employee	347	22.2	0.6710 (0.1659)		131	21.5	0.6746 (0.1801)		147	21.4	0.6582 (0.1632)		37	22.8	0.7076 (0.1534)	
self-employed/freelance	120	7.7	0.6364 (0.1338)		52	8.5	0.6414 (0.1343)		39	5.7	0.6410 (0.1147)		22	13.6	0.6369 (0.1655)	
own or run business	85	5.4	0.6547 (0.1632)		40	6.7	0.6472 (0.1623)		29	4.2	0.6436 (0.1831)		12	7.41	0.6775 (0.1348)	
Not in paid labor force	255	16.4	0.6554 (0.1493)		125	20.5	0.6497 (0.1755)		130	18.9	0.6608 (0.1194)					
(missing: N, %)	197	0.11			60	0.09			99	0.13			33	0.17		
Educational attainment																
<high school (HS) b	305	18.2	0.6693 (0.1714)	5.16(0.0058)	85	12.9	0.6687 (0.2151)	4.94(0.0074)	136	17.7	0.6541 (0.1426)	0.22(0.8013)	67	42.1	0.7002 (0.1636)	2.0 (0.1385)

VARIABLE	Allia (N=1757; UFH=807; MBMS=950)				White (N=670; UFH= 205; MBMS = 465)				Black (N=787; UFH= 302; MBMS=485)				Latino (N=195; UFH=195; MBMS=0)			
	N	% ^a	Black carbon (µg/m ⁻³); mean (SD)	F tes p value	N	%	Black carbon (µg/m ⁻³); mean (SD)	F test p value	N	%	Black carbon (µg/m ⁻³); mean (SD)	F test p value	N	%	Black carbon (µg/m ⁻³); mean (SD)	F test p value
HS and < 4 yrs college	1089	64.9	0.6600 (0.1516)		409	61.9	0.6720 (0.1655)		536	69.9	0.6453 (0.1414)		80	50.3	0.6860 (0.1425)	
4 yrs college	285	17.0	0.6314 (0.1393)		167	25.3	0.6240 (0.1500)		95	12.4	0.6455 (0.1156)		12	7.6	0.6056 (0.1264)	
(missing: N, %)	78	0.04			9	0.01			20	0.03			36	0.18		
Household-level: current																
Annual household income																
< \$12,000	412	26.1	0.6775 (0.1536)	3.47(0.0021)	117	18.6	0.6860 (0.1698)	2.45 (0.024)	200	28.6	0.6690 (0.1396)	1.46(0.1896)	67	41.4	0.6968 (0.1675)	0.67(0.6481)
\$12,00 to <\$36,000	548	34.7	0.6628 (0.1565)		201	32.0	0.6732 (0.1746)		231	33.1	0.6412 (0.1430)		79	48.8	0.6857 (0.1403)	
\$36,000 to <\$48,000	111	7.0	0.6633 (0.1838)		45	7.2	0.7056 (0.1634)		50	7.2	0.6302 (0.1936)		7	4.3	0.6968 (0.2177)	
\$48,000 to <\$72,000	259	16.4	0.6295 (0.1587)		127	20.2	0.6321 (0.1884)		120	17.2	0.6331 (0.1256)		4	2.5	0.5760 (0.0553)	
\$72,000 to <\$120,000	119	7.5	0.6340 (0.1202)		77	12.2	0.6303 (0.1222)		41	5.9	0.6368 (0.1159)		1	0.6	0.8124	
\$120,000 to < \$144,000	41	2.6	0.6467 (0.1572)		27	4.3	0.6357 (0.1634)		13	1.9	0.6778 (0.1491)		0	0		
> = \$144,000	88	5.6	0.6352 (0.1413)		35	5.6	0.6284 (0.1797)		43	6.2	0.6286 (0.1101)		4	2.5	0.6451 (0.0810)	
(missing: N, %)	179	0.10			41	0.06			89	0.11			33	0.17		
Poverty level (household)																
< 100% poverty	574	36.5	0.6722 (0.1508)	6.85 (0.0011)	152	24.2	0.6842 (0.1658)	3.41 (0.0337)	287	41.2	0.6610 (0.1390)	2.61 (0.0742)	98	60.9	0.6933 (0.1595)	1.68 (0.1905)
100 to 199% poverty	350	22.3	0.6639 (0.1722)		139	22.2	0.6729 (0.1882)		149	21.4	0.6399 (0.1616)		41	25.5	0.7054 (0.1458)	
200% poverty	648	41.2	0.6404 (0.1489)		336	53.6	0.6440 (0.1653)		260	37.4	0.6348 (0.1276)		22	13.7	0.6344 (0.1337)	
(missing: N, %)	185	0.11			43	0.06			91	0.12			34	0.17		
Census tract: current																
20% below poverty	840	47.8	0.6989 (0.1384)	69.57(<.0001)	221	33.0	0.7321 (0.1559)	34.18(<.0001)	466	59.2	0.6749 (0.1252)	27.94(<.0001)	90	46.2	0.7363 (0.1216)	16.5(<.0001)
10 to 19% below poverty	449	25.6	0.6601 (0.1548)		191	28.5	0.6725 (0.1563)		196	24.9	0.6351 (0.1463)		45	23.1	0.7247 (0.1694)	
5 to 9 % below poverty	303	17.2	0.5950 (0.1360)		153	22.8	0.6069 (0.1469)		89	11.3	0.5729 (0.1252)		44	22.6	0.5970 (0.1267)	
<5% below poverty	165	9.4	0.5521 (0.1758)		105	15.7	0.5623 (0.1886)		36	4.6	0.5170 (0.1721)		16	8.2	0.5629 (0.1000)	
(missing: N, %)	0				0				0				0			
Childhood: household education (highest level: mother, father, or guardian)																
< high school (HS)/ ^b	394	27.4	0.6624 (0.1565)	4.39(0.0126)	91	14.9	0.6772 (0.1805)	4.6(0.0104)	208	32.6	0.6492 (0.1445)	0.38(0.687)	76	65.5	0.6836 (0.1542)	0.63(0.5342)
HS and < 4 yrs college	750	52.2	0.6570 (0.1572)		338	55.2	0.6649 (0.1735)		339	53.0	0.6469 (0.1392)		33	28.4	0.6744 (0.1621)	
4 yrs college	292	20.3	0.6296 (0.1381)		183	29.9	0.6238 (0.1460)		92	14.4	0.6346 (0.1215)		7	6.0	0.6151 (0.1282)	
(missing: N, %)	321	0.18			58	0.09			148	0.19			79	0.41		

ICEIncome: N of households in 80th (highest) versus 20th (lowest) household income percentile

ICEEducation: N of adults 25 years old who have 4+ years of college vs. < high school

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ICEwhite/black: N of persons who are white versus black

ICEincome + white/black N of persons who are both high income (top quintile) and white vs are both low income (bottom quintile) and black

ICEincome + white/of color N of persons who are both high income (top quintile) and white vs are both low income (bottom quintile) and of color

^a All includes 78 participants from United for Health who self-identified as belonging to other populations of color and 17 for whom race/ethnicity was missing; all participants in My Body, My Story had to self-identify as either white or black and none had missing data on race/ethnicity.

^b >high school includes persons who have left school prior to obtaining a high school degree or 12 years of education or who have not obtained a GED certificate

^c ICE range: 1 – 1 (most privileged); the ICE comparison (extreme) groups are as follows, with quintile cut-points based on the distribution of values within the black carbon catchment area

Distribution of and correlation between study participants’ census tract measures of Index of Concentration of Extremes and poverty, for the 1757 urban working class adults (age 25–64) enrolled in United for Health (UFH, Greater Boston Area, MA, 2003–2004) and My Body, My Story (MBMS, Boston, MA, 2008–2010).

Table 2

Group	Variable	Mean (SD)	Median	Inter-quartile range (IQR)	Minimum	Maximum	Pearson correlation coefficient (p-value)				
							ICE income	ICE education	ICE white/black	ICE income + white/black	ICE income + white/of color
UFH											
Total (N=807)	ICEincome	−0.121 (0.243)	−0.115	0.301	0.794	0.601	1.000				
	ICEeducation	0.027 (0.251)	0.008	0.349	0.569	0.845	0.748	1.000			
	ICEwhite/black	0.077 (0.514)	0.124	0.812	−0.889	0.970	0.552	0.491	1.000		
	ICEincome + white/black	0.005 (0.208)	0.012	0.284	−0.552	0.591	0.787	0.619	0.905	1.000	
	ICEincome + white/of color	−0.108 (0.265)	−0.129	0.380	−0.727	0.591	0.916	0.748	0.799	0.921	1.000
	Census tract poverty	20.8 (12.7)	20.4	17.0	0.0	86.3	−0.852	−0.575	−0.475	−0.661	−0.785
Black (N=302)	ICEincome	−0.131 (0.238)	−0.134	0.295	−0.794	0.601	1.000				
	ICEeducation	−0.001 (0.253)	−0.002	0.346	−0.569	0.814	0.749	1.000			
	ICEwhite/black	0.116 (0.483)	0.178	0.499	−0.889	0.963	0.521	0.398	1.000		
	ICEincome + white/black	0.018 (0.196)	0.026	0.187	−0.552	0.591	0.760	0.542	0.903	1.000	
	ICEincome + white/of color	−0.112 (0.255)	−0.138	0.349	−0.686	0.591	0.922	0.732	0.764	0.889	1.000
	Census tract poverty	21.0 (12.1)	20.9	16.9	0.0	67.3	−0.851	−0.564	−0.432	−0.605	−0.773
Latino (N=195)	ICEincome	−0.106 (0.248)	−0.092	0.344	−0.794	0.509	1.000				
	ICEeducation	0.058 (0.249)	0.036	0.355	−0.414	0.845	0.787	1.000			
	ICEwhite/black	0.016 (0.551)	0.037	1.039	−0.889	0.958	0.603	0.589	1.000		
	ICEincome + white/black	−0.014 (0.221)	−0.007	0.342	−0.552	0.477	0.824	0.716	0.913	1.000	
	ICEincome + white/of color	−0.108 (0.277)	−0.146	0.422	−0.686	0.458	0.921	0.795	0.834	0.950	1.000
	Census tract poverty	20.2 (13.9)	18.0	18.7	1.9	86.3	−0.818	−0.608	−0.463	−0.654	−0.745
White (N=205)	ICEincome	−0.106 (0.235)	−0.092	0.258	−0.760	0.484	1.000				
	ICEeducation	0.036 (0.229)	0.002	0.310	−0.414	0.762	0.735	1.000			
	ICEwhite/black	0.057 (0.530)	0.140	0.873	−0.889	0.969	0.594	0.564	1.000		
	ICEincome + white/black	0.000 (0.214)	−0.001	0.284	−0.552	0.579	0.818	0.679	0.911	1.000	
	ICEincome + white/of color	−0.096 (0.267)	−0.096	0.364	−0.727	0.579	0.911	0.742	0.835	0.945	1.000
	Census tract poverty	20.2 (12.1)	18.0	17.6	0.6	57.1	−0.879	−0.592	−0.578	−0.747	−0.838
MBMS											
Total (N=950)	ICEincome	−0.089 (0.285)	−0.085	0.418	−0.794	0.631	1.000				
	ICEeducation	0.166 (0.276)	0.174	0.417	−0.483	0.885	0.710	1.000			
	ICEwhite/black	0.136 (0.569)	0.162	1.007	−0.889	0.993	0.587	0.674	1.000		
	ICEincome + white/black	0.027 (0.241)	0.051	0.368	−0.552	0.605	0.846	0.767	0.895	1.000	

Group	Variable	Mean (SD)	Median	Inter-quartile range (IQR)	Minimum	Maximum	Pearson correlation coefficient (<i>p</i> -value)				
							ICE income	ICE education	ICE white/black	ICE income + white/black	ICE income + white/of color
Black (N=485)	ICEincome + white/of color	−0.066 (0.300)	−0.049	0.466	−0.727	0.605	0.921	0.781	0.831	0.966	1.000
	Census tract poverty	21.5 (15.6)	17.2	22.1	0.0	67.3	−0.896	−0.538	−0.486	−0.708	−0.800
	ICEincome	−0.202 (0.249)	−0.175	0.300	−0.794	0.619	1.000				1.000
	ICEeducation	0.068 (0.251)	0.028	0.349	−0.483	0.877	0.597	1.000			
	ICEwhite/black	−0.200 (0.499)	−0.283	0.778	−0.889	0.986	0.363	0.641	1.000		
	ICEincome + white/black	−0.108 (0.204)	−0.143	0.313	−0.552	0.583	0.759	0.722	0.842	1.000	
White (N=465)	ICEincome + white/of color	−0.222 (0.249)	−0.256	0.318	−0.727	0.583	0.890	0.756	0.714	0.942	1.000
	Census tract poverty	27.0 (15.5)	24.4	22.2	0.0	67.3	−0.898	−0.424	−0.229	−0.601	−0.738
	ICEincome		0.030 (0.272)	0.078	0.287	−0.794	0.631	1.000			1.000
	ICEeducation	0.269 (0.264)	0.265	0.325	−0.442	0.885	0.718	1.000			
	ICEwhite/black	0.486 (0.403)	0.616	0.627	−0.889	0.993	0.604	0.587	1.000		
	ICEincome + white/black	0.168 (0.192)	0.158	0.263	−0.455	0.605	0.884	0.743	0.844	1.000	
	ICEincome + white/of color	0.098 (0.259)	0.110	0.310	−0.621	0.605	0.932	0.735	0.820	0.965	1.000
	Census tract poverty	15.7 (13.4)	11.3	14.1	0.0	57.2	−0.871	−0.523	−0.555	−0.725	−0.815

Note: *p* value<0.0001 for all Pearson correlation coefficients

Table 3

ICE measures: distribution of population for census tracts (CTs) in which the ICE equals 0 or is close to 0 (−0.5 to 0.5), for the black carbon air monitoring catchment area ($N=1069$ CTs), using 5-year average 2006–2010 census tract data from the American Community Survey.

ICE measure	ICE value (CT)	Nof CTs (%)	TOTAL Nof Persons in CTs	TOP CATEGORY Nof persons (%)	BOTTOM CATEGORY Nof persons (%)	TOP + BOTTOM Nof persons (%)
ICE income	0	4 (0.4%)	1323	164 (12.4%)	164 (12.4%)	328 (24.8%)
ICE education		1 (0.1%)	26	0 (0.0%)	0 (0.0%)	0 (0.0%)
ICE white/black		1 (0.1%)	52	0 (0.0%)	0 (0.0%)	0 (0.0%)
ICE income+white/black		6 (0.6%)	3001	0 (0.0%)	0 (0.0%)	0 (0.0%)
ICE income+white/of color		3 (0.3%)	36	0 (0.0%)	0 (0.0%)	0 (0.0%)
ICE income	−0.5 to 0.5	121 (11.3%)	214335	47193 (22.0%)	45798 (21.4%)	92991 (43.4%)
ICE education		72 (6.7%)	213985	43147 (20.2%)	41105 (19.2%)	84252 (39.4%)
ICE white/black		18 (1.7%)	58970	17303 (29.3%)	16794 (28.5%)	34097 (57.8%)
ICE income+white/black		107 (10.0%)	158283	9009 (5.7%)	7752 (4.9%)	16761 (10.6%)
ICE income+white/of color		94 (8.8%)	158891	16300 (10.3%)	16665 (10.5%)	16761 (10.6%)