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Neighborhood Deprivation is Associated with Increased Risk of Prenatal Smoke Exposure

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Abstract

Despite years of advisories against the behavior, smoking among pregnant women remains a persistent public health issue in the USA. Recent estimates suggest that 9.4% of women smoke before pregnancy and 7.1% during pregnancy in the USA. Epidemiological research has attempted to pinpoint individual-level and neighborhood-level factors for smoking during pregnancy, including educational attainment, employment status, housing conditions, poverty, and racial demographics. However, most of these studies have relied upon self-reported measures of smoking, which are subject to reporting bias. To more accurately and objectively assess smoke exposure in mothers during pregnancy, we used Bayesian index models to estimate a neighborhood deprivation index (NDI) for block groups in Durham County, North Carolina, and its association with cotinine, a marker of smoke exposure, in pregnant mothers ($n = 887$ enrolled 2005–2011). Results showed a significant positive association between NDI and log cotinine (beta = 0.20, 95% credible interval = [0.11, 0.29]) after adjusting for individual covariates (e.g., race/ethnicity and education). The two most important variables in the NDI according to the estimated index weights were percent females without a high school degree and percent Black population. At the individual level, Hispanic and other race/ethnicity were associated with lowered cotinine compared with non-Hispanic Whites. Higher education levels were also associated with lowered cotinine. In summary, our findings provide stronger evidence that the socio-geographic variables of educational attainment and neighborhood racial composition are important factors for smoking and secondhand smoke exposure during pregnancy and can be used to target intervention efforts.

Keywords Smoke exposure · Neighborhood · Socioeconomic status · Bayesian analysis

Introduction

Maternal smoking and secondhand smoke exposure during pregnancy are of high public health concern in the USA and worldwide (Kondracki, 2019) and it is recommended that women should not be exposed to any tobacco smoke during their pregnancy. Sources of smoke exposure during pregnancy include both maternal smoking and secondhand exposure from a partner or community member. Following declining trends in smoking in the population, primary

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smoking during pregnancy has also decreased. Recent data from the national, longitudinal Population Assessment of Tobacco and Health (PATH) Study (2013–2015) found that although only 6.1% reported smoking during pregnancy, 23% of pregnant women reported exposure to secondhand smoke (Do et al., 2018). A growing body of research has reported significant associations between prenatal smoking exposure and a variety of adverse health outcomes for the mother during her pregnancy and her child, including low birthweight, pre-term birth, and infant death (Kyrklund-Blomberg et al., 2005; Schechter et al., 2020; Xu et al., 2020). Evidence also suggests that maternal smoking and secondhand smoke exposure during pregnancy may alter differentially-methylated regions in offspring DNA associated with orofacial clefts, asthma, neuronal signaling, and cancer pathways (Fuemmeler et al., 2020; Joubert et al., 2016). Given the breadth and severity of these health outcomes for children, there is great public health value in studying and better understanding the factors that drive smoke exposure in pregnant mothers.

A number of studies have attempted to pinpoint individual-level predictors of prenatal smoke exposure (Adams et al., 2012; Bailey, 2006; Colman & Joyce, 2003; Crume, 2019; Do et al., 2018; Kaneita et al., 2007; LeClere & Wilson, 1997; Tong et al., 2016). Among pregnant women, higher levels of stress, an increased number of stressors, and having depression are strongly associated with smoking during pregnancy (Tong et al., 2016). As such, some pregnant women choose to continue smoking during pregnancy in order to alleviate their stress and depressive symptoms. Other studies have shown that lower levels of prenatal care, higher levels of tobacco addiction, having a partner who smokes, and lower socioeconomic status (SES) are also associated with smoking during pregnancy (Bailey, 2006; Colman & Joyce, 2003; Crume, 2019; Kaneita et al., 2007; LeClere & Wilson, 1997). Similarly, one study (Do et al., 2018) found that mothers who were at higher risk for smoking during pregnancy were more likely to have self-reported fair or poor mental health status. Moreover, mothers at higher risk for secondhand smoke exposure were more likely to be younger and earlier in their pregnancy. Mothers at a higher risk for any smoke exposure were more likely to be unmarried and to allow others' use of combustible tobacco products in their home (Do et al., 2018). Some of these factors, such as age and marital status, are fixed, but others could potentially be modified by behavioral and clinical interventions aimed at reducing stressors, improving mental health, or shifting maternal opinion of tobacco use and acceptance of smoke exposure in the home environment (Adams et al., 2012).

While there are numerous individual-level factors that may increase prenatal smoke exposure, researchers must consider the larger context in order to better understand these smoking behaviors and exposure. An ecological systems approach (Bronfenbrenner, 1992) suggests that the smoke exposure and smoking behaviors of pregnant women are related to their environment, and a growing body of research provides evidence that ecological factors are associated with smoke exposure (Shoff & Yang, 2013; Zawadzka et al., 2018). In a study conducted in Poland, Zawadzka and colleagues (Zawadzka et al., 2018) found that smoking behaviors of pregnant women differed depending on their urban or rural residence status. A study in the USA found that in rural counties, a higher area-level social capital index (e.g., greater number of civil associations, non-profit organizations) was associated with significantly lower odds that a woman smoked during her pregnancy (Shoff & Yang, 2013). A recent systematic review of qualitative studies examining barriers to cessation during pregnancy identified a number of important contextual factors, including secondhand smoke exposure from friends and family (Ingall & Cropley, 2010). On a more local and immediate ecological context, neighborhood-level factors are well known to be associated with many health outcomes (Galiatsatos et al., 2020; Grant et al., 2018; Wheeler et al., 2017, 2019a, b). For instance, one study conducted in an urban area in the USA found an association between neighborhood SES, tobacco store density, and smoking during pregnancy (Galiatsatos et al., 2020). Specifically, higher tobacco store density and higher levels of neighborhood disadvantage (e.g., neighborhood median income, percentage living in poverty, percentage of uninsured) were associated with higher rates of smoking during pregnancy. Similarly, outside of the USA, a study of singleton births in Finland found that lower neighborhood SES, measured by less educational attainment among residents within the geographic area, was positively associated with mothers' smoking during pregnancy after controlling for individual-level socio-economic status, age, and year of birth (Räisänen et al., 2014).

In the USA, historical and present-day residential segregation has shifted access to neighborhood and community resources such that a greater percentage of minority individuals are living in more disadvantaged neighborhoods. Neighborhood disadvantage and racial segregation may be related to levels of prenatal smoke exposure due to factors that create a culture of acceptance of tobacco use or a lack of services to support cessation within these communities. An analysis of live births in the USA in 2008 found that for black women living in a county where blacks were more segregated from whites, there was a higher probability of maternal smoking during pregnancy (Yang et al., 2014). However, living in less segregated areas with more whites was positively associated with the probability of smoking during pregnancy for both Asian and Hispanic mothers.

Furthermore, one particular study utilized 5-year census tract data in Missouri to investigate neighborhood-level influences on smoking during pregnancy (Houston-Ludlam et al., 2020) which highlighted differing risk profiles for racial/ethnic minority mothers. A particularly notable finding from this study were that Black mothers were more likely to smoke during pregnancy in rural areas with an increased percentage of white neighbors or residents, regardless of level of economic disadvantage. Though not assessed in the study, this suggests that Black mothers who smoke during pregnancy may experience more discrimination in areas with higher populations of White residents. In addition, a retrospective analysis study of female twins born in Missouri utilized a neighborhood deprivation index (NDI), which encompassed area-level variables related to educational attainment, employment status, housing conditions, poverty, racial demographics, and residential stability. In that study, mothers who lived in the most highly-deprived census tracts reported a significantly higher odds of smoking during pregnancy compared to mothers that lived in the least-deprived ones, but the association was not significant after adjusting for individual-level covariates (Lian et al., 2016). As such, further research is warranted that specifically investigates neighborhood-level factors in order to more conclusively determine to what extent neighborhood deprivation and what specific factors associated with neighborhood deprivation relate to prenatal smoke exposure.

To better examine these multiple neighborhood-level factors, a more nuanced and robust methodology is needed. First, while self-report has been used frequently to assess smoking behaviors and secondhand smoke exposure in pregnant women, more objective measures such as cotinine (a metabolite of nicotine) could reduce bias in self-report, which is particularly problematic for secondhand smoke exposure. Second, the estimation of neighborhood deprivation can be improved. In the previously mentioned study conducted by Lian and colleagues (Lian et al., 2016), the NDI was calculated using principal components analysis (PCA). Methods such as PCA and factor analysis do not consider the association with the outcome variable when calculating the NDI, which leads to sub-optimal model goodness-of-fit and reduced power in finding significant associations with neighborhood factors (Wheeler et al., 2019a, b). In addition, the NDI constructed from principal components is less interpretable than the original socio-demographic variables that go into the components and makes understanding the association with neighborhood factors difficult. In order to address these issues, the current study estimated the NDI using a Bayesian index model that considered the relationship with prenatal smoke exposure as measured by cotinine, while at simultaneously estimating the components of the index of most importance to smoke exposure.

The evidence to date suggests that the socio-geographic variables of social capital and connectedness, educational attainment, and neighborhood racial composition are important factors for smoking and secondhand smoke exposure during pregnancy. As such, this study investigated the impact of these socio-geographic variables above and beyond individual-level covariates. In this study, we used Bayesian index models (Wheeler et al., 2019a, b, 2020, 2021) to estimate an NDI for block groups in Durham County, North Carolina, and assess its association with cotinine levels in pregnant mothers after controlling for individual-level covariates (e.g., race/ethnicity, education, marital status). The Bayesian index model estimates an NDI as a weighted sum of socio-demographic variables, where the weights are estimated empirically and allow for differentiation in the importance of the variables. An advantage of Bayesian index models over PCA and factor analysis is that it estimates the NDI and its health effect simultaneously while adjusting for covariates, i.e., is a one-step instead of a two-step process. In addition, it creates a more interpretable index that is directly linked to the original socio-demographic variables, which helps identify components for intervention. Using this approach in conjunction with cotinine levels, we were able to more accurately and objectively assess smoke exposure in mothers and quantify the effect of neighborhood deprivation for smoking during pregnancy. We hypothesized there to be a positive association between the neighborhood deprivation index and cotinine after adjusting for individual-level covariates.

Materials and Methods

Study Sample

The *Newborn Epigenetics STudy (NEST)* is a prospective cohort study initiated to elucidate how maternal behavior (e.g., smoking, nutrition) and exposures (e.g., toxins) that influence the in-utero environment subsequently influence the epigenome, birth weight, and early childhood growth (Hoyo et al., 2011; Liu et al., 2012). Assembled between 2005 and 2011, 2595 women were consented and enrolled (71% response rate) at six prenatal clinics affiliated with Duke University health system in Durham County, NC, with the highest patient volume. Research staff identified eligible participants by reviewing clinic appointment logs for each clinic, and eligible participants were invited to participate. Most pregnant women were enrolled during their first prenatal clinic visit when maternal blood specimens and survey data were collected in exam rooms during the visit. If the woman was unable to complete the survey during the clinic visit, it was completed by mail or at the next clinical visit. Cotinine samples were obtained an average of

16.04 weeks (SD = 10.21) into the gestational period. Compensation for participation was provided. Inclusion criteria were age > 18 years, English or Spanish speaking, willing to provide a blood sample and intention to use a Duke-affiliated hospital for obstetric care, thus enabling collection of biospecimens. Exclusion criteria included women intending to move before the first birthday of the offspring, relinquish custody of the index child, or who had confirmed human immunodeficiency virus (HIV) infection among the first third of the cohort only. Of those consented and enrolled, cotinine levels were measured in two waves with criteria for the first wave that included those with singleton births, were English speaking, had available prenatal blood samples, and had consented to future research. As part of a second wave, eligibility criteria were expanded to include all women residing in Durham County at the time of enrollment with available prenatal blood samples who had declined further follow up as part of the parent NEST study. For this study, we include in our analyses women with available prenatal cotinine blood measures, covariate data, and residing in Durham County at the time of enrollment in NEST ($n = 887$). The 887 mothers included in this study were younger (mean age 27.19, SD = 5.80) than those not included from NEST (those without cotinine assays, mean age = 28.63, SD = 5.95), $t(2398) = -3.98$, $p < 0.001$. Additionally, the sample significantly differed from those not included from NEST in respect to race/ethnicity ($\chi^2 = 100.16$, $p < 0.001$), education ($\chi^2 = 18.17$, $p < 0.001$), and marital status ($\chi^2 = 37.35$, $p < 0.001$). Broadly, there were proportionately more Black mothers in this sample (56.03% vs 37.30%), more college graduates (32.30% vs 29%), and more never married (30.30% vs 23.30%) compared to the overall cohort.

Measures

Smoke Exposure

Cotinine assays from prenatal maternal plasma samples were performed to determine level of smoke exposure. Cotinine is a metabolite of nicotine that can be detected in a number of biological matrices. With an average half-life of 16–20 h in biological specimens (blood, urine, saliva), cotinine measurements have been shown to be superior to that of self-reported active or passive exposure during pregnancy (Jedrychowski et al., 2009; Pichini et al., 2000) especially in light of underreporting among pregnant women and parents due to social stigma of smoking among this subgroup (Dietz et al., 2011; Florescu et al., 2009). Liquid chromatography-mass spectrometry (LC–MS/MS) was used to measure cotinine levels with a detection limit of 0.05 ng/mL (Bernert et al., 2009; Dempsey et al., 2012; Jacob et al., 2011). The system consists of a ThermoFinnigan TSQ Quantum Ultra triple-stage quadrupole mass spectrometer with atmospheric pressure chemical ionization and electrospray ionization sources, coupled to an Agilent 1200 liquid chromatograph. This method offered high-sensitivity and high-accuracy measurements of cotinine concentrations, allowing us not only to do descriptive comparisons of smokers (with a cotinine level ≥ 3 ng/mL) versus non-smokers (with cotinine level < 3 ng/mL) (Benowitz et al., 2009) but also to use cotinine concentration as a continuous variable to estimate the effect of the neighborhood deprivation index (see "Statistical Analysis" method below).

Socio-demographic Data

We used 5-year (2007–2011) estimates of 16 socio-demographic variables at the census block group level from the American Community Survey (ACS) to construct neighborhood deprivation indices. The ACS is administered annually to three million households, representative of the US population. Participants complete a questionnaire and report their household's social and economic information. We chose this time period to overlap with the cotinine assays for our study subjects. The socio-demographic variables were percent Black population, percent Hispanic population, ratio of income to poverty level, percent households with public assistance income, percent renter occupied housing units, percent vacant housing units, percent females with no high school degree or higher, percent males with no high school degree or higher, rent as a percentage of household income, average household size, percent with Social Security income, percent homes built 1939 or earlier, median rent, median house value, median household income, and median year house built. We have used similar variables to estimate neighborhood deprivation indices previously (Wheeler et al., 2017, 2019a, b, 2020). We chose block groups as the spatial unit to focus on the more immediate neighborhood of subjects, in contrast to the larger census tract.

Individual-level Variables

Close to the time of their enrollment visit, women were administered a questionnaire soliciting information on socio-demographics, health, nutrition, stress, and lifestyle behaviors. As individual covariates, we used age at enrollment, race/ethnicity, education, and marital status.

Statistical Analysis

We used Bayesian index regression models to explain the variation in the natural log of cotinine, assuming that log cotinine was $y_i \sim Normal(\mu_i, \tau)$ with mean μ_i and precision τ. The log transformation of cotinine created a normally distributed variable for modeling. We used the following model for the mean of log cotinine: $\mu_i = \beta_0 + \beta_1(\sum_{j=1}^{C} w_j q_{ij}) + \alpha z_i$, where β_0 is the intercept, β_1 is the effect for the neighborhood deprivation

index, and α is a vector of regression coefficients for individual level covariates in the vector z_i that includes the covariates age at enrollment, race (White as reference), education (less than high school as reference), marital status (never married as reference), and household income (less than $10,000 as reference). We specified the neighborhood deprivation index for each block group using a weighted combination $\sum_{j=1}^{C} w_j q_j$ of the deciles $q_1, \ldots, q_c$ of the SES variables $x_1, \ldots, x_c$, where the weights $w_1, \ldots, w_C$ were estimated in the model. The weight w_j represents the relative importance of the j_{th} SES variable in the index. We used deciles of the SES variables to account for different scales of the variables, de-correlate the variables, limit the effect of outliers, and acknowledge uncertainty in the ACS covariates. We used $C = 16$ SES variables in the index. The SES variables were defined to reflect a hypothesized positive association of the index with log cotinine. Four of the SES variables were redefined to have a positive association with log cotinine in univariate analyses. These variables were median household income, median gross rent, median monthly housing costs, and year home was built. We inverted these variables by using the formula $\max(x) - x_j$, where x_j is the value of the variable. In addition to fitting this model for all subjects, we also fitted it to strata defined by cotinine level <3 ($n=670$) and ≥ 3 ($n=217$) to separate passive and active smoke exposure (Benowitz et al., 2009).

The Bayesian model specification was completed with the definition of prior distributions for the priors. The index weights were given a Dirichlet prior with parameters $\alpha = (\alpha_1, \ldots, \alpha_C)$. The Dirichlet prior was used because it assures that the SES variable weights $w_j \in (0, 1)$ and $\sum_{j=1}^{C} w_j = 1$. The intercept followed an improper uniform distribution $\alpha \sim dflat()$, while the index regression coefficient had a vague normal prior $\beta_1 \sim Normal(1, \tau_1)$ with precision $\tau_1 = 1/\sigma_1^2$ and $\sigma_1 \sim Uniform(0, 100)$. Each of the covariate regression coefficients in the α vector received a vague normal prior of $\alpha_k \sim Normal(1, \tau_k)$ with $1/\sigma_1^2$ precision and $\sigma_k \sim Uniform(0, 100)$.

We used Markov chain Monte Carlo (MCMC) to estimate the model parameters with a total of 60,000 iterations from one chain and a thinning parameter of one, where the first 30,000 iterations were used for burn-in. We assessed the convergence of the MCMC algorithm for parameters of interest using the Geweke convergence diagnostic (Geweke, 1991). A parameter was considered to have converged if its diagnostic absolute value was less than 2. The 95% credible interval was used to determine the statistical significance of the deprivation index and covariate effects, with there being a significant effect if the interval did not contain the value of 1. We fit the Bayesian models using WinBUGS 1.4.1 (Lunn et al., 2000) and completed all other analyses in the R computing environment.

Results

The summaries of cotinine levels and key variables are listed in Table 1 for all subjects and stratified by cotinine levels of <3 and ≥ 3 ng/mL, the cutpoints recommended for distinguishing smokers from non-smokers in US samples (Benowitz et al., 2009). The median cotinine level was 0.70 ng/mL. Age, race, education level, and marital status were significantly different between the two cotinine strata (all $p<0.001$). In particular, there are some clear differences in the values of certain variables between the low and high cotinine groups. Mothers in the high cotinine group were generally younger than in the low cotinine group (25 vs 27 years old). The majority (56.0%) of mothers were Black; however, the proportion of Black mothers was substantially higher in the higher cotinine stratum compared with the lower cotinine stratum (71.4% vs 51%). Conversely, the proportion of White mothers was higher in the low cotinine group compared with the high cotinine group (30.6% vs 19.4%). The proportion with a college degree was much higher (40.4%) in the lower cotinine stratum than the higher cotinine stratum (6.5%). Similarly, the proportion with education of less than a high school degree was substantially higher in the high cotinine stratum (33.2%) compared with the low cotinine stratum (12.1%). The low cotinine group had a higher proportion of married women (42.2% vs 14.3%) while the high cotinine group had higher proportions of never married (41.5% vs. 26.7%) and divorced/separated (5.1% vs 2.4%) mothers. The geographic pattern of cotinine levels (with a random jittering) shows that cotinine levels are generally higher in the central urban area within Durham County and lower in the suburban areas in the periphery of the county (Fig. 1).

The regression coefficients and 95% credible intervals from the Bayesian index models show that the neighborhood deprivation index effect was significant in all three models (Table 2). For all subjects, there was a 0.2 increase in log cotinine with a one-unit increase in the NDI. At the individual level, both race/ethnicity and education were significantly related to cotinine levels for all subjects combined and for the high cotinine group. Hispanic and other race/ethnicity were associated with decreased cotinine and higher education levels were associated with decreased cotinine.

The estimated weights for the variables in the NDI (Fig. 2) show that the two most important variables in the index for all subjects were percent females without a high school degree (0.18) and percent Black population (0.11). For the low cotinine and high cotinine groups, percent Black population was the most highly weighted variable with weights of 0.15 and 0.10, respectively. The estimated NDI from the Bayesian index model for all subjects mapped at the block group level (Fig. 3) shows that the NDI is highest in the urban core of Durham and lowest in the suburban peripheral area of Durham County.

Table 1 Characteristics of mothers in the NEST study

	All subjects ($n = 887$)	Cotinine < 3 ng/mL ($n = 670$)	Cotinine ≥ 3 ng/mL ($n = 217$)	*P*-Value[b]
Age (years)	27.19 (5.80)	27.84 (5.90)	25.17 (4.98)	< 0.001*
Cotinine (ng/mL)[a]	0.70 [0.26, 2.90]	0.47 [0.20, 0.92]	27.64 [7.09, 112.49]	< 0.001*
Race				< 0.001*
Black	497 (56.03)	342 (51.05)	155 (71.43)	
Hispanic	94 (10.60)	83 (12.39)	11 (5.07)	
Other	48 (5.41)	39 (5.82)	9 (4.15)	
White	247 (27.85)	205 (30.60)	42 (19.35)	
Missing	1 (0.11)	1 (0.14)	0 (0.00)	
Education Level				< 0.001*
College graduate	285 (32.13)	271 (40.45)	14 (6.45)	
Some college	158 (17.81)	115 (17.16)	43 (19.82)	
High school grad/ GED	186 (20.97)	124 (18.51)	62 (28.57)	
Less than high school	153 (17.25)	81 (12.09)	72 (33.18)	
Missing	105 (11.84)	79 (11.79)	26 (11.98)	
Marital status				< 0.001*
Never married	269 (30.33)	179 (26.72)	90 (41.47)	
Married	314 (35.40)	283 (42.23)	31 (14.29)	
Living with partner	155 (17.47)	102 (15.22)	53 (24.44)	
Divorced/separated	27 (3.04)	16 (2.39)	11 (5.06)	
Other	14 (1.58)	10 (1.49)	4 (1.84)	
Missing	108 (12.18)	80 (11.94)	28 (12.90)	

Continuous variables summarized with mean and standard deviation unless otherwise indicated. Categorical variables summarized with count and percent

[a]Summarized with median and [25th percentile, 75th percentile] due to skewness

[b]Tested with *t*-tests for continuous variables and chi-squared tests for categorical variables

*Represents significance on the 0.05 level

Discussion

In this study, we simultaneously estimated a neighborhood deprivation index and its association with cotinine levels measured in pregnant mothers in Durham County, NC, while considering individual-level factors. We found a significant and positive association between the NDI and cotinine levels while adjusting for the individual factors such as education, race, and marital status. The most important factors at the neighborhood level were percent of females without a high school degree and percent Black population. At the individual level, race/ethnicity and education were significantly associated with cotinine levels. Specifically, Hispanic and other race/ethnicity were associated with decreased cotinine compared with non-Hispanic Whites, and higher education levels were associated with decreased cotinine. Together, these data support that lower educational attainment is associated with greater tobacco smoke exposure, as is Black racial segregation at the block group level.

Our findings add to the existing evidence suggesting that the socio-demographic variables of educational attainment and neighborhood racial composition are important correlates of smoking during pregnancy while more accurately and objectively assessing smoke exposure in mothers during pregnancy. In fact, our evidence of an association between neighborhood deprivation and smoking during pregnancy is stronger than some previous evidence. Lian et al. (Lian et al., 2016) found that the highest quartile compared with the lowest quartile of a neighborhood socioeconomic deprivation index was associated with an increased ($OR = 1.9$) likelihood of smoking during pregnancy. However, this association was no longer significant after adjusting for individual-level covariates related to demographics, socioeconomic conditions, alcohol use, and parents' cohabitation. In contrast, our significant finding of a positive association between NDI and smoke exposure could not be explained by individual-level covariates. Our finding is consistent with Räisänen et al. (Räisänen et al., 2014), who found a significant positive association between smoking during pregnancy and area level deprivation based on education, income, and unemployment variables after adjusting for individual level covariates including SES, age, and year of birth. In addition, Shoff and Yang (Shoff & Yang, 2013) found a significant positive association between social

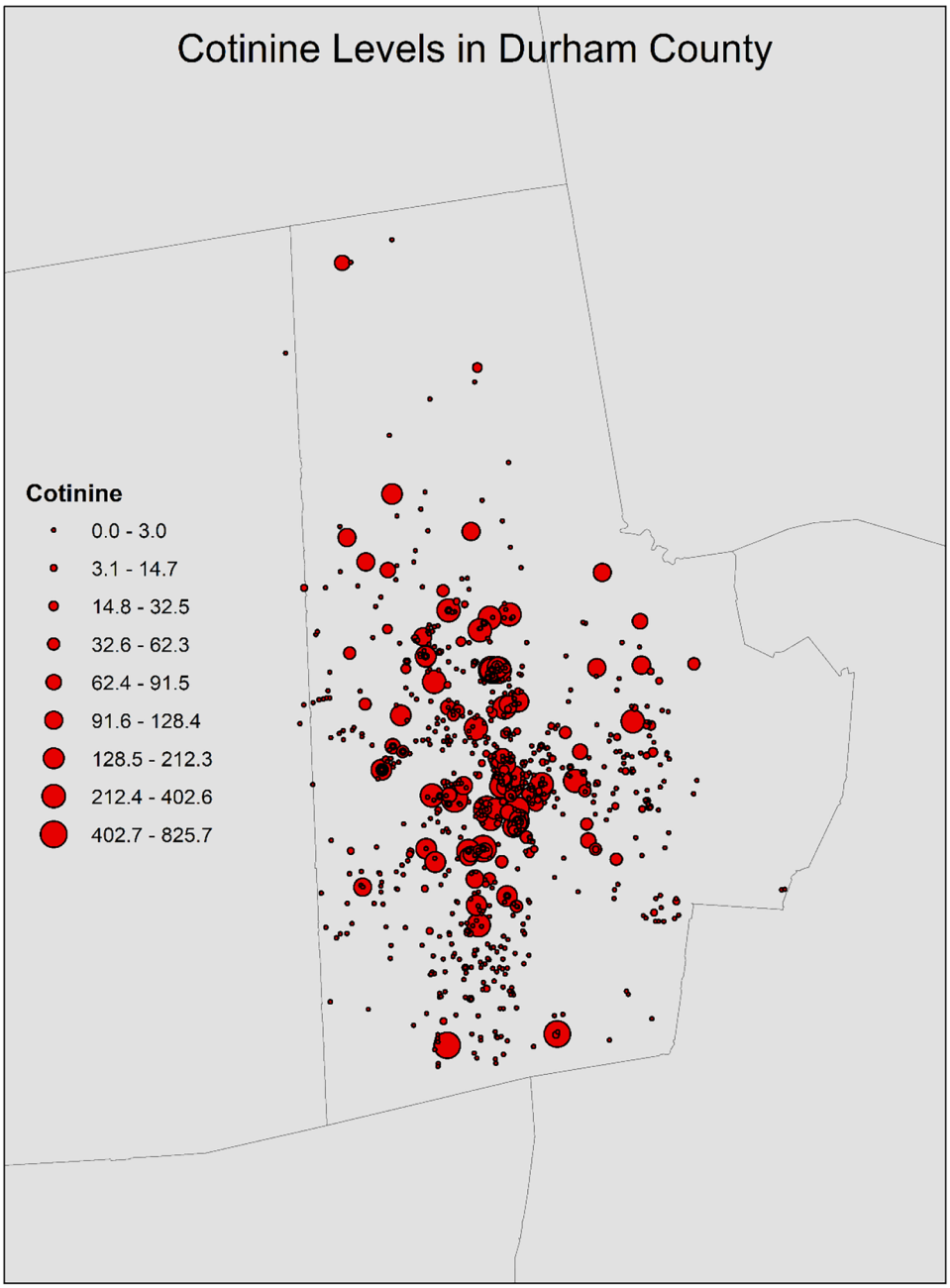

Fig. 1 Cotinine levels for NEST mothers in Durham County

capital at the county level and maternal smoking during pregnancy after adjusting for individual level covariates including age, race, ethnicity, and education. However, for women living in rural counties, higher social capital was associated with a decrease in the odds that a woman smoked during pregnancy.

One of the striking findings was that one of the components of neighborhood deprivation most related to smoke exposure was the percent of African Americans living within a census block group. While Durham was at one point in history a flourishing town supportive of upward mobility among the African American community, it has also had a history of segregation buttressed by redlining and other institutional racist policies (BullCity150, 2018). The legacy of this are racially segregated communities with racial gaps in home ownership and generational wealth. Although not directly evaluated here, the relationship between a higher level of percent African Americans and greater smoke exposure during pregnancy could reflect this legacy of white supremist policies that deprive neighborhoods of the protective factors that exist in white communities. Such factors could be better schools resulting in higher educational attainment within a community, reduced exposure to tobacco marketing, or early access to early prenatal care, all of which

Table 2 Coefficient estimates and 95% credible intervals for Bayesian index models to explain variation in cotinine levels among pregnant mothers

	All subjects		*Cotinine < 3 ng/mL*		*Cotinine ≥ 3 ng/mL*	
Parameter	**Mean**	**95% credible int**	**Mean**	**95% credible int**	**Mean**	**95% credible int**
Intercept	0.883	(−0.060, 1.892)	**−0.911**	**(−1.574, −0.222)**	**2.261**	**(0.916, 3.586)**
Deprivation	**0.200**	**(0.113, 0.294)**	**0.067**	**(0.002, 0.133)**	**0.127**	**(0.005, 0.247)**
Age	−0.004	(−0.034, 0.023)	−0.007	(−0.025, 0.011)	**0.051**	**(0.008, 0.092)**
Race/ethnicity						
Black	−0.391	(−0.817, 0.020)	0.029	(−0.261, 0.309)	−0.527	(−1.108, 0.079)
Hispanic	**−1.806**	**(−2.366, −1.263)**	−0.267	(−0.640, 0.098)	**−1.732**	**(−2.749, −0.700)**
Other	**−0.702**	**(−1.358, −0.054)**	−0.356	(−0.774, 0.060)	**−1.426**	**(−2.521, −0.346)**
Education						
HS graduate	**−0.895**	**(−1.352, −0.439)**	−0.063	(−0.421, 0.299)	−0.545	(−1.082, 0.004)
Some college	**−1.177**	**(−1.672, −0.699)**	−0.147	(−0.525, 0.223)	**−0.601**	**(−1.197, −0.005)**
College graduate	**−1.986**	**(−2.524, −1.448)**	−0.159	(−0.546, 0.220)	**−1.029**	**(−1.987, −0.089)**
Missing	**−1.116**	**(−2.188, −0.079)**	0.471	(−0.328, 1.256)	**−1.306**	**(−2.588, −0.049)**
Marital status						
Married	−0.274	(−0.743, 0.187)	−0.150	(−0.471, 0.159)	−0.107	(−0.821, 0.616)
Living with partner	0.388	(−0.042, 0.810)	0.133	(−0.179, 0.436)	0.291	(−0.247, 0.821)
Divorced or separated	0.701	(−0.117, 1.536)	0.263	(−0.363, 0.895)	0.487	(−0.467, 1.441)
Other	0.094	(−0.982, 1.173)	0.025	(−0.718, 0.803)	0.981	(−0.470, 2.439)
Missing	0.506	(−0.510, 1.528)	−0.116	(−0.900, 0.698)	1.018	(−0.185, 2.251)

are related to lower levels of smoke exposure. The findings here highlight the need for place-based strategies targeting increased efforts toward education, prevention, and cessation. Other types of community improvement could include outreach strategies to improve prenatal care and polices to address tobacco marketing in African American communities. Moreover, anti-poverty programs such as state Earned Income Tax Credit programs (eliminated in North Carolina in 2014) have been shown to reduce maternal smoking (Averett & Wang, 2013; Cowan & Tefft, 2012), though

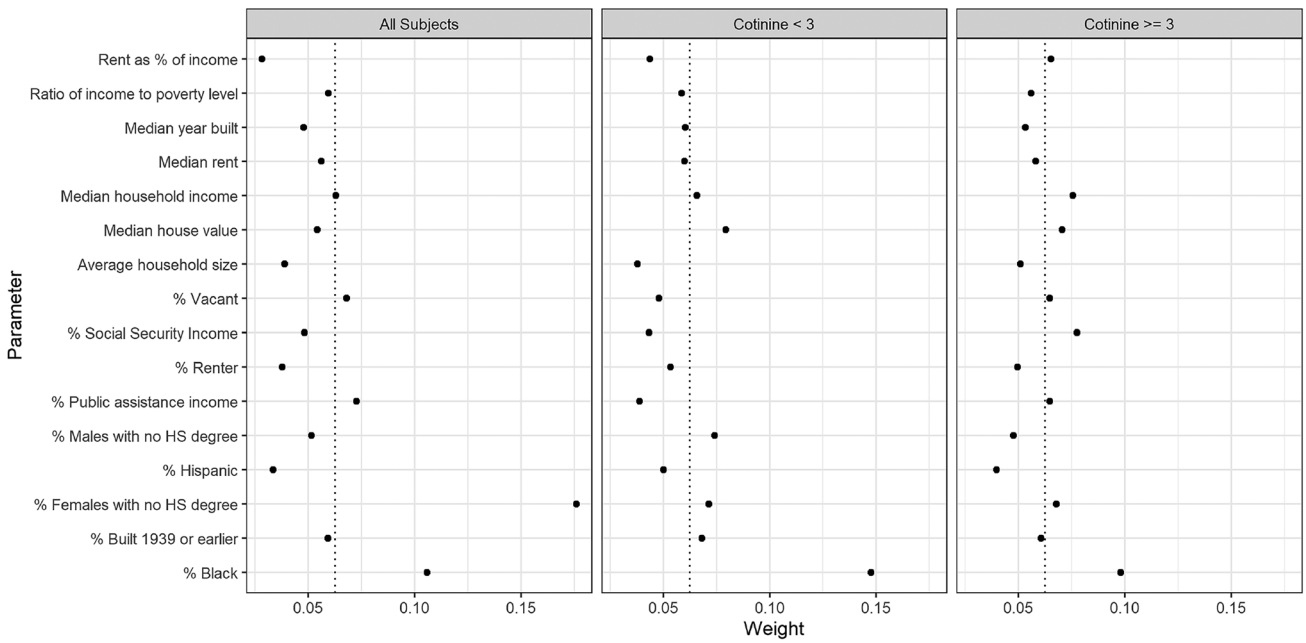

Fig. 2 Estimated weights from Bayesian index models with a dashed line for the equal weight value (0.063)

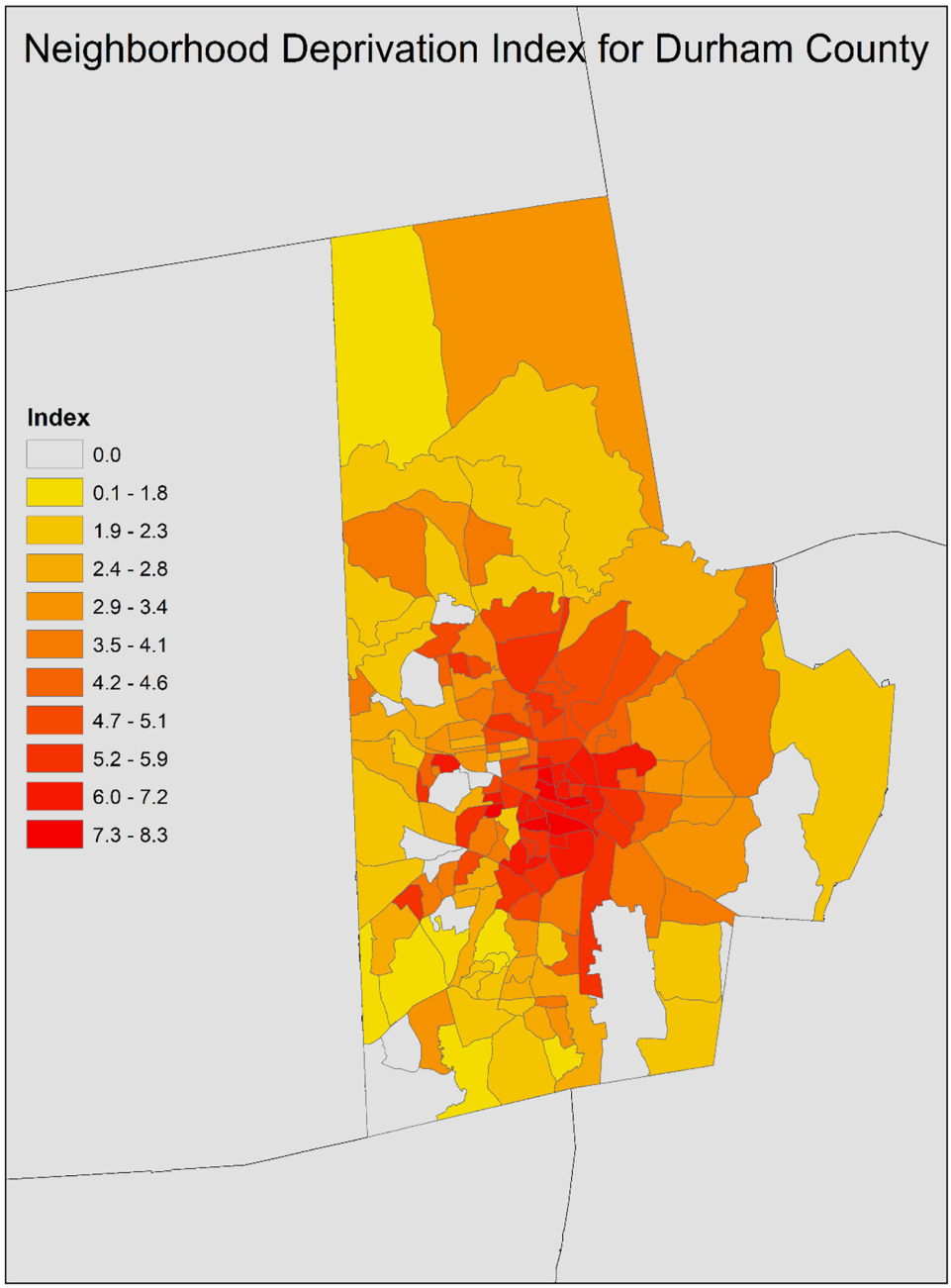

Fig. 3 Neighborhood deprivation index at the block group level in Durham County estimated from the Bayesian index model for all subjects

not consistently (Wagenaar et al., 2019). In addition, more efforts are needed to redress a history of institutional racism in the USA.

This study has a number of strengths. Using an objective measure of smoke exposure reduces bias associated with self-reported smoking status. Cotinine measurements have been shown to be superior to that of self-reported active or passive exposure during pregnancy (Jedrychowski et al., 2009; Pichini et al., 2000), particularly in light of underreporting among pregnant women due to social stigma of smoking. While using cotinine rather than self-report, our findings also highlight the associations between greater NDI and risk of higher levels of secondhand smoke exposure. In addition, using the Bayesian index model to estimate the NDI is advantageous compared with other dimension reduction techniques that have been used (Lian et al., 2016; Shoff & Yang, 2013) such as PCA and factor analysis, which produce components that are difficult to interpret and are constructed independently of the association with the outcome. In contrast, our Bayesian index model estimates the index weights considering associations with the health outcome and produces easily interpretable relative importance weights, some of which can be zero for unimportant variables. We previously demonstrated that using an

index approach to simultaneously estimate the NDI and its health effect leads to significantly better model goodness-of-fit than using PCA to construct the index (Wheeler et al., 2019a, b). Finally, this study includes a large proportion of racial minority mothers living in a county with a large racial minority and diversity in social determinants of health and rural/urban status. Regarding limitations, while we adjusted for several individual-level variables, there could still be residual confounding of the association of NDI and maternal smoking during pregnancy. Not all individual-level variables potentially related to cotinine and neighborhood deprivation (e.g., maternal stress and depressive mood) were collected as part of the NEST study and therefore could not be included. While our use of cotinine as an objective measure of smoke exposure is novel, cotinine was only measured at one time point for each subject. In addition, our study area is relatively small and future work in other geographic areas is needed to help validate these findings. Also, the subsample of NEST participants with cotinine assays is somewhat selective, in that these mothers represented a moderate difference in the proportion who identified as Black and who were never married and small differences in age and proportion of college graduates. While this indicates that the subsample may not reflect the overall cohort with regard to some demographic characteristics, these differences should not limit the conclusions drawn from the associations being examined, especially because we are taking a number of steps to ensure high internal validity (e.g., use of biomarkers for smoke exposure and data on the neighborhood environment).

Conclusion

Our findings on the relationship between neighborhood deprivation and cotinine levels add to the evidence suggesting that the socio-demographic variables of educational attainment and neighborhood racial composition are important factors for smoking during pregnancy. Given the breadth and severity of adverse health outcomes for children related to smoke exposure, there is great public health value in continuing to study and better understand both the individual and neighborhood factors that drive smoke exposure, both actively and passively, in pregnant mothers. Multilevel efforts and strategies may be needed to reduce maternal smoking during pregnancy and prevent SHS exposure during pregnancy. The findings here highlight the need for precision prevention efforts that help to reduce smoking and SHS smoke exposure among communities of color and communities of limited educational opportunity and attainment. This could come in the form of community-based educational outreach and education about the harms of tobacco use and exposure during pregnancy, as well as attempts to address structural factors in communities related to neighborhood disadvantage, such as providing programs to improve educational opportunities for young women and/or increasing generational wealth through micro-loans or "baby bonds" to residents living in more socio-economically deprived neighborhoods. Contingency management programs have also demonstrated success in reducing smoking during pregnancy (Higgins et al., 2010; Wen et al., 2019). In short, given the findings here showing that characteristics of the neighborhood environment relate significantly to levels of cotinine among pregnant women, prevention efforts will likely need to extend from the individual to society in order to make a meaningful impact at reducing the harms associated with prenatal smoke exposure.

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Declarations

Ethics Approval This study was approved by the Institutional Review Board at Virginia Commonwealth University in accordance with the ethical standards as laid down in the 1964 Declaration of Helsinki and its later amendments or comparable ethical standards.

Informed Consent Informed consent was obtained from all individual participants included in the study.

Conflicts of Interest The authors declare no competing interests.

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