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Short communication

Black carbon exposure more strongly associated with census tract poverty compared to household income among US black, white, and Latino working class adults in Boston, MA (2003–2010)

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A B S T R A C T

We investigated the association of individual-level ambient exposure to black carbon (spatiotemporal model-based estimate for latitude and longitude of residential address) with individual, household, and census tract socioeconomic measures among a study sample comprised of 1757 US urban working class white, black and Latino adults (age 25–64) recruited for two studies conducted in Boston, MA (2003–2004; 2008–2010). Controlling for age, study, and exam date, the estimated average annual black carbon exposure for the year prior to study enrollment at the participants' residential address was directly associated with census tract poverty (beta = 0.373; 95% confidence interval (CI) 0.322, 0.423) but not with annual household income or education; null associations with race/ethnicity became significant only after controlling for socioeconomic position.

1. Introduction

Despite growing awareness of the need to integrate social epidemiologic and environmental health analyses (Morello-Frosch, 2002; Payne-Sturges et al., 2006; Brulle and Pellow, 2006; Krieger, 2011), only four studies (3 European, 1 US) have simultaneously investigated the association of contextual, household, and individual-level socioeconomic position with residential exposure to air pollution. These studies, all of urban populations, all found that exposure to air pollution – whether nitrogen dioxide (NO_2)(Chaix et al., 2006; Hajat et al., 2013), nitrogen oxides (NO_x)(Goodman et al., 2011), fine particulate matter $\leq$ 2.5 micrometers in diameter ($PM_{2.5}$) (Hajat et al., 2013), or traffic indicators (Cesaroni et al, 2010) – was more strongly associated with neighborhood-level compared to individual- and household-level measures of socioeconomic position.

We add to this limited literature by investigating the association of exposure to black carbon with individual, household, and census tract socioeconomic measures among US urban working class white, black and Latino adults. We focus on black carbon because it is a major component of traffic-related air pollution, a key contributor to urban air pollution (Gryparis et al., 2007). Informed by the ecosocial theory of disease distribution and its approach to analyzing the adverse impact of multiple types of social injustice at diverse levels and spatiotemporal scales (Krieger, 2011), our *a priori* hypothesis was that the observed social patterning of exposure to black carbon would depend on both the level of measurement of socioeconomic position and race/ethnicity.

2. Materials and methods

To test our hypothesis, we linked 3 data sets, each geocoded to latitude–longitude based on exact street address of residence: two with data on the study participants, and the third with spatiotemporal data on black carbon exposure. Our investigation was approved as exempt by the Harvard School of Public Health Institutional Review Board (Protocol #23169-101), effective November 5, 2012.

2.1. Study population

The two Boston-based studies included the same socioeconomic measures. The first was the *United for Health* (UFH) study (2003–2004), which recruited 1202

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Table 1
Sociodemographic and economic characteristics and average exposure to black carbon among study participants ($N = 1757$) residing in catchment area for monitoring black carbon exposure and geocoded to latitude–longitude: *United for Health* (Greater Boston Area, 2003–2004) and *My Body, My Story* (Boston, 2008–2010).

Characteristic		United for Health (UFH) ($n = 807$)		My Body, My Story (MBMS) ($n = 950$)	
		N	Value[a]	*N*	Value[a]
Sociodemographic characteristics					
Age (yrs): mean (SD) (range: UFH = 25–64; MBMS = 35–64)		807	43.6 (9.7)	950	48.9 (7.9)
Race/ethnicity + nativity: n (%)					
White (non-Hispanic)	US-born	134	16.6	485	51.1
	Not US-born	160	19.8		
	Nativity unknown	8	1.0		
Black (non-Hispanic)	US-born	184	22.8	465	48.9
	Not US-born	20	2.5		
	Nativity unknown	1	0.1		
Latino/Hispanic	US-born	50	6.2		
	Not US-born	124	15.4		
	Nativity unknown	21	2.6		
Additional race/ethnicities	US-born	27	3.4		
	Not US-born	47	5.8		
	Nativity unknown	4	0.5		
	(Missing data: *n* and %)	(27)	(3.4)		
Gender: n (%)					
Women		303	37.5	626	65.9
Men		489	60.6	324	34.1
	(Missing: *n* and %)	(15)	(1.9)	(0)	(0)
Sexuality: n (%)					
Heterosexual		642	80.0	845	89.0
Lesbian/gay/bisexual/transgender		49	6.1	105	11.0
Other		68	8.4	0	0
	(Missing: *n* and %)	(48)	(6.0)	(0)	(0)
Economic Characteristics					
Current: Individual					
Occupational class: n (%)					
Working class: non-supervisory employee		453	56.1	300	37.0
Not working class: supervisory employee		206	25.5	141	17.4
Self-employed/freelance		53	6.6	67	8.3
Own or run business		38	4.7	47	5.8
Not in the paid labor force		0	0.0	255	31.5
	(Missing: *n* and %)	(57)	(7.1)	(140)	(14.7)
Educational attainment: n (%)					
<High school (HS)/12 years/General Education Development (GED)		175	21.7	130	13.8
≥HS/GED and < 4 yrs college		480	59.5	609	64.3
≥4 yrs college		78	9.7	207	21.9
	(Missing: *n* and %)	(74)	(9.2)	(4)	(0.4)
CURRENT: HOUSEHOLD					
Annual household income: n (%)					
<$12,000		241	29.9	171	20.0
$12,000–<$36,000		306	37.9	242	28.3
$36,000–<$48,000 (US median household income in 2006[b])		67	8.3	44	5.2
$48,000–<$72,000		53	6.6	206	24.0
$72,000–<$120,000		19	2.4	100	11.7
$120,000–<$144,000		10	1.2	31	3.6
≥$144,000 (3× US median household income in 2006[b])		27	3.4	61	7.1
	(Missing: *n* and %)	(84)	(10.4)	(95)	(10.0)
Poverty level (household): n (%)					
Below poverty (<100% poverty line)		333	41.3	241	28.3
Above poverty: 100 − 199% poverty line		176	21.8	174	20.4
≥200% poverty line		210	26.0	438	51.3
	(Missing: *n* and %)	(88)	(10.9)	(97)	(10.2)
Household economic deprivation (occurred at least 2 times in last year), by type and number of types: n (%)					
Not enough money for food, rent, or mortgage		183	22.7	349	36.8
Had to borrow money for medical expenses		103	12.8	126	13.2
Not enough money to make ends meet		198	24.5	392	41.2
Received public assistance or welfare		95	11.8	349	36.7
Experienced 0 of these 4 types of economic deprivation		481	59.6	386	40.8
Experienced 1–2 of these 4 types of economic deprivation		194	24.0	352	37.1
Experienced 3–4 of these 4 types of economic deprivation		91	11.3	210	22.2
	(Missing: *n* and %)	(41)	(5.1)	(0)	(0)
CURRENT: CENSUS TRACT (2006–2010[c])					
Census tract poverty level: n (%)					
≥20% below poverty (poverty area)		414	51.3	426	44.8
10–19% below poverty		192	23.8	257	27.0
5–9% below poverty		140	17.4	163	17.2
<5% below poverty		61	7.6	104	11.0
	(Missing: *n* and %)	(0)	(0)	(0)	(0)

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Table 1 (*continued*)

Characteristic	United for Health (UFH) ($n = 807$)		My Body, My Story (MBMS) ($n = 950$)	
	N	Value[a]	*N*	Value[a]
CHILDHOOD: HOUSEHOLD				
Highest educational attainment of mother, father, or guardian: n (%)				
<High school (HS)/12 years/General Education Development (GED)	228	28.3	166	19.9
≥ HS/GED and < 4 yrs college	296	36.7	454	54.4
≥ 4 yrs college	77	9.5	215	25.9
(Missing: *n* and %)	(206)	(25.5)	(115)	(12.1)
EXPOSURE TO BLACK CARBON (prior to exam)				
1-year cumulative average exposure (μg/m^{-3}): mean (SD)	0.68	0.17	0.64	0.14
24-h average exposure (μg/m^{-3}): mean (SD)	0.64	0.36	0.63	0.35
Day prior to exam	0.64	0.39	0.67	0.34
4 weeks prior to exam	0.60	0.23	0.63	0.18
8 weeks prior to exam	0.60	0.22	0.63	0.17
12 weeks prior to exam	0.61	0.22	0.63	0.16
(Missing: *n* and %)	(0)	(0)	(0)	(0)

[a] Observed percent based on participants with no missing values (percent missing separately reported).
[b] Note: 2006 is the mid-point of the years encompassed by UFH and MBMS; source of US household median income data (in current dollars): US Census Bureau, Current Population Survey (available at: http://www.census.gov/hhes/www/income/data/historical/household/; accessed: November 29, 2013).
[c] Source: US Census Bureau, American Community Survey (available at: https://www.census.gov/acs/www/; accessed: November 29, 2013).

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 second was the *My Body, My Story* (MBMS) study (2008–2010), comprised of a random sample of 1005 black and white non-Hispanic US-born members, age 35–64, from four Boston community health centers; the study response rate was 82% (Krieger et al., 2011). The proportion of participants geocoded to latitude–longitude based on residential street address was, respectively, 93% for UFH and 95% for MBMS. In both studies, race/ethnicity – conceptualized as a social construct arising from inequitable race relations that shape living and working conditions and hence population health (Winant, 2000; Krieger, 2012) – was measured based on self-report using pre-specified categories employed in the US census (US Census Bureau, 2013).

2.2. Socioeconomic measures

We conceptualized socioeconomic position as an inherently multidimensional construct, whose manifest dimensions (e.g., educational attainment, occupational class, and income) can each be measured at different levels (e.g., individual, household, neighborhood) and at different points in time (e.g., childhood, adulthood) (Krieger et al., 1997; Lynch and Kaplan, 2000; Shaw et al., 2007). Logically and materially consequent to social class, these manifest socioeconomic variables arise from interdependent economic relationships determined by a society's forms of property, ownership, and labor, as well as their connections through production, distribution, and consumption of goods, services, and information (Krieger et al., 1997; Shaw et al., 2007; Grusky and Szelenyi, 2011). Table 1 details the validated self-report and census tract socioeconomic measures employed (Krieger et al., 1997, 2005, 2006, 2011; US Census Bureau, 2013).

2.3. Exposure to black carbon

We obtained the black carbon exposure from a new Boston-based spatiotemporal data set that enables precise estimation, to latitude and longitude, of time-specific ambient exposure to traffic-related air pollution, reflected by black carbon concentrations in $PM_{2.5}$ (Gryparis et al., 2007). Using this model, 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 exam; we also estimated the corresponding 24-h average exposure for the day prior to the exam and also for the 4, 8, and 12 weeks prior to the exam.

Informing the black carbon model are data collected over the period of 1999–2008, involving over 8700 daily observations obtained from 134 sites, most of which monitored black carbon continuously using aethalometers; some sites collected particles on a filter over 24 h and measured elemental carbon using reflectance analysis (Gryparis et al., 2007). 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) (Alexeeff et al., 2011), and separate models were fit for warm and cold seasons. Exposure levels are predicted using semi-parametric models that included regression splines which allow for non-linear main effects, and thin-plate splines which measure the residual spatial variability not explained by the spatial predictors. Using this model, predicted daily concentrations showed over a 3-fold variation in exposure levels across measurement sites (adjusted $R^2 = 0.83$), and 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).

2.4. Analytic methods

We restricted the analytic data set to the 1757 participants (UFH: 807; MBMS: 905) with records geocoded to latitude–longitude who resided in the air monitor catchment area (Gryparis et al., 2007). We first analyzed the distribution of the included participants' sociodemographic and economic characteristics and their black carbon exposure, overall and in relation to these social characteristics. We then conducted multivariable linear regression to quantify the association between individual, household, and census tract socioeconomic measures and annual average black carbon exposure, controlling for relevant covariates.

3. Results and discussion

The 1757 UFH and MBMS participants included in this investigation (Table 1) were, as per the total study populations (Krieger et al., 2006, 2011), predominantly working class adults who, like their parents, typically had less than a college education. Overall, 46% and 28% of the UFH and MBMS participants, respectively, lived in households below the poverty line, and ~40% of participants lived in high poverty census tracts (≥20% below poverty) and ~12% lived in low poverty census tracts (<5% below poverty); the risk of living in a poor household or census tract was 1.4–2.2 times higher among black and Latino compared to white participants. The mean 1-year cumulative average black carbon exposure (μg/m^{-3}) at residential latitude–longitude equaled 0.68 (standard deviation (SD): 0.17) among the UFH participants and equaled 0.64 (SD 0.14) among the MBMS participants (mean difference: 0.04; 95% confidence interval (CI) 0.03, 0.05); results were similar for cumulative exposure 4, 8, and 12 weeks prior to the exam, as was the mean exposure for 24-h prior to the exam (albeit with a greater standard deviation).

In bivariate analyses (Table 2), within each racial/ethnic group the annual average black carbon exposure at residential latitude–longitude was consistently associated with age (inversely) and census tract poverty (positively). Only among the white participants, however, was this black carbon exposure associated with education (inverse, for both the participants' and that of their parents/guardian), annual household income (inverse), and household poverty (positive); no associations existed among any racial/ethnic group for occupational class or self-reported household economic deprivation (Table 2). Inconsistent associations with black carbon exposure also existed for gender (white: higher among women compared to men; black: higher among men

Table 2
Average annual black carbon exposure by sociodemographic and economic characteristics among white (non-Hispanic), black (non-Hispanic), and Latino study participants residing in catchment area for monitoring black carbon exposure and geocoded to latitude–longitude: *United for Health* (Greater Boston Area, 2003–2004) and *My Body, My Story* (Boston, 2008–2010).

Variable	Annual average black carbon exposure (μg/m^{-3})																	
	White (N = 670: MBMS = 465, UFH = 205)						Black (N = 787: MBMS = 485, UFH = 302)						Latino (N = 195: MBMS = 0, UFH = 195)					
	N	Mean (SD)	Median	IQR	Min	Max	*N*	Mean (SD)	Median	IQR	Min	Max	*N*	Mean (SD)	Median	IQR	Min	Max
Sociodemographic characteristics																		
Age (years)																		
25–44 yrs	242	0.69 (0.16)	0.68	0.21	0.2	1.24	300	0.66 (0.15)	0.65	0.16	0.29	1.61	129	0.71 (0.15)	0.71	0.19	0.29	1.14
45–54 yrs	258	0.65 (0.19)	0.64	0.22	0.13	1.45	309	0.64 (0.14)	0.62	0.16	0.23	1.21	52	0.67 (0.14)	0.68	0.19	0.47	0.96
55–65 yrs	168	0.64 (0.16)	0.62	0.19	0.19	1.15	176	0.63 (0.11)	0.62	0.13	0.37	1.04	14	0.58 (0.15)	0.58	0.29	0.37	0.85
F test (exact *p*-value)						**0.008**						**0.010**						**0.007**
Nativity																		
US-born	649	0.66 (0.17)	0.65	0.21	0.13	1.45	619	0.66 (0.13)	0.64	0.13	0.23	1.61	50	0.70 (0.14)	0.71	0.16	0.29	0.96
Not US-born	20	0.66 (0.16)	0.66	0.27	0.37	0.94	160	0.60 (0.16)	0.54	0.22	0.30	1.12	124	0.69 (0.16)	0.70	0.24	0.37	1.14
F test (exact *p*-value)						0.952						**<0.0001**						0.879
Gender																		
Women	302	0.68 (0.18)	0.68	0.23	0.13	1.45	335	0.63 (0.14)	0.63	0.18	0.23	1.12	112	0.70 (0.16)	0.70	0.23	0.35	1.14
Men	367	0.64 (0.16)	0.63	0.20	0.17	1.24	443	0.66 (0.14)	0.64	0.14	0.29	1.61	80	0.68 (0.14)	0.68	0.19	0.29	0.96
F test (exact *p*-value)						**0.017**						**0.001**						0.346
Sexuality																		
Heterosexual	572	0.66 (0.17)	0.65	0.21	0.13	1.45	702	0.65 (0.14)	0.63	0.15	0.23	1.61	135	0.70 (0.14)	0.71	0.19	0.35	1.12
Lesbian/gay/bisexual/transgender	84	0.64 (0.16)	0.62	0.19	0.29	1.06	45	0.67 (0.10)	0.66	0.14	0.43	0.89	18	0.67 (0.20)	0.64	0.25	0.38	1.14
Other	9	0.77 (0.19)	0.74	0.11	0.53	1.23	22	0.65 (0.18)	0.60	0.26	0.30	0.96	23	0.65 (0.16)	0.70	0.27	0.29	0.92
F test (exact *p*-value)						**0.119**						0.594						0.323
Economic characteristics																		
CURRENT: INDIVIDUAL																		
Occupational class																		
Working class: non-supervisory employee	262	0.67 (0.18)	0.66	0.24	0.13	1.45	343	0.64 (0.14)	0.62	0.17	0.29	1.22	91	0.70 (0.15)	0.70	0.23	0.37	1.14
Not working class: supervisory employee	131	0.68 (0.18)	0.67	0.22	0.30	1.28	147	0.66 (0.16)	0.64	0.16	0.36	1.61	37	0.71 (0.15)	0.71	0.21	0.39	1.12
Self-employed/freelance	52	0.64 (0.13)	0.63	0.15	0.34	1.01	39	0.64 (0.11)	0.65	0.15	0.47	1.04	22	0.64 (0.17)	0.67	0.22	0.29	0.94
Own or run business	40	0.65 (0.16)	0.64	0.18	0.19	1.01	29	0.64 (0.18)	0.64	0.16	0.23	1.22	12	0.68 (0.13)	0.70	0.19	0.49	0.96
Not in the paid labor force	125	0.65 (0.18)	0.63	0.21	0.19	1.24	130	0.66 (0.12)	0.65	0.13	0.34	1.21	0	–	–	–	–	–
F test (exact *p*-value)						0.620						0.391						0.349
Educational attainment																		
<High school (HS)/12 years/GED	85	0.67 (0.22)	0.63	0.26	0.19	1.45	136	0.65 (0.14)	0.64	0.15	0.34	1.22	67	0.70 (0.16)	0.70	0.22	0.35	1.14
≥HS/GED and < 4 yrs college	409	0.67 (0.17)	0.67	0.20	0.19	1.22	536	0.65 (0.14)	0.63	0.15	0.23	1.61	80	0.69 (0.14)	0.71	0.21	0.29	0.96
≥4 yrs college	167	0.63 (0.15)	0.61	0.17	0.13	1.28	95	0.65 (0.12)	0.64	0.15	0.39	0.99	12	0.61 (0.13)	0.61	0.19	0.40	0.83
F test (exact *p*-value)						**0.007**						0.801						0.139
CURRENT: HOUSEHOLD																		
Annual household income																		
<\$12,000	117	0.69 (0.17)	0.69	0.20	0.23	1.24	200	0.67 (0.14)	0.66	0.16	0.29	1.21	67	0.70 (0.17)	0.72	0.23	0.37	1.14
\$12,000–<\$36,000	201	0.67 (0.17)	0.65	0.21	0.31	1.45	231	0.64 (0.14)	0.63	0.17	0.34	1.12	79	0.69 (0.14)	0.70	0.21	0.35	0.99
\$36,000–<\$48,000	45	0.71 (0.16)	0.73	0.24	0.45	1.21	50	0.63 (0.19)	0.60	0.17	0.36	1.61	7	0.70 (0.22)	0.73	0.29	0.29	0.95
\$48,000–<\$72,000	127	0.63 (0.19)	0.62	0.21	0.13	1.28	120	0.64 (0.12)	0.63	0.12	0.23	1.22	4	0.58 (0.06)	0.55	0.06	0.54	0.66
\$72,000–<\$120,000	77	0.63 (0.12)	0.62	0.17	0.34	0.96	41	0.64 (0.12)	0.62	0.15	0.38	0.94	1	0.81 (–)	0.81	0	0.81	0.81
\$120,000–<\$144,000	27	0.64 (0.16)	0.61	0.17	0.40	1.12	13	0.68 (0.15)	0.63	0.25	0.49	0.95	0	–	–	–	–	–
≥\$144,000	35	0.63 (0.18)	0.62	0.29	0.19	1.07	43	0.63 (0.11)	0.61	0.14	0.37	0.91	4	0.65 (0.08)	0.67	0.09	0.53	0.71
F test (exact *p*-value)						**0.024**						0.190						0.648
Poverty level (household)																		
<100% poverty	152	0.68 (0.17)	0.69	0.19	0.23	1.24	287	0.66 (0.14)	0.65	0.16	0.29	1.21	98	0.69 (0.16)	0.69	0.21	0.35	1.14
100–199% poverty	139	0.67 (0.19)	0.65	0.23	0.19	1.45	149	0.64 (0.16)	0.62	0.15	0.35	1.61	41	0.71 (0.15)	0.72	0.16	0.40	0.99
≥200% poverty	336	0.64 (0.17)	0.63	0.20	0.13	1.23	260	0.63 (0.13)	0.63	0.14	0.23	1.22	22	0.63 (0.13)	0.66	0.17	0.29	0.85
F test (exact *p*-value)						**0.034**						0.074						0.191
Household economic deprivation score																		
0 types of economic deprivation	368	0.66 (0.18)	0.65	0.21	0.13	1.45	347	0.64 (0.15)	0.62	0.17	0.34	1.61	89	0.69 (0.16)	0.71	0.24	0.29	1.01

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Table 2 (*continued*)

Variable	Annual average black carbon exposure (μg/m^{-3})																	
	White (N = 670: MBMS = 465, UFH = 205)						Black (N = 787: MBMS = 485, UFH = 302)						Latino (N = 195: MBMS = 0, UFH = 195)					
	N	Mean (SD)	Median	IQR	Min	Max	N	Mean (SD)	Median	IQR	Min	Max	N	Mean (SD)	Median	IQR	Min	Max
1–2 types	181	0.65 (0.15)	0.65	0.18	0.17	1.15	291	0.65 (0.13)	0.64	0.14	0.23	1.22	52	0.70 (0.15)	0.72	0.18	0.35	1.12
3–4 types	117	0.66 (0.18)	0.63	0.26	0.29	1.24	137	0.67 (0.12)	0.66	0.13	0.39	1.00	32	0.69 (0.16)	0.68	0.18	0.47	1.14
F test (exact p-value)						0.741						0.103						0.974
CURRENT: CENSUS TRACT																		
Census tract poverty level (2006–2010)																		
≥20% below poverty (poverty area)	221	0.73 (0.15)	0.73	0.17	0.29	1.45	466	0.67 (0.13)	0.66	0.15	0.43	1.21	90	0.74 (0.12)	0.74	0.14	0.44	1.01
10–19% below poverty	191	0.67 (0.16)	0.63	0.22	0.34	1.23	196	0.64 (0.15)	0.61	0.13	0.29	1.61	45	0.72 (0.17)	0.72	0.15	0.29	1.14
5–9% below poverty	153	0.61 (0.15)	0.60	0.20	0.19	0.95	89	0.57 (0.13)	0.55	0.16	0.30	0.98	44	0.60 (0.13)	0.57	0.15	0.37	0.96
<5% below poverty	105	0.56 (0.19)	0.55	0.21	0.13	1.28	36	0.52 (0.17)	0.52	0.18	0.23	1.22	16	0.56 (0.10)	0.55	0.16	0.38	0.70
F test (exact p-value)						**<0.0001**						**<0.0001**						**<0.0001**
CHILDHOOD: HOUSEHOLD																		
Highest level of education for mother, father, or guardian																		
<High school (HS)/12 years/GED	91	0.68 (0.18)	0.67	0.23	0.33	1.24	208	0.65 (0.14)	0.64	0.18	0.34	1.22	76	0.68 (0.15)	0.70	0.23	0.29	1.14
≥HS/GED and < 4 yrs college	338	0.66 (0.17)	0.66	0.22	0.19	1.45	339	0.65 (0.14)	0.63	0.14	0.23	1.61	33	0.67 (0.16)	0.66	0.24	0.37	0.96
≥4 yrs college	183	0.62 (0.15)	0.60	0.18	0.13	1.06	92	0.63 (0.12)	0.62	0.12	0.41	1.21	7	0.62 (0.13)	0.66	0.20	0.44	0.78
F test (exact p-value)						**0.010**						0.687						0.534

compared to women) and nativity (black only: higher among US-compared to foreign-born); no differences existed comparing heterosexual versus lesbian/gay/bisexual/transgender participants in any racial/ethnic group.

Fig. 1 illustrates the interplay between census tract poverty, race/ethnicity, and black carbon exposure, whereby symbols indicating level of exposure to black carbon by race/ethnicity are superimposed on a dot density depiction of census tract poverty. As shown by this map, among participants in the top two quintiles of exposure, the white compared to the black and Latino participants lived in different neighborhoods comprised of less impoverished census tracts.

All 3 models for the multivariable regression analyses (Table 3) controlled for age, study, and date of exam. In Model 1, race/ethnicity was not associated with annual black carbon exposure, but significant associations (95% CI excluded 0) occurred for age (inverse), study (higher in MBMS compared to UFH), and exam date (lower exposure with more recent date); together, these variables explained little of the observed variance ($R^2 = 0.0474$). In Model 2, which included socioeconomic but not racial/ethnic data, the R^2 increased to 0.1638, but black carbon exposure was associated only census tract poverty (beta = 0.373; 95% confidence interval (CI) 0.322, 0.443) and not annual household income (beta = −0.002; 95% CI −0.006, 0.002). Finally, in Model 3, which included all variables (R^2 = 0.1699), the association for census tract poverty remained unchanged (beta = 0.385; 95% CI 0.335, 0.436) and the associations for race/ethnicity became significant, whereby compared to the white participants, exposures were lower among black participants (beta = −0.024; 95% CI −0.041, −0.007) and Latino participants (beta = −0.034; 95% CI −0.061, −0.0006).

Consequently, our study offers several important contributions to the small literature (n = 4 studies) documenting that exposure to air pollution is more strongly associated with area-based versus household- or individual-level socioeconomic measures. Thus, ours is the first investigation to focus on black carbon and to diversify the range of study participants by investigating associations among US working class black, Latino, and white adults age 25–64 residing in a major US city (Boston, MA; 2003–2004 and 2008–2010). This is because the prior four investigations focused on: (1) NO_2 exposure (in 2001) among children (age 7–15) in Malmö in 2001 (Chaix et al., 2006); (2) NO_x exposure (in 2003) among London civil servants (age 50–74; Whitehall 2 cohort) examined in 2002–2004 (Goodman et al., 2011); (3) 2005 data on traffic indicators and a 2001 random sample (age <1–≥75) of the population of Rome (Cesaroni et al., 2010); and (4) NO_2 and $PM_{2.5}$ data (in 2000) among a population-based sample of adults age 45 to 84 recruited in 2000–2002 from 5 US cities and 1 county (Baltimore, MD, Chicago, IL; Forsyth County, NC; Los Angeles, CA; New York, NY; and St. Paul, MN) (Hajat et al., 2013). Our additional novel finding was that controlling for socioeconomic position revealed a lower on-average exposure among the black and Latino compared to white participants, which, as suggested by Fig. 1, was likely due to the highly exposed white participants residing in several non-impoverished census tracts, in which none of the black and Latino participants lived.

Strengths of the study include its use of validated measures of socioeconomic position employed in two population-based studies with high response rates whose participants' residential addresses were geocoded to latitude–longitude (Krieger et al., 2006, 2011) and also validated model-based spatiotemporal estimates, for latitude–longitude, of ambient black carbon exposure (Gryparis et al., 2007). Limitations include the restricted socioeconomic composition and geographic location of the study populations (Krieger et al., 2008, 2013). Even so, similar results pertaining to the stronger association between air pollution and area-based

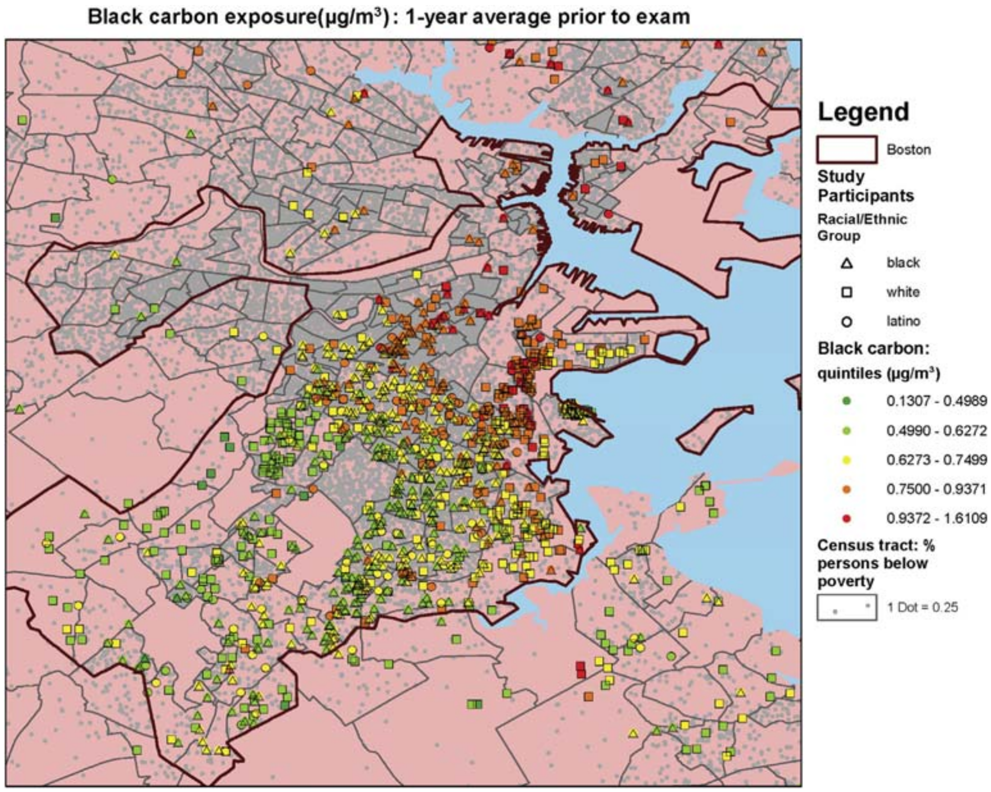

Fig. 1. Average annual black carbon exposure (μg/m^{-3}) by quintile for black, Latino, and white study participants (*United for Health*, 2003-2004; *My Body, My Story*, 2008–2010), and average annual census tract poverty level (2006–2010), Boston, MA air monitoring catchment area.

Table 3
Regression of annual black carbon exposure (μg/m^{-3}) against economic variables and covariates among white (non-Hispanic), black (non-Hispanic), and Latino study participants residing in catchment area for monitoring black carbon exposure and geocoded to latitude–longitude: *United for Health* (Greater Boston Area, 2003–2004) and *My Body, My Story* (Boston, 2008–2010).

Variable	Outcome: annual average black carbon exposure (μg/m^{-3})					
	Model 1		Model 2		Model 3	
	beta	(95% CI)	beta	(95% CI)	beta	(95% CI)
Age (year; continuous)	−0.00211	(−0.00297, −0.00124)	**−0.00173**	**(−0.00253, −0.0009)**	**−0.00191**	**(−0.00271, −0.00110)**
Race/ethnicity						
Black	0.00132	(−0.01677, 0.01940)			**−0.02380**	**(−0.04102, −0.00658)**
Latino	−0.01792	(−0.04683, 0.01100)			**−0.03373**	**(−0.06096, −0.00651)**
Other	−0.02117	(−0.06120, 0.01886)			−0.03742	(−0.07486, 0.00003)
White (referent)	0.0				0.0	
Census tract poverty (continuous)			**0.37251**	**(0.32241, 0.42261)**	**0.38540**	**(0.33466, 0.43615)**
Household income (annual)[a]			−0.00201	(−0.00634, 0.00231)	−0.00271	(−0.00705, 0.00164)
Study						
MBMS	**0.17899**	**(0.08686, 0.27111)**	**0.26845**	**(0.19076, 0.34614)**	**0.22823**	**(0.14191, 0.31455)**
UFH (referent)	0.0		0.0		0.0	
Exam date (continuous)	**−0.00010**	**(−0.000140, −0.0000551)**	**−0.00014**	**(−0.00017, −0.000101)**	**−0.000121**	**(−0.000160, −0.000082)**
R-square	0.0474		0.1638		0.1699	

Note: parameter estimates in bold have 95% CI that exclude 0.
[a] **Household income categories:** 1 = <\$12,000; 2 = \$12,000 to < \$36,000; 3 = \$36,000–<\$48,000; 4 = \$48,000–<\$72,000; 5 = \$72,000–<\$120,000; 6 = \$120,000–<\$144,000; 7 = ≥\$144,000.

compared to individual- and household-level socioeconomic measures were obtained in the one analogous US study, whose population-based sample included a higher proportion of affluent and college-educated participants (Hajat et al., 2013) compared to the UFH and MBMS participants.

In conclusion, our brief report underscores the salience of residential location, and not just individual- and household-level characteristics, for analyzing the socioeconomic patterning of exposure to air pollution and their contribution to health inequities. An additional implication is that, at least in the US context, attention to not only racial/ethnic residential segregation (Lopez, 2002; Morello-Frosch, 2002; Payne-Sturges et al., 2006; Brulle and Pellow, 2006) but also its complex interplay with residential economic segregation requires further analysis as co-determinants of exposure to air pollution.

Conflict of interest

None of the authors have any conflicts of interest to declare.

Author contributions

NK and BC designed the study and its analyses, which were implemented by PDW, using black carbon data provided by AG; NK drafted the manuscript, BC, PDW, and AG contributed to the manuscript, and all 4 authors reviewed and approved the final version prior to submission.

IRB

This study was approved as exempt [B4] by the Harvard School of Public Health Institutional Review Board (IRB) as Protocol #23169-101, effective November 5, 2012.

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