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Do Fine Particulate Air Pollution (PM_{2.5}) Exposure and its Attributable Premature Mortality Differ for Immigrants Compared to those Born in the United States?

Kelvin C Fong¹, Michelle L Bell¹

¹Yale School of the Environment, Yale University, New Haven, Connecticut, USA

Abstract

In the United States (US), immigrants constitute a considerable and growing proportion of the general population. Compared to the US-born, immigrants have differential health risks, and it is unclear if environmental exposures contribute. In this work, we estimated disparities between immigrants and the US-born in fine particulate matter (PM_{2.5}) exposure and attributable premature mortality, including by region of origin and time since immigration. With PM_{2.5} estimates from a validated model at ~1 km² spatial resolution and residential Census tract population data, we calculated the annual area-weighted average PM_{2.5} exposure for immigrants overall, the US-born, and immigrants separately by geographic region of origin and time since immigration. We then calculated the premature mortality attributed to PM_{2.5} for each population group, assessing disparities by immigrant status in PM_{2.5} exposures and attributable premature mortality for the US as a whole, and to assess spatial heterogeneity, in each US county. Overall, immigrants were exposed to slightly higher PM_{2.5} (0.36 µg/m³, 3.8%) than the US-born. This exposure difference translates to 2.11 more premature deaths attributable to PM_{2.5} per 100,000 in population for immigrants compared to the US-born in 2010. Immigrant – US-born disparities in PM_{2.5} and attributable premature mortality were more severe among immigrants originating from Asia, Africa, and Latin America than those from Europe, Oceania, and North America. Disparities between immigrant groups by time since immigration were comparatively small. Sensitivity analyses using 2000 data and a non-linear set of PM_{2.5} attributable mortality coefficients identified

Corresponding Author: Kelvin Fong, ScD, 301 Prospect St, New Haven, CT 06511, kelvin.fong@yale.edu.

Author Contributions:

Kelvin C Fong: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – Original draft. **Michelle L Bell:** Conceptualization, Methodology, Funding acquisition, Project administration, Resources, Supervision, Writing – Review & editing.

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Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Human Subjects or Experimental Animals

This paper does not deal with research on human subjects or experimental animals.

Data Statement

All data used in this study are publicly-available. Please refer to the methods and references to access these data.

similar patterns. Our findings suggest that environmental exposure disparities, such as in PM_{2.5}, may contribute to immigrant health disparities in the US.

Keywords

Air pollution; Health disparity; Immigrant health; PM_{2.5}; Environmental justice

1. Introduction

Fine particulate air pollution, or particulate matter 2.5 µm or less in aerodynamic diameter (PM_{2.5}), is a well-established environmental exposure associated with health detriments (Brook et al., 2010; Cohen et al., 2017). Prior research in clinical and experimental settings found that PM_{2.5} evokes detrimental bodily responses such as vascular dysfunction, heart arrhythmia, inflammatory cytokine release, impaired glucose metabolism, and neurohormonal imbalance (Franklin et al., 2015; Zhang et al., 2020). Long-term, yearly-averaged exposure to PM_{2.5} has been linked to increased risk for cardiovascular disease (Hayes et al., 2019), respiratory disorders (Pun et al., 2017), premature mortality (Di et al., 2017), and type 2 diabetes (Yang et al., 2020), among other adverse health endpoints (Ritz et al., 2019). Globally, PM_{2.5} ranks as the fifth highest contributor to mortality, with an estimated 4.2 million (95% confidence interval (CI): 3.7, 4.8 million) deaths in 2015 (Cohen et al., 2017). In the United States (US), an estimated 100,000 to 200,000 premature deaths per year are attributable to PM_{2.5} exposure (Fann et al., 2018).

Despite its importance as an exposure with high public health burden, little is known regarding disparities in PM_{2.5} exposure between immigrants and the US-born, and amongst immigrants. In the US, immigrants (*i.e.* foreign-born) exhibit different health risks compared to the US-born and amongst themselves depending on factors such as country of origin (Dupre et al., 2012; Mehta et al., 2016). For instance, while immigrants overall have been shown to have longer life expectancy than the US-born, immigrants from Asia exhibited lower life expectancy than Asians born in the US (Singh and Miller, 2004). Moreover, cause-specific mortality risks vary when comparing immigrants and the US-born with lower mortality risks from cardiovascular disease, but higher risks from some cancers for immigrants (Singh and Siahpush, 2001). Furthermore, within some racial/ethnic groups (*e.g.* East Asian) risks for morbidities such as hypertension, obesity, and diabetes are higher when comparing immigrants to their US-born counterparts (Horlyck-Romanovsky et al., 2019; Singh et al., 2013). Differences in health risks between immigrants and the US-born could be affected by variation in diet, linguistic and cultural barriers, and health care as a higher proportion of immigrants are without health insurance compared to the US-born (Arandia et al., 2012; Eamranond and Hu, 2008; Singh and Miller, 2004). Initial research in other countries such as Canada found that immigrants had higher PM_{2.5} exposures and were at higher risks for cardiovascular mortality attributable to PM_{2.5} exposure compared to the Canada-born (Erickson et al., 2020).

Evaluating environmental exposures of immigrants and the US-born, and among immigrants by region of origin or time since immigration, can help us gauge the impact of the

environment on immigrant health disparities. Currently around 44 million people, or 14% of the total population, in the US are immigrants (Passel and Cohn, 2008; Vespa et al., 2018). This figure is expected to rise to 69 million, or 17% of the total population, by 2060 (Vespa et al., 2018). The extent to which environmental exposures such as PM_{2.5} contribute to health disparities between immigrants and the US-born, and among immigrants, is not well understood (Eamranond and Hu, 2008). Compared to other health determinants such as socioeconomic status, environmental exposures and their health effects comprise an understudied area. A better understanding of PM_{2.5} exposure disparities can lead to insights on how to reduce the health burden of PM_{2.5} on vulnerable immigrant population subgroups.

To address this research gap, we explore annual average PM_{2.5} exposure disparities between immigrants and the US-born. Among immigrants, we further calculate disparities by region of origin and time since immigration. To gauge the implications of PM_{2.5} exposure disparities, we conduct a health impact analysis and estimate the number of premature deaths attributable to PM_{2.5} in immigrants and the US-born.

2. Materials and Methods

2.1 PM_{2.5} Exposure Disparity by Immigrant Status

PM_{2.5} ambient monitoring networks do not provide the spatial coverage necessary to estimate exposure at all locations in the study area of the contiguous US. Therefore, we used monthly modelled estimates at 0.01° x 0.01° resolution, equivalent to around 1 km² (van Donkelaar et al., 2019). These PM_{2.5} exposure surfaces were generated using geographically weighted regression with inputs from satellite observations of aerosol optical depth (AOD), PM_{2.5} composition estimates from a chemical transport model (GEOS-Chem), and ground-level observations from monitoring networks. Over its prediction period across North America, the PM_{2.5} estimation model achieved a cross-validation R² of 0.70 for annual PM_{2.5} mass concentrations, indicating high prediction accuracy. There were spatial differences in PM_{2.5} model performance; its prediction accuracy, when compared to ground-level monitoring, was highest in the midwestern US, followed by the southwest, northeast, south, and northwest. In general, areas with higher PM_{2.5} had higher prediction accuracy. We estimated annual PM_{2.5} averages in 2010 for 72,539 contiguous US Census tracts via area weighting of gridded estimates.

We then calculated PM_{2.5} exposure by immigrant status using data from the decennial 2010 US Census (U.S. Census Bureau, 2019). The decennial Census has the most complete coverage of the US residential population and has lower sampling error compared to the American Community Survey (U.S. Census Bureau, 2018). We retrieved counts of the number of residents who were immigrants (*i.e.* foreign-born) and US-born for each of 72,539 Census tracts. Of these areas, 642 reported zero total population and an additional 2,533 had zero immigrant residents. Within the immigrant population, we collected data on resident counts by immigrants' region of origin: Africa, Asia, Europe, Latin America, North America, and Oceania (Supplementary Material: Table S1). We additionally retrieved immigrant resident counts by time since immigration (< 10 years, 10 to 20 years, 20 to 30 years, and 30 years). Lastly, we assigned each Census tract resident to the corresponding Census tract average PM_{2.5} exposure estimate. With this data set, we calculated average

yearly PM_{2.5} exposure by immigrant status (immigrant or US-born), immigrants by region of origin, and immigrants by time since immigration subgroups. Furthermore, we calculated the exposure disparity by immigrant status, estimating the difference in yearly average PM_{2.5} exposure between an immigrant and US-born resident at the national scale while accounting for overall PM_{2.5} prediction error. To evaluate possible spatial heterogeneity, we repeated these calculations of exposure disparities at the US county scale. We also generated annual estimates and corresponding US Census tract averages for 2000 for sensitivity analysis.

2.2 Estimating Premature Mortality Attributable to PM_{2.5}

To assess the health burden associated with the PM_{2.5} exposure disparities between immigrants and the US-born, and among immigrants by region of origin, we applied a health impact function (Fann et al., 2018; Hubbell et al., 2009). For each population group, we estimated the number of premature deaths attributable to PM_{2.5} exposure in 2010 (and 2000 for sensitivity analysis) using the following formula:

$$y_{ijk} = m_{0ik} \times (e^{\beta \times C_{ij}} - 1) \times P_{ijk} \quad [1]$$

where y_{ijk} is the total number of premature deaths in year i (*i.e.* 2000 or 2010), in Census tract j , of population group k (*i.e.* immigrants, US-born, immigrants from a specific region of origin, or immigrants of a certain time since immigration); m_0 represents the baseline mortality rate in year i for group k ; β is the mortality risk coefficient linking PM_{2.5} to mortality; C_{ij} is the average yearly PM_{2.5} mass concentration for year i and tract j ; and P_{ijk} is the population count in year i for tract j and group k .

We obtained baseline yearly mortality rates (m_0) from the US Census of Disease Control and Prevention (CDC) (Centers for Disease Control and Prevention, 2020). Mortality rates by immigrant status, and more specifically by region of origin or time since immigration were not available; we therefore retrieved adult (> 30 years old) mortality rates for the general population. Moreover, as data were not available at a spatial resolution as fine as Census tracts, we retrieved county-level rates and applied them to matching Census tracts using area-weighted averaging. Area-weighting is accomplished by computing the weighted mean of every PM_{2.5} estimate pixel overlapping a predefined Census tract based on the % overlap each pixel has with the Census tract. To account for temporal variability in mortality rates, we used yearly mortality rates for three-year periods around the year of interest (*i.e.* 2009-2011 for year 2010). Further details on these parameters are given in Supplementary Material: Equation S1.

The mortality risk coefficient (β) was based on results from a re-analysis study of the long-term effects of PM_{2.5} exposure in the American Cancer Society Cancer Prevention Study II cohort (Krewski et al., 2009). That study, which tracked a large national cohort of over 360,000 participants with over 12 years of follow-up, estimated a hazard ratio of 1.06 (95% CI: 1.04, 1.08) per 10 µg/m³ increase in annual average exposure to PM_{2.5}. We derived the mortality risk coefficient from this study since it used a population representative of US demographics and has been used in other health impact analyses (Fann et al., 2017; Thind et

al., 2019), allowing us to compare our results to existing literature. As a sensitivity analysis, we applied a set of mortality coefficients allowing for non-linearity in the PM_{2.5} concentration and attributable premature mortality relationship (Nasari et al., 2016; Pope et al., 2019).

We determined population counts (P) of residents in each group (immigrant, US born, immigrant group by region of origin) residing in each Census tract by year (from the US Census (U.S. Census Bureau, 2019)). For each Census tract, we ascertained the number of US-born, total immigrants, immigrants from each of the regions of origin (Africa, Asia, Europe, Latin America, North America, and Oceania, and immigrants by time since immigration (< 10 years, 10 to 20 years, 20 to 30 years, and ≥ 30 years). Some Census tracts had no residents who were immigrants.

Finally, we summated the total number of estimated premature deaths associated with PM_{2.5} exposure in each year (2010, 2000 for sensitivity analysis) for each population group in all Census tracts nationally or by county to assess spatial heterogeneity:

$$y_{ik} = \sum_j y_{ijk} \quad [2]$$

We performed all analysis with the statistical programming language R (R Core Team, 2020). We evaluated statistical significance at an alpha level of 0.05; we used weighted two-sided t -tests to compare averages of two groups.

3. Results

3.1 PM_{2.5} Exposure of Population Groups

Overall, immigrants had slightly higher average annual PM_{2.5} exposure than the US-born at the national level. Table 1 summarizes the population and average annual PM_{2.5} exposure of US residents by immigrant status. On average, immigrants were exposed to annual average PM_{2.5} levels 0.36 (2.5th and 97.5th percentile: 0.19, 0.53) µg/m³ higher compared to the US-born. With respect to immigrants from different regions of origin, those originating from Asia, Africa, and Latin America had higher annual average exposures than those from Europe, Oceania, and North America. Differences in average PM_{2.5} exposure were smaller between immigrants by time since immigration than by region of origin; those who immigrated 20 to 30 years prior to 2010 had the highest exposure, followed by 10 to 20 years, < 10 years, and ≥ 30 years. Table S3 tested for statistically significant differences between average PM_{2.5} exposures between population subgroups. Most of the comparisons between population subgroups by region of origin were statistically significant while only immigrants who immigrated ≥ 30 years prior to 2010 had statistically lower exposure compared to those who immigrated 20 to 30 years prior to 2010.

We observed spatial heterogeneity in county-level annual average PM_{2.5} exposure (Figure 1A). The county-level annual average PM_{2.5} exposure for the total general population was highest in southern California at 14.96 µg/m³ (Supplementary Material: Table S2). Overall,

counties in eastern US had higher $PM_{2.5}$ than those in the west, with the lowest county averages east of the Rocky Mountains.

3.2 Immigrant Proportion in General Population

On the national level, the proportion of the general population who were immigrants was 12.7% (Table 1). Of the 38.39 million immigrant residents in the US, the most populous group originated from Latin America (53.5% of total immigrant population), followed by Asia (27.5%).

We also observed spatial heterogeneity in the immigrant proportion by county (Figure 1B). Immigrant proportions by US counties were highest by the Californian coast, close to the US-Mexico border, and in Southern Florida. The percent of immigrants in each county ranged from 0.01% to 51.1% with an average of 4.34% and median of 2.39% (Supplementary Material: Table S2).

3.3 Disparity between Immigrants and US-born in Premature Deaths Attributable to $PM_{2.5}$ Exposure

Table 2 summarizes the estimated number of premature deaths attributable to $PM_{2.5}$ by population group for the US-born, immigrants to the US (overall), and immigrants by region of origin. In the general US population, we estimated 163,940 (2.5th and 97.5th percentiles: 31,140, 379,270) total deaths attributable to $PM_{2.5}$ in 2010. We also calculated the number of premature deaths per 100,000 persons attributable to $PM_{2.5}$ in each population group by immigrant status (US-born, immigrants overall, immigrants by region of origin, and immigrants by time since immigration). Based on higher exposures, immigrants overall had higher premature mortality attributable to $PM_{2.5}$ than the US-born. In 2010, this immigrant – US-born disparity in premature mortality attributable to $PM_{2.5}$ was 2.11 deaths per 100,000 in population.

Based on exposure differences among immigrants, those originating from Asia, Africa, and Latin America had the highest premature mortality attributable to $PM_{2.5}$ (Table 2). Immigrants from Europe and Oceania had lower-than-average premature mortality attributable to $PM_{2.5}$ and immigrants from North America had the lowest. By time since immigration, premature mortality attributable to $PM_{2.5}$ were similar between groups, with those in the 20 to 30 years since immigration having the highest mortality burden. In sensitivity analyses that applied a set of non-linear $PM_{2.5}$ concentration and premature mortality coefficients, the attributable premature mortality from $PM_{2.5}$ estimates were smaller overall compared to the main analysis (Supplementary Material: Table S4). Differences between population groups in premature mortality attributable to $PM_{2.5}$ were in the same direction but larger in magnitude. We present results with a constant parameter for the $PM_{2.5}$ concentration and premature mortality relationship as they are more comparable with prior studies, and that the differences between population groups were more conservative.

We evaluated spatial heterogeneity of the overall immigrant vs. US-born disparities in premature mortality attributable to $PM_{2.5}$ exposure. Figure 2 maps the county-level disparity between an immigrant group by region of origin and US-born in premature mortality

attributable to PM_{2.5}. A density plot shows a slight skew towards higher premature mortality attributable to PM_{2.5} among immigrants than in the US-born, which we identify as a *positive* immigrant – US-born *premature mortality disparity*. We found that there was a higher premature mortality attributable to PM_{2.5} for immigrants than the US-born in 58.9% of US counties. There was no clear geographic pattern for where counties with immigrant – US-born premature mortality disparity are located, although there are some areas in the US with clusters of immigrant – US-born premature mortality disparity (*e.g.* coastal California, southern Florida, and along the US-Mexico border). We visualized the error in the estimated premature mortality attributable to PM_{2.5} exposure, noting slightly higher errors in the western parts of the US (Supplementary Material: Figure S1). Figure 2 also visualizes the county-level immigrant proportion in the total general population, and shows whether or not a county is below or above the national median. We observed that the proportion of the population that is immigrants in a county was higher along the coasts and in the Southwest; most counties in the northern Midwest and in the inland areas of the eastern US had a county immigrant proportion lower than the median. We also identified counties at the extreme ends of premature mortality disparity attributable to PM_{2.5} and immigrant population proportion (Supplementary Material: Figure S2). Counties with high immigrant – US-born disparity and high immigrant population proportion (*i.e.* top 10% of each measure) were in northern Washington, southern California, and southeastern New York. Counties with lower immigrant – US-born disparity and low immigrant proportion (*i.e.* lowest 10% of each measure) were mostly scattered throughout the mid-eastern half of the US.

We also investigated the disparities in PM_{2.5}-attributable premature mortality among immigrants from specific regions of origin and the US-born (Figure 3). For immigrants from some regions (*i.e.* Africa and Oceania), there were many counties for which no immigrants who originated from these regions resided. Thus, the immigrant – US-born disparity for these groups of immigrants, especially in central US, could not be calculated and are thus displayed as white in the maps. In the remaining counties with a non-zero number of immigrants from Africa or Oceania, the spatial pattern of immigrant – US-born disparities in premature mortality attributable to PM_{2.5} appears similar to that of the overall immigrant – US-born disparities (Figure 2). Comparing the spatial patterns for immigrants from Asia, Europe, Latin America, and North America, differences depending on region of origin are more apparent. The region of origin whose spatial pattern most resembles that of the overall immigrant population is Latin America, followed by Asia (Figure 3). This is expected since among immigrants, the most populous group comes from Latin America then Asia (Table 1). Counties along the northern US border had the highest percentages of immigrants from North America (*i.e.* Canada). Counties in New York and along the Northeast Corridor had the highest proportions of immigrants from Europe. Some inland counties of California had high immigrant proportion from Europe, North America, or Latin America and lower immigrant – US-born disparity, indicating a higher premature mortality burden from PM_{2.5} in the US-born than in the immigrant group.

Finally, we explored disparities in PM_{2.5}-attributable premature mortality among immigrants by times since immigration (Figure 4). The spatial pattern of immigrant – US-born disparities in premature mortality attributable to PM_{2.5} was similar to the overall immigrant – US-born map (Figure 2). There were some spatial differences in immigrant proportion by

times since immigration. Recent (< 10 years) immigrants' proportion of the total population were low in northern areas compared to the rest of the country. In contrast, the proportion of the total population for immigrants who immigrated ≥ 30 years prior to 2010 was high in northern areas compared to other parts of the country, relative to the immigrant proportion of the total population patterns for those with shorter times since immigration. In summary, spatial patterns in PM_{2.5} mortality disparities between immigrants and the US-born, when comparing immigrant groups with different times since immigration to the US-born were similar to spatial patterns comparing immigrants overall to the US-born. When comparing between immigrant subgroups by time since immigration, there were some minor differences in immigrant proportion of the total population when comparing the map for those who immigrated ≥ 30 years prior to 2010 to more recent immigrants.

3.4 Sensitivity Analysis with 2000 Data

We repeated our analysis using 2000 data as sensitivity analysis. We found similar patterns of spatial heterogeneity in county-level annual average PM_{2.5} and immigrant proportion in total population (Supplementary Material: Figure S3). Overall, there were fewer immigrants living in the US in 2000 than in 2010 (Supplementary Material: Table S5). The US-born population outnumbered immigrants overall 8-to-1 in 2000 and just under 7-to-1 in 2010. The annual average PM_{2.5} was higher in 2000 than 2010. The immigrant – US-born disparity in average annual PM_{2.5} exposure was larger in 2000 at 1.25 $\mu\text{g}/\text{m}^3$. Compared to 2010, county-specific average annual PM_{2.5} was higher while immigrant, overall and by region of origin, proportion in the total population was lower in 2000 (Supplementary Material: Table S8)

PM_{2.5} and attributable premature mortality disparities overall, by immigrants' region of origin, by immigrants' times since immigration, and their respective spatial patterns by county in 2000 were similar to those of 2010. As PM_{2.5} exposure disparities were larger in 2000, the overall immigrant – US-born disparity in premature mortality attributable to PM_{2.5} was also larger at 7.59 deaths per 100,000 in population. By region of origin, those who immigrated from Asia, Latin America, and Africa, as in 2010, had the highest PM_{2.5} exposure and premature mortality burden from PM_{2.5} in 2000 compared to immigrants from Europe, Oceania, and North America (Supplementary Material: Tables S5 and S6). In contrast to 2010, PM_{2.5} exposure and attributable premature mortality in 2000 were higher among immigrants from Europe or Oceania compared to the US-born (Supplementary Material: Tables S6 and S9). When comparing subgroups by time since immigration, those who immigrated 10 to 20 years prior to 2000 (20 to 30 years prior to 2010) had the highest PM_{2.5} exposure and attributable premature mortality. Although the differences between subgroups by times since immigration in PM_{2.5} exposure were larger in 2000, similar to 2010, those who had the longest time since immigration (≥ 30 years) were the least exposed followed by the most recent immigrants (< 10 years since immigration). Applying a set of non-linear PM_{2.5} and attributable premature mortality coefficients found, in contrast to 2010, larger premature mortality attributable to PM_{2.5} in the total population, US-born, and immigrants overall, compared to the main analysis (Supplementary Material: Tables S6 and S7). Similar to 2010 results, the differences in premature mortality attributable to PM_{2.5} between subgroups by immigrants' region of origin or time since immigration were more

conservative in the main analysis compared to the sensitivity analysis with non-linear premature mortality coefficients. Inspecting county-specific premature mortality disparities between immigrants and the US-born, or immigrants from specific regions of origin or of a specific time period since immigration and the US-born, the spatial patterns across the US were similar to those in 2010 (Supplementary Material: Figures S4 to S7). A slightly higher majority of US counties (60.0%) had a higher premature mortality burden attributable to PM_{2.5} for immigrants overall than the US-born in 2000 than in 2010.

4. Discussion

Using US Census data and air pollution modeling predictions, we found that PM_{2.5} exposures were 3.8% higher in immigrants to the US than the US-born. Consequently, premature mortality attributable to PM_{2.5} was estimated to be higher in immigrants compared to the US-born. Across the US, there was spatial heterogeneity in the immigrant – US-born disparity in PM_{2.5} exposure and its attributable premature mortality. Furthermore, there were differences in disparities depending on the immigrants' region of origin.

Higher PM_{2.5} exposures and attributable premature mortality in immigrants overall compared to the US-born, and in immigrants originating in some world regions compared to others, may be explained by differences in immigrant settlement patterns and socioeconomic status (SES). Historically, immigrants to the US settle in more urban areas, usually in select *gateway* cities (Hempstead, 2007). Immigrant settlement patterns show a preference for existing immigrant communities, where there may be existing family and cultural ties (National Academies of Sciences, 2015). As urban areas tend to have higher PM_{2.5} levels compared to rural areas, immigrant settlement preferences may explain the immigrant – US-born disparity in PM_{2.5} exposure. SES differences between immigrants and the US-born, and among immigrant groups, may influence some immigrants' residence in areas with higher PM_{2.5}, and may contribute to other disparities, although other factors could also play a role. On average, immigrants had lower household income compared to the US-born (Singh and Hiatt, 2006). Among immigrant groups by region of origin, those from Latin America had lower SES compared to those from other regions (National Academies of Sciences, 2015). Prior research found that metropolitan areas with lower costs of living had the largest increases in immigrants from 1990 to 2000 (Baird et al., 2008). Since areas with lower SES had higher levels of PM_{2.5} (Hajat et al., 2015), links between immigration migration and SES likely contribute to our finding of higher PM_{2.5} exposures and premature mortality burden in immigrants overall compared to the US-born, and in some immigrant groups (*i.e.* from Latin America) compared to others (*i.e.* Europe).

To our knowledge, no study to date has investigated air pollution exposure disparities between immigrants and the US-born on the national scale. Existing research on environmental exposures and immigrants has been in occupational settings (Gany et al., 2017; Moyce and Schenker, 2017; Pappalardo and Mosnaim, 2018). These studies are limited in informing PM_{2.5} exposure disparities by foreign-born status in the general population. Questionnaire-based studies have assessed immigrants' perception of air pollution. Hispanic immigrants interviewed in Spanish expressed lower concern for air pollution as a health concern compared to those interviewed in English (Johnson, 2011). On

the other hand, residents of a neighborhood with predominantly Chinese immigrant population in Boston expressed high concern for health effects from traffic exhaust exposure (Brugge et al., 2000). These questionnaire-based studies did not quantify PM_{2.5} exposure disparities between immigrants and the US-born.

A study using Census data and modeled air pollution, similar to our study, found that in 2006, immigrants to Canada were exposed to 1.55 µg/m³ higher PM_{2.5} than the Canada-born (Pinault et al., 2017). The magnitude of this exposure disparity in Canada is larger than the overall national disparity we found between immigrants and the US-born (Table 1).

We can also draw comparisons to prior US-based studies that investigated PM_{2.5} exposure disparities by race/ethnicity, although not by immigrant status. A recent study using Census data found that average annual PM_{2.5} exposures between 1990 and 2010 were highest for non-Hispanic African Americans, followed by Asians and Hispanics (Woo et al., 2019). These disparities by race/ethnicity were estimated to be between 1 to 2 µg/m³ in PM_{2.5}, which are similar to the magnitude of PM_{2.5} exposure disparities by immigrant status in our study. Other studies using cohort and administrative data also documented racial/ethnic differences in exposure to air pollution, with higher exposure for minorities compared to whites (Parker et al., 2018). Although results from these prior studies cannot be directly compared to those in this study, almost all immigrants from Asia, Africa, and Latin America are racial/ethnic minorities in the US while the majority of immigrants from Europe, North America, and Oceania are white. In this way, our finding of higher PM_{2.5} exposures in immigrants overall compared to the US-born, and higher exposures in immigrants from Asia, Africa, and Latin America compared to those from Europe, North America, and Oceania are consistent with results from prior studies on exposure disparities by race/ethnicity.

We did not find convincing evidence of differences in PM_{2.5} exposure and attributable premature mortality by time since immigration (Tables 1 and 2). Although the immigrant subgroup with the longest time since immigration (> 30 years) was the least exposed to PM_{2.5} in both 2010 and 2000, there was no clear pattern of increased or decreased exposures by time since immigration. We are not aware of existing studies that evaluated PM_{2.5} exposure differences by immigrant time since immigration, which limits our ability to compare our results to prior work.

Our estimates of premature deaths attributable to PM_{2.5} are similar with those from recent studies. In the total US population, we estimated 163,940 (2.5th and 97.5th percentiles: 31,140, 379,270) premature deaths attributable to PM_{2.5} in 2010 (Table 1). An US EPA study that employed a similar methodology but with a different set of PM_{2.5} data estimated 120,000 (95% CI: 83,000, 160,000) premature deaths from PM_{2.5} in 2010 (Fann et al., 2017). Other recent studies employing a health impact analysis approach on other years between 2005 and 2014 also estimated a similar number of premature deaths attributable to PM_{2.5}, with lower estimates in later years (Fann et al., 2018; Thind et al., 2019).

Consistent with the lack of studies on immigrant – US-born disparities in PM_{2.5} exposure, we are unaware of a national analysis on immigrant – US-born disparities in premature

mortality attributable to PM_{2.5}. Regarding disparities in air pollution-related mortality between immigrants and the US-born, one study found that, in 2005, high Latino immigrant population and economic deprivation was the strongest predictor of a Census tract being a spatial cluster of high lifetime cancer risk from air toxic exposures (Lievanos, 2015). Absent previous estimates of the disparities between immigrants and the US-born in premature mortality attributable to PM_{2.5}, we make comparisons to disparities by other demographic factors and to premature mortality attributable to other causes. When estimating premature deaths attributable to PM_{2.5} generated from electricity generation in 2014, researchers found disparities by race/ethnicity with African Americans having the highest mortality burden followed by whites, Asians, then Latinos (Thind et al., 2019). The disparity between African Americans and Latinos, the racial/ethnic groups with the largest disparity, was about 3.0 deaths per 100,000 population. This is almost 0.9 larger than the disparity between immigrants and the US-born, which in 2010 was 2.11 deaths per 100,000 population. To put our estimates into perspective with other causes of premature mortality, we note that the overall disparity between immigrants and the US-born in premature mortality attributable to PM_{2.5} was around one-fifth of premature mortality attributable to motor vehicle accidents, which was 11.3 deaths per 100,000 population (2010), or to drug poisonings, which was 12.3 deaths per 100,000 population (2010) (Johnson et al., 2014).

Our study had limitations. For PM_{2.5} exposure assessment and calculation of disparities by immigrant status, we relied on US Census data with estimated counts of each population group in each Census tract. Exposure assessment based on residential Census tract might not accurately represent each person's annual average PM_{2.5} exposure due to PM_{2.5} prediction model error, mobility patterns away from place of residence, and possible misreporting of immigrant population counts. Additionally, the Census data do not differentiate between documented and undocumented immigrants, and it was likely that those who were undocumented were not counted. Despite these limitations, Census data represent the largest source of residential information of US residents by immigrant status (U.S. Census Bureau, 2018). Furthermore, we expect that possible errors from our PM_{2.5} exposure assessment and calculations of disparities are non-differential and random, although future research could investigate this issue. Moving to our calculation of premature mortality attributable to PM_{2.5}, we were limited by the unavailability of population subgroup specific mortality rates. Ideally, we would employ a different baseline mortality rate specific to the US-born, immigrants overall, and immigrant subgroups by region of origin or time since immigration. If baseline mortality rates were higher in immigrants compared to the US-born overall, we would have found larger immigrant – US-born disparities in premature mortality attributable to PM_{2.5}. The all-cause mortality risk coefficient is another component of our calculations that could potentially differ by population subgroups. Our main analysis based this coefficient on a hazard ratio of 1.06 (95% CI: 1.04, 1.08) per 10 µg/m³ in PM_{2.5} (Krewski et al., 2009), which is commonly used in other recent health impact analyses on premature mortality attributable to PM_{2.5} (Fann et al., 2018; Fann et al., 2017; Thind et al., 2019). We assumed a mortality coefficient for the general population due to the lack of PM_{2.5} mortality hazard ratios by immigrant status and by immigrant region of origin. A recent Canadian study suggests that the PM_{2.5} mortality hazard ratio may be higher among immigrants to Canada than those born in Canada (Erickson et al., 2020). This study estimated slightly

higher all-cause mortality risk attributable to PM_{2.5} exposure among immigrants than those born in Canada, although the difference was not statistically significant. As the general population in the US is different than that in Canada, the estimation of hazard ratios by immigrant status, further divided by region of origin and time since immigration, should be an aim of future environment health disparities research. If the premature mortality coefficient due to PM_{2.5} exposure were higher among immigrant residents in the US than the US-born, then our estimates of premature mortality differences between immigrants overall and the US-born would have been conservative. Adding to this, our estimates of premature mortality attributable to PM_{2.5} could be conservative since the mortality coefficient we applied was lower relative to those found in other studies, such as that from a reanalysis of the Harvard Six Cities Study data, where the estimated mortality hazard ratio was 1.14 (95% CI: 1.07, 1.22) per 10 µg/m³ in PM_{2.5} (Lepeule et al., 2012). With a higher PM_{2.5} all-cause mortality hazard ratio, our estimates of premature mortality attributable to PM_{2.5} in all groups would have been larger, as would have been estimated disparities between groups. An important future direction would be a cohort study estimating the hazard ratios from PM_{2.5} exposure by immigrant status, including region of origin and time since immigration. Furthermore, understanding of PM_{2.5} exposure and attributable health disparities can advance via research into the contribution of factors such as age at the time of immigration or combinations of race/ethnicity with immigrant status, should such data be available. In summary, our estimates of disparities between immigrants and the US-born, and among immigrant groups by region of origin, in premature mortality attributable to PM_{2.5} were likely to be conservative and biased towards the null due to limited data that impacted our analytical choices, although further research is needed.

Our study led to novel insights on PM_{2.5} exposure and attributable premature mortality disparities between immigrants and the US-born, and among immigrant subgroups by region of origin or by time since immigration. Compared to prior work that estimated premature mortality attributable to PM_{2.5} nationally, we used PM_{2.5} exposure predictions with higher spatial resolution (~1 km² vs. 144 km²) (Fann et al., 2018; Fann et al., 2017). The increased spatial resolution likely decreased PM_{2.5} exposure assessment error. Our study also had almost complete spatial coverage of the contiguous US and high sample size. We were able to generate a national estimate of immigrant – US-born disparities in PM_{2.5} exposure and attributable premature mortality in the general population. At the same time, we also considered results by US county to highlight spatial heterogeneity. We found that the spatial heterogeneity in immigrant – US-born disparities in PM_{2.5} exposure was most likely driven by the sizable immigrant population from Latin America. Finally, although there have been prior studies on immigrant mortality disparities using US national data (Argeseanu Cunningham et al., 2008; Mehta et al., 2016; Singh and Siahpush, 2002), PM_{2.5} exposure disparities and their contribution to these health disparities were previously unexplored. Our findings motivate more research into immigrant – US-born disparities in other environmental exposures as well as the differences in health response to exposures by immigrant status.

5. Conclusion

Environmental health disparities among immigrants of the general US population is an understudied area. In this paper, we showed that average annual PM_{2.5} exposure was 0.36

(2.5th and 97.5th percentile: 0.19, 0.53) $\mu\text{g}/\text{m}^3$ or 3.8% higher among immigrants than the US-born, which led to higher premature mortality from $\text{PM}_{2.5}$ among immigrants overall and some immigrant subgroups. Between groups of immigrants by region of origin, we found higher exposures and premature mortality attributable to $\text{PM}_{2.5}$ in those who immigrated from Africa, Asia, and Latin America than those who immigrated from Europe, North America, and Oceania, which provides further insight into US racial/ethnic disparities. We did not find large differences by immigrants' time since immigration. Our results demonstrated spatial heterogeneity by county across the contiguous US, with the highest immigrant population proportion and immigrant – US-born disparities in southern California, northern Washington, and southeastern New York. This study represents an important step towards a better understanding of environmental health disparities between immigrants and the US-born, as well as among immigrant groups by region of origin. As immigrants are an increasing part of the US population, and many immigrants are entering old age, public health planning would benefit from further research on how environmental exposures contribute to immigrant health disparities.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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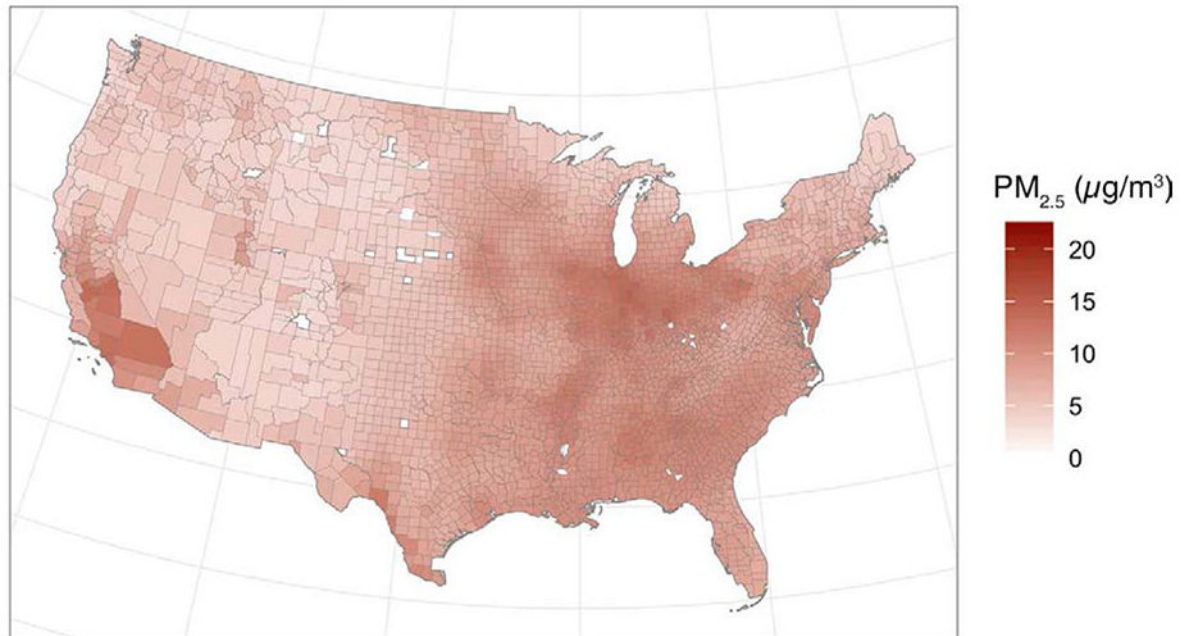
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Highlights

- Contributions of the environment to immigrant health disparities are understudied.
- Immigrants had higher fine particulate air pollution exposure than US native-born.
- Immigrants from Asia, Africa, and Latin America had the highest exposures.
- Air pollution exposure differences may lead to disparities in premature mortality.
- Disparities in air pollution and attributable premature mortality varied spatially.

A) County-Level Average Annual $PM_{2.5}$ 

B) Population Immigrant Proportion

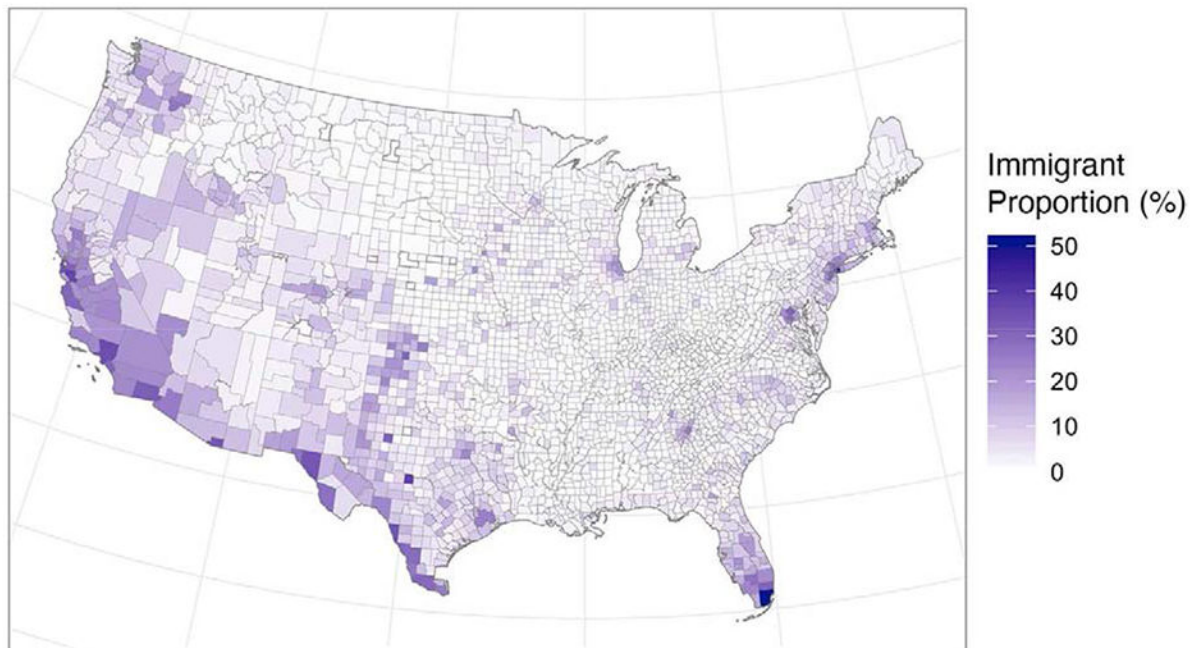


Figure 1: County-Level Average Annual $PM_{2.5}$ and Population Immigrant Proportion (%) in United States Counties in 2010.

Note: Immigrant proportion refers to the percentage of the population that was not born in the US. Counties. Census tracts with zero immigrants were shaded in white.

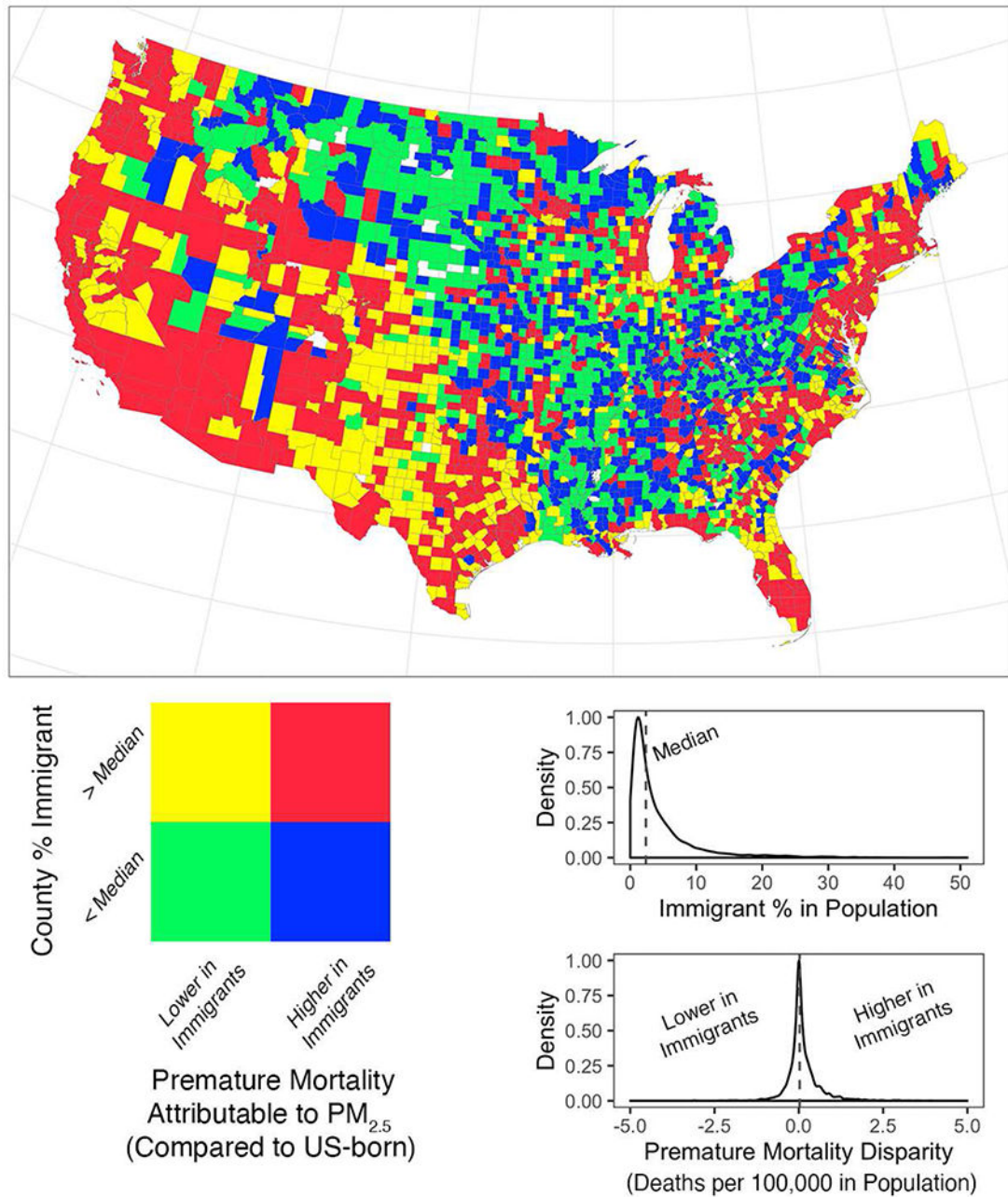


Figure 2:

Disparity between Immigrants and the US-Born in Premature Mortality Attributable to PM_{2.5} Exposure in 2010. The coloring scheme indicates whether a county had higher or lower estimated premature deaths attributable to PM_{2.5} in immigrants compared to the US-born (*positive or negative premature mortality disparity*) and whether the county was in the upper or lower half of county immigrant population proportions nationally. Counties with any Census tracts with zero immigrants were shaded in white. Density plots for each measure with its median value (dotted line) are also shown.

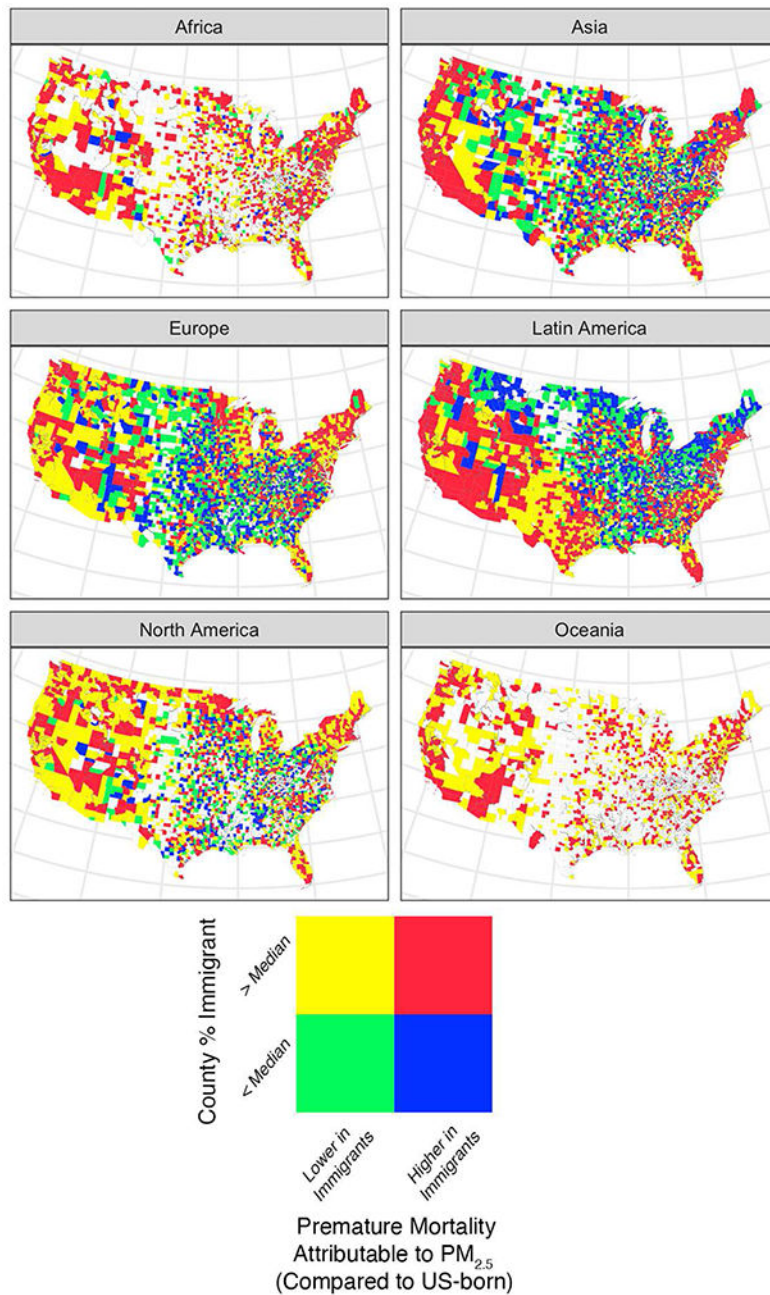


Figure 3: Disparity between Immigrants and the US-Born in Premature Mortality Attributable to PM_{2.5} Exposure by Immigrants' Region of Origin in 2010. The coloring scheme indicates whether a county had higher or lower estimated premature deaths attributable to PM_{2.5} in immigrants of the specified region of origin compared to the US-born and whether the county was above or below the national median for county immigrant population from the specified region of origin proportions.

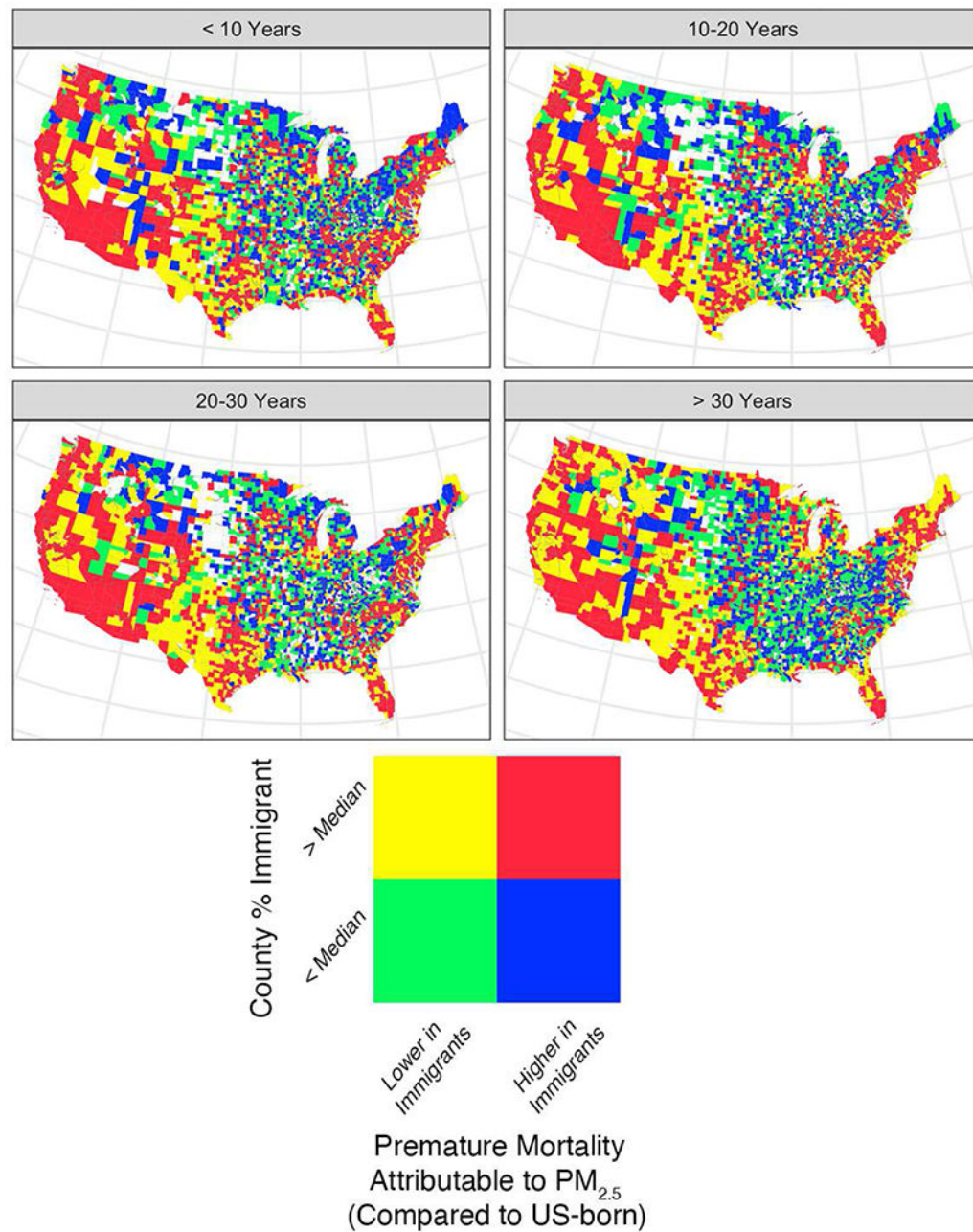


Figure 4:

Disparity between Immigrants and the US-Born in Premature Mortality Attributable to PM_{2.5} Exposure by Immigrants' Time since Immigration in 2010. The coloring scheme indicates whether a county had higher or lower estimated premature deaths attributable to PM_{2.5} in immigrants of certain time periods since immigration compared to the US-born and whether the county was above or below the national median for county immigrant population of a certain time since immigration proportions.

Table 1:

Average Fine Particulate Air Pollution (PM_{2.5}) Exposure for Those Born in the United States (US), Immigrants overall, Immigrants by Region of Origin, and by Time since Immigration in 2010. Values in parentheses indicate the 2.5th and 97.5th percentiles.

	Population (in millions)	Average PM _{2.5} (µg/m ³) Exposure
Total	301.94	9.57 (5.39, 13.41)
US-born	263.55	9.52 (5.28, 13.32)
Immigrants <i>overall</i>	38.39	9.88 (6.10, 13.75)
<i>by origin:</i>		
Africa	1.46	9.99 (6.40, 13.40)
Asia	10.54	10.02 (6.10, 13.80)
Europe	4.83	9.49 (5.77, 13.24)
Latin America	20.54	9.95 (6.17, 13.80)
North America	0.83	8.78 (4.88, 13.10)
Oceania	0.19	9.15 (5.10, 13.42)
<i>by time since immigration:</i>		
< 10 years	11.61	9.85 (6.10, 13.70)
10 to 20 years	10.97	9.89 (6.10, 13.70)
20 to 30 years	7.63	10.01 (6.11, 13.80)
30 years	8.18	9.79 (5.91, 13.75)

Table 2:

Premature Deaths and Mortality Rate Attributable to Fine Particulate Air Pollution (PM_{2.5}) for Those Born in the United States (US), Immigrants overall, Immigrants by Region of Origin, and Time since Immigration. Values in parentheses indicate the 2.5th and 97.5th percentiles and are reflective of variation in PM_{2.5} exposure exclusive of other uncertainties such as those in model predictions of PM_{2.5}.

	Total Premature Deaths in Thousands	Premature Mortality per 100,000
Total	163.94 (31.14, 379.27)	54.30 (10.31, 125.61)
US-born	142.39 (26.14, 329.09)	54.03 (9.92, 124.87)
Immigrants <i>overall</i>	21.55 (4.97, 49.30)	56.14 (12.96, 128.42)
<i>by origin:</i>		
Africa	0.83 (0.21, 1.84)	56.78 (14.08, 125.49)
Asia	6.00 (1.37, 13.58)	56.95 (12.96, 128.84)
Europe	2.60 (0.57, 5.99)	53.83 (11.75, 124.16)
Latin America	11.61 (2.71, 26.47)	56.51 (13.21, 128.84)
North America	0.41 (0.07, 1.02)	49.74 (8.42, 122.99)
Oceania	0.10 (0.02, 0.24)	51.87 (9.24, 125.70)
<i>by time since immigration:</i>		
< 10 years	6.49 (1.50, 14.86)	55.94 (12.96, 128.00)
10 to 20 years	6.17 (1.42, 14.05)	56.21 (12.96, 128.00)
20 to 30 years	4.34 (0.99, 9.83)	56.91 (13.01, 128.84)
30 years	4.55 (1.00, 10.51)	55.59 (12.23, 128.42)