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Racial isolation and exposure to airborne particulate matter and ozone in understudied US populations: Environmental justice applications of downscaled numerical model output

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ABSTRACT

Background: Researchers and policymakers are increasingly focused on combined exposures to social and environmental stressors, especially given how often these stressors tend to co-locate. Such exposures are equally relevant in urban and rural areas and may accrue disproportionately to particular communities or specific subpopulations.
Objectives: To estimate relationships between racial isolation (RI), a measure of the extent to which minority racial/ethnic group members are exposed to only one another, and long-term particulate matter with an aerodynamic diameter of <2.5 μ ($PM_{2.5}$) and ozone (O_3) levels in urban and nonurban areas of the eastern two-thirds of the US.
Methods: Long-term (5 year average) census tract-level $PM_{2.5}$ and O_3 concentrations were calculated using output from a downscaler model (2002–2006). The downscaler uses a linear regression with additive and multiplicative bias coefficients to relate ambient monitoring data with gridded output from the Community Multi-scale Air Quality (CMAQ) model. A local, spatial measure of RI was calculated at the tract level, and tracts were classified by urbanicity, RI, and geographic region. We examined differences in estimated pollutant exposures by RI, urbanicity, and demographic subgroup (e.g., race/ethnicity, education, socioeconomic status, age), and used linear models to estimate associations between RI and air pollution levels in urban, suburban, and rural tracts.
Results: High RI tracts (≥80th percentile) had higher average $PM_{2.5}$ levels in each category of urbanicity compared to low RI tracts (<20th percentile), with the exception of the rural West. Patterns in O_3 levels by urbanicity and RI differed by region. Linear models indicated that $PM_{2.5}$ concentrations were significantly and positively associated with RI. The largest association between $PM_{2.5}$ and RI was observed in the rural Midwest, where a one quintile increase in RI was associated with a 0.90 $\mu g/m^3$ (95% confidence interval: 0.83, 0.99 $\mu g/m^3$) increase in $PM_{2.5}$ concentration. Associations between O_3 and RI in the Northeast, Midwest and West were positive and highest in suburban and rural tracts, even after controlling for potential confounders such as percentage in poverty.
Conclusion: RI is associated with higher 5 year estimated $PM_{2.5}$ concentrations in urban, suburban, and rural census tracts, adding to evidence that segregation is broadly associated with disparate air pollution exposures. Disproportionate burdens to adverse exposures such as air pollution may be a pathway to racial/ethnic disparities in health.

1. Introduction

An extensive literature has demonstrated a deleterious relationship between exposure to air pollution and adverse human health outcomes, including poor pregnancy outcomes (Ritz et al., 2002; Miranda et al., 2009; Bell et al., 2010; Miranda et al., 2013; Gray et al., 2014), asthma (McConnell et al., 2002), and cardiovascular- and respiratory-related mortality (Dominici et al., 2003; Bateson and Schwartz, 2004; Laurent et al., 2007) and morbidity (Dominici et al., 2006; Peng et al., 2009; Bell et al., 2014). The close relationship between race/ethnicity and residential location in the US (Gee and Payne-Sturges, 2004) suggests that racial disparities in health (e.g., poor pregnancy outcomes, asthma, etc.) may be partly attributed to systematic differences in adverse exposure burdens, such as exposure to environmental pollution, poor quality built environments, or social stressors. For example, disproportionate air pollution exposure burdens among non-Hispanic blacks (NHB)

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versus non-Hispanic whites (NHW) have been implicated in racial disparities in health outcomes such as asthma (Hill et al., 2011; Nachman and Parker, 2012) and cancer (Apelberg et al., 2005). Racial residential segregation (RRS) of NHB, which refers to the purposeful and systematic geographic separation of NHB into different residential spaces separate from the majority NHW population, may underlie race-based disparities in environmental exposures (Massey and Denton, 1988; Gee and Payne-Sturges, 2004; Morello-Frosch and Lopez, 2006). Through the disinvestment of educational resources and employment opportunities and the concomitant concentration of multiple disadvantages related to such factors as environmental hazards, poor quality built environment, and food insecurity, among others, segregation fosters residential environments inimical to health (Williams and Collins, 2001; Acevedo-Garcia et al., 2003). Indeed, RRS has been associated with a range of adverse health outcomes like infant and adult mortality (Laveist, 1993), poor pregnancy outcomes (Grady, 2006; Osypuk and Acevedo-Garcia, 2008; Anthopolos et al., 2014), and poor cardiovascular health (Kershaw et al., 2011).

RRS is a multidimensional phenomenon with five distinct dimensions, namely, evenness (also called dissimilarity), isolation (or exposure), concentration, centralization, and clustering (Massey and Denton, 1988). Evenness refers to the degree to which racial minority group members may be over or underrepresented across spatial units in a metropolitan area relative to overall group representation. Isolation (exposure) is defined as the extent to which minorities are exposed to majority group members by sharing a residential neighborhood. Concentration, centralization, and clustering capture aspects of the geographic distribution of racial minorities relative to majority group members across a metropolitan area. Historically, RRS developed through the systematic steering of NHB into separate residential spaces through political, economic, and social forces (Williams and Collins, 2001). Despite legal measures to abolish segregation, the consequences of RRS persist today: according to the dimension of evenness, in US metropolitan areas in 2000, on average, two-thirds of the NHB population would need to relocate to another neighborhood to de-segregate a given US city (Gee and Payne-Sturges, 2004). While often overlooked, NHB outside of urban areas in the US also remain segregated. For example, Lichter et al. (2007) find that levels and trends in evenness of NHB in suburban and rural US communities are similar to those observed in urban areas.

In studies examining the role of RRS in racial disparities in air pollution exposures, US metropolitan areas with higher levels of segregation have been shown to have higher overall levels of air pollution (Morello-Frosch and Lopez, 2006). Few in number, these studies have been limited to urban areas (Jones et al., 2014; Rice et al., 2014), and typically measure segregation at a global scale (for example, using city or metropolitan area boundaries) based on the dimension of evenness. In complementary research, a plethora of studies have used racial composition (e.g., percentage NHB) to reveal racial disparities in air pollution exposure, without necessarily intending to proxy segregation (Miranda et al., 2011; Bell and Ebisu, 2012). While important, these studies have not accounted for the relationships among nearby neighborhoods (Brochu et al., 2011); were often limited to areas proximate to air pollution monitors e.g., (Miranda et al., 2011; Bell and Ebisu, 2012); or overlooked potential differences in exposure burdens in urban versus nonurban areas, due to limited ambient monitoring data in less urban areas (Bell and Ebisu, 2012).

We assess the role of one dimension of RRS, racial isolation (RI), in racial differences in exposure to particulate matter with an aerodynamic diameter of $<2.5\ \mu$ ($PM_{2.5}$) and ozone (O_3), in both urban and nonurban tracts across the eastern two-thirds of the US. Ozone and $PM_{2.5}$ are criteria air pollutants that are linked with adverse health outcomes (World Health Organization, 2004) and in nonattainment of the National Ambient Air Quality Standards (NAAQS) in multiple US communities (U.S. Environmental Protection Agency, 2008; U.S. Environmental Protection Agency, 2012a). We choose to focus on RI of NHB because, compared to the commonly employed dimension of evenness, isolation may be more closely linked to health by serving as a proxy for the concentration of multiple disadvantage into a single ecological space (Shihadeh and Flynn, 1996; Acevedo-Garcia et al., 2003). While RRS is standardly conceived as a global construct, we use a previously derived spatial measure of local RI of NHB. At a more resolved geographic scale than the city or metropolitan area level, the local RI index may be more proximally linked to individual health (Anthopolos et al., 2011), and unlike commonly applied aspatial measures of segregation, our spatial index accounts for relationships among nearby geographic units (i.e., census tracts). We use simulated air pollution concentrations to estimate exposure burdens among subpopulations living in areas without air pollution monitors. Although previous work has examined disparities in air pollution exposure for urban and rural populations in selected US cities and states (Yanosky et al., 2008; Brochu et al., 2011; Gray et al., 2013; Jones et al., 2014), the few studies examining disparities based on larger study samples noted that the use of monitoring data precluded assessing exposure in more rural populations (Miranda et al., 2011; Bell and Ebisu, 2012). Furthermore, studies examining other dimensions of RRS and air pollution have done so almost exclusively in metropolitan areas (Lopez, 2002; Morello-Frosch and Jesdale, 2006; Jones et al., 2014; Rice et al., 2014). This study extends the current understanding of racial disparities in air pollution exposures by: 1) estimating ambient air pollutant concentrations in understudied (i.e., rural) populations; and 2) using a spatial measure of local RI to estimate its association with air pollution in urban, suburban, and rural US census tracts.

2. Methods

2.1. Study area

We focus on the eastern two-thirds of the US because this is the area for which the Community Multiscale Air Quality Model (CMAQ) downscaler provides census tract level estimates of $PM_{2.5}$ and O_3 concentrations (census tracts = 53,124).

2.2. Data sources

2.2.1. Demographic data

For each census tract in the study area, we obtained population characteristics from 2000 Census data, including racial composition (U.S. Census Bureau, 2000a), age, educational attainment, poverty, and unemployment (U.S. Census Bureau, 2000b), in addition to tract-level Rural-Urban Commuting Area (RUCA) codes (U.S. Department of Agriculture, 2003). Although 2000 is not the most recent census year, it best matches our study timeframe of 2002–2006, which is determined by the years for which downscaler output are available. According to the US Census Bureau, tracts are small, relatively permanent statistical subdivisions of counties, designed to be fairly homogenous units with respect to socio-demographic characteristics and living conditions, containing on average 4,000 residents (U.S. Census Bureau, 2000c). Consistent with at least one previous study of racial/ethnic disparities in air pollution exposure (Bell and Ebisu, 2012), tracts with population < 100 ($n = 317$, <1%) were excluded from analysis.

2.2.2. Air pollution data

Concentrations of $PM_{2.5}$ and O_3 were obtained for 2002–2006 from two different sources: (1) the CMAQ downscaler (Berrocal et al., 2012; Holland, 2012); and (2) the US EPA Air Quality System (AQS) database (U.S. Environmental Protection Agency, 2012b). The AQS database contains observations from the National Air Monitoring Stations and State and Local Air Monitoring Stations (NAMS/SLAMS) network. Annual averages of 24-h ambient $PM_{2.5}$ and 8-h maximum O_3 concentrations were obtained for each year between 2002 and 2006 for 1215 $PM_{2.5}$ and 1,043 O_3 monitoring locations in the study area.