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Original Investigation

Tobacco Retail Outlets, Neighborhood Deprivation and the Risk of Prenatal Smoke Exposure

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Abstract

Introduction: Smoking and smoke exposure among pregnant women remain persistent public health issues. Recent estimates suggest that approximately one out of four nonsmokers have measurable levels of cotinine, a marker indicating regular exposure to secondhand smoke. Epidemiological research has attempted to pinpoint individual-level and neighborhood-level factors for smoking during pregnancy. However, most of these studies have relied upon self-reported measures of smoking.

Aims and Methods: To more accurately assess smoke exposure resulting from both smoking and secondhand exposure in mothers during pregnancy, we used Bayesian regression models to estimate the association of cotinine levels with tobacco retail outlet (TRO) exposure and a neighborhood deprivation index (NDI) in six counties in North Carolina centered on Durham County.

Results: Results showed a significant positive association between TRO exposure ($\beta = 0.008$, 95% credible interval (CI) = [0.003, 0.013]) and log cotinine after adjusting for individual covariates (eg, age, race/ethnicity, education, marital status). TRO exposure was not significant after including the NDI, which was significantly associated with log cotinine ($\beta = 0.143$, 95% CI = [0.030, 0.267]). However, in a low cotinine stratum (indicating secondhand smoke exposure), TRO exposure was significantly associated with log cotinine ($\beta = 0.005$, 95% CI = [0.001, 0.009]), while in a high cotinine stratum (indicating active smoking), the NDI was significantly associated with log cotinine ($\beta = 0.176$, 95% CI = [0.005, 0.372]).

Conclusions: In summary, our findings add to the evidence that contextual factors are important for active smoking during pregnancy.

Implications: In this study, we found several significant associations that suggest a more nuanced understanding of the potential influence of environmental- and individual-level factors for levels of prenatal smoke exposure. Results suggested a significant positive association between TRO exposure and cotinine levels, after adjusting for the individual factors such as race, education, and marital status. Individually, NDI was similarly positively associated with cotinine levels as well. However, when combining TRO exposure alongside NDI in the same model, TROs were no longer significantly associated with overall cotinine levels.

Introduction

Globally and in the United States, smoking and secondhand smoke exposure during pregnancy remain incredibly important public health concerns.[1] Although smoking rates during pregnancy have been declining, approximately 6% of women report smoking during pregnancy,[2] and 23% of pregnant women in the United States still report exposure to secondhand smoke.[3] Multiple studies have consistently shown that smoke exposure during pregnancy is associated with a host of negative health outcomes for both mother and child, including epigenetic alterations, low birth weight, preterm birth, and infant death.[4–6] Furthermore, even low levels of smoke exposure during pregnancy have been associated with health complications during pregnancy as well as epigenetic alterations in regulatory regions associated with carcinogenesis and neuronal functioning among babies born to mothers exposed to secondhand smoke.[7] Understanding social determinants that could be modified in order to reduce tobacco use or secondhand smoke exposure in this vulnerable population is needed to reduce harms to both expectant mothers and their children.

Recent research has focused on tobacco retail outlet (TRO) density and its association with tobacco use.[8] The presence of TROs in and around one's neighborhood has been linked

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to adolescent and adult smoking behaviors and tobacco-use-related health outcomes[9–12] and at least one recent study found an association between TRO density within community statistical areas (CSAs) and the prevalence of maternal prenatal smoking within those CSAs.[13] The study, however, lacked individual-level data on smoking behaviors or other important individual-level covariates known to be associated with smoking (eg, education). Additional studies using more rigorous methods and analyses that can account for factors on multiple levels (ie, individual as well as environmental) are needed to help further corroborate and expand upon these initial findings.

TRO density and tobacco-use prevalence have both been shown to be independently associated with socioeconomic status (SES) and other demographic characteristics and qualities of neighborhoods.[14] Lian et al. calculated a neighborhood deprivation index (NDI) that included a number of neighborhood SES variables (eg, housing conditions, poverty, racial demographics) and found that mothers living in more highly deprived areas were more likely to report smoking during pregnancy.[15] The association, however, was not significant after controlling for individual-level covariates. In a more recent study, Wheeler et al. fitted Bayesian index models to estimate the association between NDI and plasma cotinine levels among pregnant women and found a significant association between NDI and elevated cotinine indicative of both active smoking and secondhand smoke exposure.[16] The association remained significant with the inclusion of individual-level covariates (eg, race, education, and marital status).

Decoupling the effects of TRO exposures and neighborhood-level covariates for smoking-related outcomes can be challenging, given that these factors tend to be correlated. As such, a more nuanced methodology to examine the neighborhood-level factors (ie, neighborhood deprivation and TROs) alongside individual-level factors (ie, sociodemographic variables) is necessary. The purpose of this paper was to consider simultaneously the impact of TROs as well as neighborhood deprivation in order to gain a more complete understanding of the area-level neighborhood factors associated with maternal smoking and secondhand smoke exposure during pregnancy. To do so, we have employed Bayesian index models similar to those used previously[16–18] in order to quantify the individual and combined effects of neighborhood deprivation and TRO density for maternal cotinine levels, while simultaneously accounting for a host of individual-level covariates (age, race/ethnicity, education, marital status).

Methods

Study Sample

The *Newborn Epigenetics STudy* (NEST) is a prospective cohort study designed to elucidate how maternal behavior (eg, smoking, nutrition) and exposures (eg, toxins) that influence the in utero environment subsequently influence the epigenome, birth weight, and early childhood growth and health.[19,20] Assembled between 2005 and 2011, 2595 women were consented and enrolled at six prenatal clinics in Durham County, NC. Most pregnant women were enrolled during their first prenatal clinic visit when maternal blood specimens and survey data were collected. Of those who consented and enrolled, cotinine levels were measured in two waves with criteria for the first wave (n = 853) 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 (n = 288), 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 and the adjacent five counties (Chatham, Granville, Orange, Person, and Wake) at the time of enrollment in NEST (n = 1055).

Measures

Smoke Exposure

Cotinine assays from prenatal maternal plasma samples were performed to determine the level of smoke exposure. Liquid chromatography-mass spectrometry (LC-MS/MS) was used to measure cotinine levels with a detection limit of 0.05 ng/mL.[21–23] 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. Self-reported smoking during pregnancy (yes, no) was available for 1018 mothers, but cotinine was used as an objective measure of smoke exposure. For the 1018 mothers where smoking status was self-reported and cotinine was measured, 68% (157/231) of those with cotinine >3 ng/mL reported smoking and only 8% (66/787) of those with cotinine <3 ng/ml reported smoking. The cutpoint of 3 ng/mL is recommended for distinguishing smokers from nonsmokers in US samples.[24]

Sociodemographic Data

We used 5-year (2007–2011) estimates of 15 sociodemographic variables at the census block group level from the American Community Survey (ACS) to estimate an NDI similar to previous work.[17,18,25] We chose this time period to overlap with the cotinine assays for our study participants. The sociodemographic 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, 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 converted the percent Black population and percent Hispanic population to Black segregation and Hispanic segregation by dividing each variable by the average for the variable over the study area. We have used similar sociodemographic variables and segregation measures[26,27] to estimate neighborhood disadvantage indices previously.[14,28,29] We chose to estimate the NDI using a Bayesian index model described below because it can handle many correlated sociodemographic measures (eg, education and poverty) when estimating the index and has better model performance than other methods of calculating neighborhood deprivation such as principal components analysis.[17] This more comprehensive treatment of neighborhood deprivation also avoids residual confounding issues associated with assessing only individual sociodemographic measures.

Individual-Level Variables

At their enrollment visit, women were administered a questionnaire soliciting information on sociodemographics, health, nutrition, stress, and lifestyle behaviors including age at enrollment, race/ethnicity, education, and marital status.

Tobacco Retail Outlets

We used a two-step process to assign TRO exposures to study participants. The first step entailed creating a database of likely TROs within Durham County and proximate to all subjects in the five adjacent counties over all years in the sample period. The primary data source for this was the National Establishment Time Series (NETS), a record of businesses of all types in the United States from 2000 to 2019. We used an algorithm[30] that filtered these businesses using their North American Industry Classification System (NAICS) codes to include only likely TROs, then deleted duplicate records, and finally removed records for TROs in years after state- or municipality-specific bans were enacted on the sale of tobacco by certain business types or for stores that stopped selling tobacco (eg, CVS). We manually verified the potential TRO locations using the archive feature in Google Street View (GSV) to locate each TRO in the database in prior years, extending back to 2007. In doing this, we noted the status of each TRO that existed in 2015 for each prior year until 2007. We also verified TRO locations within Durham County using a database from Duke University and the University of North Carolina at Chapel Hill, whose researchers ground-truthed TROs in Durham County in 2015.[31] We made extensive efforts to attain a definite conclusion for each potential TRO near a study subject, searching for county business listings, mentions in local newspapers, etc. We confirmed 99.99% of the TROs active during the years of interest.

The second step of the process was to create several measures of TRO exposure for all study participants based on their residential location at study enrollment. We created 1 and 2 mile buffers around residential locations of participants and used the buffers to select the TROs inside the buffers that existed in the same year as the participant's study enrollment. Using the selection set, we calculated the number of TROs and the rate of TROs per the population living within 1 and 2 miles of each participant. The population within each buffer was calculated by multiplying the proportion of each block group's area that intersected the buffer by the population of the block group according to the ACS estimates and assuming equal population distribution across each block group. In addition, we calculated the straight-line distance to the closest TRO, the number of TROs in the study participant's residential block group, and the rate of TROs per population living in the block group. We evaluated these TRO exposure metrics using crude and covariate-adjusted linear regression models for the natural log of cotinine and selected the best metric according to the Akaike information criterion (AIC). The covariate-adjusted models included the following covariates: Age at enrollment, race/ethnicity (White as reference), education (less than high school as reference), and marital status (never married as reference). The lowest (ie, best) AIC values were associated with the number of TROs within 2 miles (Supplementary Table S1) and this exposure measure was used in all subsequent models.

Statistical Analysis

We used Bayesian hierarchical regression models to explain the variation in the natural log of cotinine with neighborhood deprivation and TRO exposure (ie, the number of TROs within 2 miles), assuming that log cotinine was $y_i \sim \text{Normal}(\mu_i, \tau)$ with mean μ_i and precision τ. We considered crude and covariate-adjusted models with different measures of TRO exposure, covariate-adjusted models with either TRO exposure or NDI, adjusted models with both TRO exposure and NDI, and an adjusted model with TRO exposure as part of the NDI. The adjusted model to estimate the association of cotinine with TRO was

$$\mu_i = \beta_0 + \beta_1 x_i + \alpha z_i, \quad (1)$$

where β_0 is the intercept, β_1 is the effect for TRO exposure, x_i is the measure of TRO exposure for the ith subject, α is a vector of regression coefficients for individual-level covariates in the vector z_i that includes the covariates listed above. To estimate the NDI while modeling the mean log cotinine, we used the following Bayesian index regression model:

$$\mu_i = \beta_0 + \beta_2 \left(\sum_{j=1}^{C} w_j q_{ij} \right) + \alpha z_i, \quad (2)$$

where β_2 is the effect for the NDI. We specified the NDI 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 15 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. 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 formulamax$(x) - x_j$, where x_j is the value of the variable.

The model with separate terms for TRO exposure and NDI was

$$\mu_i = \beta_0 + \beta_1 x_i + \beta_2 \left(\sum_{j=1}^{C} w_j q_{ij} \right) + \alpha z_i \quad (3)$$

Also, to consider the potential correlation between TRO exposure and the NDI, we fitted a model for Equation 2 with TRO exposure included in the NDI instead of as a separate term as in Equation 1. To select the best TRO exposure metric to use in the final models, we compared the model fit of crude and adjusted TRO models using the deviance information criterion (DIC). In addition to fitting the models for all participants (n = 1055), we also fitted them to strata defined by cotinine level <3 (n = 806) and ≥3 (n = 249) to separate passive and active smoke exposure. The prior distribution and model fitting details are included in Supplemental material.

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. There are differences in race/ethnicity, education, and marital status between the cotinine strata. The goodness-of-fit DIC values for the final adjusted models with terms for TRO, NDI, and TRO and NDI together are listed in Supplementary Table S2 for all study subjects and stratified by cotinine level, where differences of more than 3 are considered

Table 1. Characteristics of Mothers in the *Newborn Epigenetics STudy* (NEST) Study for the Six Counties in the Study Area

	All participants (*n* = 1055)	Cotinine <3 ng/mL (*n* = 806)	Cotinine>3 ng/mL (*n* = 249)
Age (years)	27.48 (5.77)	28.11 (5.85)	25.41 (4.98)
Cotinine (ng/mL) [a]	0.68 [0.25, 2.52]	0.45 [0.19, 0.92]	29.58 [7.42, 112.49]
Race			
Black	540 (51.2)	373 (46.3)	167 (67.1)
Hispanic	100 (9.5)	89 (11.0)	11 (4.4)
Other	52 (4.9)	43 (5.3)	9 (3.6)
White	362 (34.3)	300 (37.2)	62 (24.9)
Missing	1 (0.1)	1 (0.1)	0 (0.0)
Education level			
College graduate	364 (34.5)	345 (42.8)	19 (7.6)
Some college	208 (19.7)	147 (18.2)	61 (24.5)
High school grad/GED	205 (19.4)	140 (17.4)	65 (26.1)
Less than high school	165 (15.6)	89 (11.0)	76 (30.5)
Missing	113 (10.7)	85 (10.5)	28 (11.2)
Marital status			
Never married	291 (27.6)	194 (24.1)	97 (39.0)
Married	419 (39.7)	379 (47.0)	40 (16.1)
Living with partner	179 (17.0)	115 (14.3)	64 (25.7)
Divorced/separated	32 (3.0)	20 (2.5)	12 (4.8)
Other	18 (1.7)	12 (1.5)	6 (2.4)
Missing	116 (11.0)	86 (10.7)	30 (12.0)

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) because of skewness.

Table 2. Coefficient Estimates and 95% Credible Intervals (CI) for Bayesian Models to Explain Variation in Cotinine Levels Among Pregnant Mothers Using Tobacco Retail Outlet (TRO) Exposure and Covariates for All Cotinine Levels and Stratified by Cotinine Level

	All cotinine levels			Cotinine < 3			Cotinine >= 3		
Parameter	β	2.5% CI	97.5% CI	β	2.5% CI	97.5% CI	β	2.5% CI	97.5% CI
Intercept	1.272	0.458	2.069	−1.032	−1.576	−0.528	2.694	1.512	3.934
TRO	**0.008**	**0.003**	**0.013**	**0.005**	**0.002**	**0.008**	0.003	−0.004	0.009
Age	0.002	−0.022	0.028	0.000	−0.017	0.016	**0.051**	**0.009**	**0.092**
Race/									
Black	−0.311	−0.672	0.038	−0.012	−0.241	0.211	−0.369	−0.901	0.123
Hispanic	**−1.660**	**−2.173**	**−1.150**	−0.237	−0.569	0.076	**−1.653**	**−2.637**	**−0.650**
Other	**−0.709**	**−1.337**	**−0.074**	**−0.416**	**−0.809**	**−0.017**	**−1.317**	**−2.402**	**−0.186**
Education									
High school	**−0.854**	**-1.301**	**−0.406**	0.048	−0.255	0.358	−0.421	−0.941	0.071
Some college	**−0.949**	**−1.409**	**−0.488**	−0.015	−0.324	0.290	−0.453	−0.994	0.060
College	**−1.988**	**−2.476**	**−1.488**	−0.129	−0.447	0.164	**−1.308**	**−2.146**	**−0.461**
Missing	−1.051	−2.192	0.007	0.426	−0.293	1.233	**−1.356**	**−2.669**	**−0.056**
Marital status									
Married	**−0.485**	**−0.923**	**−0.033**	−0.153	−0.436	0.115	−0.197	−0.835	0.384
Living with partner	0.367	−0.028	0.783	0.091	−0.179	0.372	0.175	−0.276	0.656
Divorced/separated	0.503	−0.231	1.296	0.202	−0.328	0.775	0.432	−0.400	1.346
Other	−0.031	−0.988	0.908	−0.153	−0.841	0.504	0.620	−0.500	1.857
Missing	0.366	−0.646	1.465	−0.069	−0.863	0.666	1.013	−0.196	2.286

Table 3. Coefficient Estimates and 95% Credible Intervals (CI) for Bayesian Models to Explain Variation in Cotinine Levels Among Pregnant Mothers Using Neighborhood Deprivation and Covariates for All Cotinine Levels and Stratified by Cotinine Level

	All cotinine levels			Cotinine < 3			Cotinine ≥3		
Parameter	β	2.5% CI	97.5% CI	β	2.5% CI	97.5% CI	β	2.5% CI	97.5% CI
Intercept	0.699	−0.184	1.617	−1.043	−1.626	−0.407	2.385	1.176	3.579
NDI	**0.166**	**0.079**	**0.258**	0.046	−0.005	0.102	**0.110**	**0.002**	**0.205**
Age	0.004	−0.021	0.029	0.000	−0.018	0.016	**0.052**	**0.011**	**0.092**
Race/ethnicity									
Black	−0.325	−0.685	0.024	−0.009	−0.248	0.224	−0.450	−0.993	0.066
Hispanic	**−1.686**	**−2.204**	**−1.170**	−0.215	−0.548	0.097	**−1.680**	**−2.665**	**−0.683**
Other	**−0.698**	**−1.313**	**−0.074**	−0.390	−0.792	0.005	**−1.343**	**−2.424**	**−0.224**
Education									
High school	**−0.853**	**−1.289**	**−0.410**	0.029	−0.284	0.340	−0.399	−0.919	0.085
Some college	**−0.944**	**−1.397**	**−0.490**	−0.059	−0.376	0.242	−0.393	−0.934	0.112
College	**−1.855**	**−2.345**	**−1.358**	−0.121	−0.454	0.184	**−1.221**	**−2.077**	**−0.356**
Missing	−1.018	−2.141	0.009	0.437	−0.275	1.224	−1.285	−2.622	0.002
Marital status									
Married	**−0.452**	**−0.877**	**−0.020**	−0.179	−0.462	0.087	−0.186	−0.819	0.408
Living with partner	0.386	−0.015	0.796	0.103	−0.167	0.388	0.185	−0.270	0.665
Divorced/separated	0.528	−0.212	1.322	0.253	−0.277	0.835	0.419	−0.416	1.334
Other	−0.059	−1.005	0.869	-0.152	−0.847	0.511	0.583	−0.531	1.810
Missing	0.397	−0.597	1.503	−0.109	−0.870	0.601	0.953	−0.255	2.236

Table 4. Coefficient Estimates and 95% Credible Intervals (CI) for Bayesian Models to Explain Variation in Cotinine Levels among Pregnant Mothers Using Tobacco Retail Outlet (TRO) Exposure, Neighborhood Deprivation, and Covariates for All Cotinine Levels and Stratified by Cotinine Level

	All cotinine levels			Cotinine < 3			Cotinine >= 3		
Parameter	β	2.5% CI	97.5% CI	β	2.5% CI	97.5% CI	β	2.5% CI	97.5% CI
Intercept	0.711	−0.162	1.623	−1.051	−1.671	−0.439	2.069	0.689	3.319
NDI	**0.143**	**0.030**	**0.267**	0.008	−0.048	0.069	**0.176**	**0.005**	**0.372**
TRO	0.002	−0.004	0.009	**0.005**	**0.001**	**0.009**	−0.005	−0.016	0.005
Age	0.005	−0.019	0.029	−0.001	−0.018	0.017	**0.052**	**0.015**	**0.092**
Race/ethnicity									
Black	−0.342	−0.706	0.012	−0.022	−0.255	0.201	−0.404	−0.951	0.107
Hispanic	**−1.703**	**−2.219**	**−1.183**	−0.245	−0.584	0.070	**−1.666**	**−2.659**	**−0.667**
Other	**−0.720**	**−1.342**	**−0.097**	**−0.423**	**−0.814**	**−0.025**	**−1.288**	**−2.376**	**−0.173**
Education									
High school	**−0.841**	**−1.279**	**−0.398**	0.047	−0.263	0.360	−0.398	−0.919	0.092
Some college	**−0.920**	**−1.372**	**−0.462**	−0.015	−0.331	0.292	−0.397	−0.938	0.103
College	**−1.857**	**−2.354**	**−1.361**	−0.121	−0.446	0.188	**−1.196**	**−2.050**	**−0.328**
Missing	−1.006	−2.152	0.040	0.425	−0.294	1.239	**−1.360**	**−2.676**	**−0.040**
Marital status									
Married	**−0.445**	**−0.881**	**−0.002**	−0.150	−0.434	0.112	−0.168	−0.812	0.434
Living with partner	0.386	−0.013	0.795	0.092	−0.174	0.375	0.180	−0.266	0.670
Divorced/separated	0.500	−0.222	1.294	0.210	−0.326	0.793	0.463	−0.365	1.374
Other	−0.054	−1.002	0.885	−0.148	−0.845	0.511	0.515	−0.607	1.747
Missing	0.397	−0.619	1.517	−0.064	−0.855	0.659	1.021	−0.198	2.281

meaningful.[32] For all subjects together, the models that included NDI fit better than the model with only TRO exposure, and the model with only NDI fit the best. For the low cotinine stratum, the models with TRO exposure fit better than the model with only NDI, and the model with only TRO fit the best. For the high cotinine stratum, models with NDI fit better than the model with only TRO and the best model included only NDI. These results imply that while TRO exposure is important for explaining variability in low cotinine levels, NDI is more important for explaining variability in higher cotinine levels.

The regression coefficients and 95% credible intervals (CIs) from the models with TRO exposure show that the TRO exposure effect was significant overall and for low cotinine levels but not high cotinine levels (Table 2). For all subjects, there was a 0.008 (95% CI: 0.003, 0.013) increase in log cotinine with a one-unit increase in TROs within 2 miles. On the cotinine scale, this equates to approximately a one-unit increase in cotinine with an additional TRO within 2 miles. 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. Being Hispanic or of other races/ethnicities were associated with decreased cotinine, and higher education levels compared with no high school diploma were associated with decreased cotinine. Being married was also associated with a significant decrease (−0.485, 95% CI: −0.923, −0.033) in log cotinine compared with those who were never married.

The regression coefficients and 95% CI from the models with neighborhood deprivation show that the NDI effect was significant overall and for high cotinine levels (Table 3). For all subjects, there was a 0.166 (95% CI: 0.079, 0.258) increase in log cotinine for a one-unit increase in the NDI. There were similar significant associations for race/ethnicity, education, and marital status as in the TRO-only model. The estimated weights for the variables in the NDI in the model for all subjects (Supplementary Figure S1) reveal that the most important variable in the index was clearly percent females without a high school degree (0.185), followed by Black segregation (0.081), and percent of vacant housing units (0.080). The Spearman correlation coefficient between this NDI and TRO exposure within 2 miles was 0.68. Combining this with the correlations of TRO exposure and log cotinine (0.20) and NDI and log cotinine (0.28) is an argument for choosing the model that includes both TRO exposure and the NDI.

The results for the model with both TRO exposure and neighborhood deprivation show that overall only the NDI is significant with an effect of 0.143 (95% CI: 0.030, 0.267), but that TRO exposure is significantly related (0.005, 95% CI: 0.001, 0.009) to log cotinine in the low cotinine group (Table 4). The NDI is also significant in the high cotinine exposure group (0.176, 95% CI: 0.005, 0.372). We also note that there is evidence of confounding of TRO density and NDI when comparing their effects in separate models (Tables 2 and 3) with their effects in the joint model (Table 4). In the model where TRO exposure was included in the NDI, it received a weight of 0.055, which was in the lower half of the estimated weights. This finding is consistent with the earlier model results showing that TRO exposure is not as strongly associated with cotinine overall as neighborhood deprivation when it is represented by sociodemographic variables.

Conclusion

In this study, we found several significant associations that suggest a more nuanced understanding of the potential influence of environmental- and individual-level factors for levels of prenatal smoke exposure. Results suggested a significant positive association between TRO exposure and cotinine levels, after adjusting for the individual factors such as race, education, and marital status. Individually, NDI was similarly positively associated with cotinine levels as well. However, when combining TRO exposure alongside NDI in the same model, TROs were no longer significantly associated with overall cotinine levels. When stratifying the cotinine levels, though, TROs were significantly and positively associated with the low cotinine stratum, and NDI was similarly associated with both overall cotinine and the high cotinine stratum. Based on these findings, there seem to be important implications for passive maternal smoke exposure compared to active smoking during pregnancy.

Our findings highlight a potential distinction in environmental smoke exposure in pregnant women. Overall, NDI and TROs seem to be important predictors of cotinine levels, although it would be difficult to completely separate these two factors from one another. Regarding the association between TROs and passive smoke exposure, this can be explained by consistent findings across studies showing that closer proximity to TROs is associated with higher rates of smoking in general and fewer quit attempts.[9,33] As such, pregnant mothers in our sample could live near and interact with a higher number of smokers, perhaps even in their own household, as a function of being around a greater density of TROs. As for our other finding, it could be possible that in more deprived neighborhoods, women who were smoking before pregnancy continue doing so into pregnancy because of a number of potential factors. Disadvantaged neighborhoods tend to have higher rates of crime, noise, and other stressors that may cause individuals to cope using behaviors such as smoking, and additionally, smoking may be seen as more normative as a result.[34,35] Another explanation could be that educational attainment tends to be less in disadvantaged neighborhoods, which may translate to poorer awareness of the negative consequences of smoking and fewer resources to facilitate quitting.

The results of this study build upon the findings of previous literature in ways that are both supportive and novel. In terms of individual-level predictors, the results of this study reinforce the role of race and education as important correlates of smoke exposure in mothers during pregnancy. Across the various models, education was consistently and negatively associated with cotinine levels—mothers who had fewer years of education (eg, no high school diploma) had higher cotinine levels compared to mothers with some college education or college degrees. This suggests that mothers with higher education either successfully quit smoking during pregnancy, which is consistent with a systematic review of smoking cessation during pregnancy,[36] or are able to avoid smoke exposure in ways related to their socioeconomic status, such as being able to self-select into neighborhoods of higher SES.[37] Furthermore, one finding in this study was that being Hispanic or of other races/ethnicities were associated with decreased cotinine levels compared to non-Hispanic White mothers, which supports our previous work.[16] Although Black mothers had slightly decreased cotinine levels compared to White mothers, this association was not statistically significant across any of our models, which may be explained by the large number of Black mothers in the high cotinine stratum. Overall, smoking during pregnancy has declined among less-educated mothers recently, with similar rates between Black and White mothers[37]; however, further research should examine other racial differences highlighted in this study, such as between Hispanic mothers compared to their White peers.

Overall, this study has a number of strengths in its scope and design. Instead of relying on self-report measures of smoking status and smoke exposure, we used cotinine as an objective biomarker. Cotinine measurements have been shown to be more reliable than self-reported active or passive exposure during pregnancy,[38,39] especially because of the social stigma of smoking while pregnant. Furthermore, our differential findings regarding high versus low strata of cotinine levels highlight the nuance in the associations between smoke exposure and TROs and neighborhood disadvantage. Another particular strength involves our novel analytic approach. Using the Bayesian index regression model to estimate the NDI is advantageous compared with other dimension reduction techniques that have been used previously[15,40] 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 effectively zero for unimportant variables. In addition, our model considers other important individual covariates and exposures (eg, TROs) when estimating the NDI and its effect.

This study, however, is not without its limitations. Notably, we only measured the cotinine levels of the mothers in the sample. Measuring the cotinine levels of the fathers or any partners cohabitating would have allowed for a more complete understanding of smoke exposure from other sources. It may be that fathers or partners could continue to smoke even when the mother does not, which may mediate the association between TROs and maternal smoke exposure, especially in the low cotinine stratum. In addition, although we made substantive efforts to verify the accuracy of our TRO database, reliance on historical business records has inherent limitations. While our procedures provide reasonable assurance that included stores were highly likely to be TROs, there remains a possibility that other TROs exist but were not included in the database for several possible reasons (eg, were not registered, were open only briefly). In addition, our study area was localized to only six counties around Durham, NC, having a combined estimated population of approximately 1.47 million in 2010,[41] which limits the generalizability of the findings.

Our findings on the associations between TROs, neighborhood deprivation, and cotinine levels delineate a potential distinction between passive and active smoke exposure in pregnant mothers. TROs seem to be more highly associated with passive smoke exposure, in contrast to neighborhood deprivation being associated with active smoke exposure. Regardless, our study provides novel evidence of how both TROs and neighborhood deprivation are important environmental-level factors for pregnant mothers. Additionally, our study supports evidence suggesting that educational attainment and neighborhood racial composition are important factors for smoking during pregnancy. Future endeavors should focus on addressing education disparities in disadvantaged areas, especially as they relate to smoking and its outcomes, as well as addressing the structural inequalities that influence smoking in these neighborhoods, which often have disproportionately higher numbers of racial and ethnic minorities. Prevention efforts could include community-based educational outreach 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 increasing generational wealth through micro-loans or "baby bonds" to residents and providing programs to improve educational opportunities for young women living in more socioeconomically deprived neighborhoods. Contingency management programs have also been successful in reducing smoking during pregnancy.[42,43] In addition, policy interventions designed to reduce the density of TROs should also be considered as a pathway toward reducing maternal exposure to secondhand smoke. Moreover, using available data to identify high-risk areas of smoke exposure can be useful to translational population prevention efforts, as it can highlight areas and subsamples of the population where there may be a need for increased surveillance to improve targeted community efforts to improve education and prevention interventions.

Supplementary Material

A Contributorship Form detailing each author's specific involvement with this content, as well as any supplementary data, are available online at https://academic.oup.com/ntr.

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Declaration of Interests

The authors have no conflicts of interest to declare that are relevant to the content of this article.

Data Availability

The data underlying this article cannot be shared publicly because of the privacy of individuals that participated in the study. The data will be shared on reasonable request to the corresponding author.

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