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Exposures to ambient particulate matter are associated with reduced adult earnings potential

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ABSTRACT

The societal costs of air pollution have historically been measured in terms of premature deaths (including the corresponding values of statistical lives lost), disability-adjusted life years, and medical costs. Emerging research, however, demonstrated potential impacts of air pollution on human capital formation. Extended contact with pollutants such as airborne particulate matter among young persons whose biological systems are still developing can result in pulmonary, neurobehavioral, and birth complications, hindering academic performance as well as skills and knowledge acquisition. Using a dataset that tracks 2014–2015 incomes for 96.2% of Americans born between 1979 and 1983, we assessed the association between childhood exposure to fine particulate matter ($PM_{2.5}$) and adult earnings outcomes across U.S. Census tracts. After accounting for pertinent economic covariates and regional random effects, our regression models indicate that early-life exposure to $PM_{2.5}$ is associated with lower predicted income percentiles by mid-adulthood; all else equal, children raised in high pollution tracts (at the 75th percentile of $PM_{2.5}$) are estimated to have approximately a 0.51 decrease in income percentile relative to children raised in low pollution tracts (at the 25th percentile of $PM_{2.5}$). For a person earning the median income, this difference corresponds to a $436 lower annual income (in 2015 USD). We estimate that 2014–2015 earnings for the 1978–1983 birth cohort would have been ~$7.18 billion higher had their childhood exposure met U.S. air quality standards for $PM_{2.5}$. Stratified models show that the relationship between $PM_{2.5}$ and diminished earnings is more pronounced for low-income children and for children living in rural environments. These findings raise concerns about long-term environmental and economic justice for children living in areas with poor air quality where air pollution could act as a barrier to intergenerational class equity.

1. Introduction

Among Americans raised by families with equal household incomes, earnings in adulthood are largely shaped by where people are born (Chetty et al., 2018). For example, low-income children raised in Los Angeles in the 1980s earned a household income in mid-adulthood that ranged from $25,700 to over 1.5 times that value ($42,000), depending on the Census tract in which they were raised. Such disparities in earnings persist even after accounting for race and ethnicity. While a variety of socioeconomic factors are hypothesized to drive regional differences in economic mobility, including job availability, poverty, school achievement, social capital, and urbanicity, in sum, these factors only explain about half of the variability observed in adult economic mobility outcomes at the Census tract level (Chetty et al., 2018).

A growing body of research has investigated the extent to which earning outcomes are influenced by environmental exposures, especially among children. The study of air pollution in this context is potentially illuminating, as economic mobility and air pollutant concentrations can

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vary at a similarly fine spatial scale. Initial findings in this domain indicate that early-life air pollution exposure has an adverse effect on earnings; using birth-year concentrations of total suspended particulates (TSP) as a proxy for *in utero* exposures, O'Brien et al. (2018) find that county-level TSP is negatively associated with earning outcomes for children born to low-income parents (those at the 25th percentile of household income). No significant trend was observed for the effect of TSP on earnings for children with more affluent parents (at the 75th income percentile). Similarly, Isen et al. (2013) show that a 10% decrease in birth-year TSP concentrations is associated with a 1% increase in adult earnings for children born in counties that were subject to pollution reductions mandated by the U.S. Clean Air Act.

Childhood exposure to fine particulate matter ($PM_{2.5}$) has been associated with adverse behavioral and health complications with effects that hinder educational attainment and cascade throughout life. Prenatal and early-life exposure to $PM_{2.5}$ is associated with incidence and severity of childhood asthma (Khreis et al., 2017; Lavigne et al., 2018; Slaughter et al., 2003), a chronic respiratory condition that persists into adulthood (Tai et al., 2014). Asthmatic children have significantly higher rates of school absenteeism and poorer labor market outcomes than their non-asthmatic counterparts (Milton et al., 2004), and adults with asthma are less likely to be employed (Belova et al., 2020; Sullivan et al., 2011) and have lower earnings (Belova et al., 2020) than adults without. $PM_{2.5}$ is also linked to harmful cognitive effects; prenatal $PM_{2.5}$ exposure is associated with diminished full-scale IQ in children aged 5–7 years (Chiu et al., 2016), as well as deficits in psychomotor and mental function in toddlers and young children (Lertxundi et al., 2015, 2019; Yorifuji et al., 2016). Calderón-Garcidueñas et al. (2011) demonstrated that children living in Mexico City, a dense urban environment with high levels of air pollution, had deficiencies with respect to attention, memory, and learning relative to matched controls from a less polluted area. Though appearing healthy, the children from Mexico City exhibited high rates of brain lesions that were not observed in the control group (Calderón-Garcidueñas et al., 2011). $PM_{2.5}$ exposure is also linked to higher rates of Attention-Deficit/Hyperactivity Disorders (ADHD) (Donzelli et al., 2020) and the development of Autism Spectrum Disorder (Raz et al., 2015; Talbott et al., 2015; Volk et al., 2013) in children. Taken in sum, adverse health effects induced by particulate matter are associated with hindered educational attainment. Acute exposures to $PM_{2.5}$ have been linked to diminished test performance among primary and secondary school children (Lavy et al., 2014; Zweig et al., 2009), and children exposed to higher levels of larger particulates (PM_{10}) *in utero* have poorer 4th grade math and language test scores than siblings with lower PM_{10} exposure (Bharadwaj et al., 2014).

Prenatal $PM_{2.5}$ exposure may additionally instigate birth defects, with life course effects that can be detrimental and nonspecific. Meta-analyses show that exposure to particulates and other air pollutants is associated with increased risk of congenital heart defects, which can require surgical intervention and reduce survivability (Vrijheid et al., 2011). Meta-analyses similarly indicate that $PM_{2.5}$ is linked to low birthweight (Stieb et al., 2012) and preterm birth (Li et al., 2017). While not the indicator of any specific disease, birth weight is a single, well-measured parameter that is strongly associated with several aspects of health including heart disease (Valdez et al., 1994), diabetes (Valdez et al., 1994), and neurological development (Newcombe et al., 2007). Multiple studies indicate that low birthweight babies also have increased risk of developing asthma from air pollution later in life (Lavigne et al., 2018; Sbihi et al., 2016). Independent of any specific health complications, among twins, lower birth weight is associated with poorer high school completion rates and lower adult earnings (Black et al., 2007). Similarly, meta-analyses find that both preterm birth and low birthweight are associated with lower rates of employment and higher education (Bilgin et al., 2018). The associations that underpin the relationship between early-life particulate exposure and adult earnings are summarized in Fig. 1, a directed acyclic graph (DAG).

The health effects and, by extension, the behavioral and social consequences of particulate exposure in childhood, may be conditional on a child's familial income. Mechanisms explaining the relationship between parent's socioeconomic status and children's health are diverse. Wealthier families can provide better nutrition and housing; have access to better, often more costly health care; and may have increased capacity to notice signs and seek treatment for symptoms of poor health in children. These factors could lessen the burden of air pollution-related disease in children in higher-income households, independent of ambient exposures. Indeed, though the rate of asthma in the U.S. is 1.2 times higher among children from low-income families than children from richer families, low-income children are 3.2 times more likely to report activity limitations related to asthma (Currie and Lin, 2007). Among children grades 1 to 12, the risk of failure to advance to the next grade is 2.0 times greater for asthmatic than non-asthmatic children in low-income families ($p < 0.05$), but not richer families ($p > 0.1$) (Fowler et al., 1992). Given that particulate exposure is associated with both disproportionate health burdens and adverse labor market outcomes among low-income children (O'Brien et al., 2018), it is possible that, on a population level, elevated levels of ambient pollution may reduce income earning potential and class mobility, exacerbating income inequity.

Our research makes several important contributions to understanding of air pollution's effects on earnings outcomes. Whereas previous studies evaluated this question with respect to TSP, we evaluate the influence of $PM_{2.5}$ (Meng et al., 2019), which can be inhaled more deeply into the lung and is widely thought to be more consequential for human health (Kim et al., 2015). The U.S. Environmental Protection Agency (EPA) promulgated health-based air quality standards for TSP in 1971 and based on scientific evidence subsequently revised the regulations to other forms of particulate matter, with current regulations governing $PM_{2.5}$ and PM_{10}, but not TSP. By using a more recent income mobility dataset that includes data at the Census tract level (Chetty et al., 2018), our research assesses this question at the finest spatial resolution to date, allowing examination of small scale geographic differences in pollution and earning outcomes that prior studies, using county level data, could not. This is consistent with work by Clark et al. (2022) that shows the spatial scale used to examine disparities for air pollution can greatly impact results, with coarser spatial resolution obscuring disparities. Additionally, the updated income dataset allowed us to explore comparisons among children raised by parents with more varied incomes than in previous research, and we investigate relationships between $PM_{2.5}$ and earnings across several income and urbanicity subgroups.

2. Materials and methods

2.1. Data sources

Data on adult earnings for a cohort of 20.5 million children, accounting for 96.2% of children legally born in the U.S. between 1978 and 1983, were obtained from Opportunity Insights (Opportunity Insights, 2019). Through collaboration with the U.S. Census Bureau, this dataset leverages deidentified decennial Censuses, federal tax returns, and American Community Survey data to unify individual-level information of members of the cohort, spanning childhood household characteristics to earnings in adulthood, with that of their parents. Based on this information, estimates of adult outcomes are generated for members of the cohort as a function of their parents' household income, race/-ethnicity, gender, and the Census tract in which they were raised. Summaries of these estimates at five discrete parental income percentiles are publicly available: 1st (the lowest income), 25th, 50th, 75th, and 100th (the highest income) percentiles, hereafter referred to as P1, P25, P50, P75, and P100, respectively. Of primary interest to our research is the estimated individual-income percentile of members of the cohort in adulthood—calculated for 2014–2015, when they have

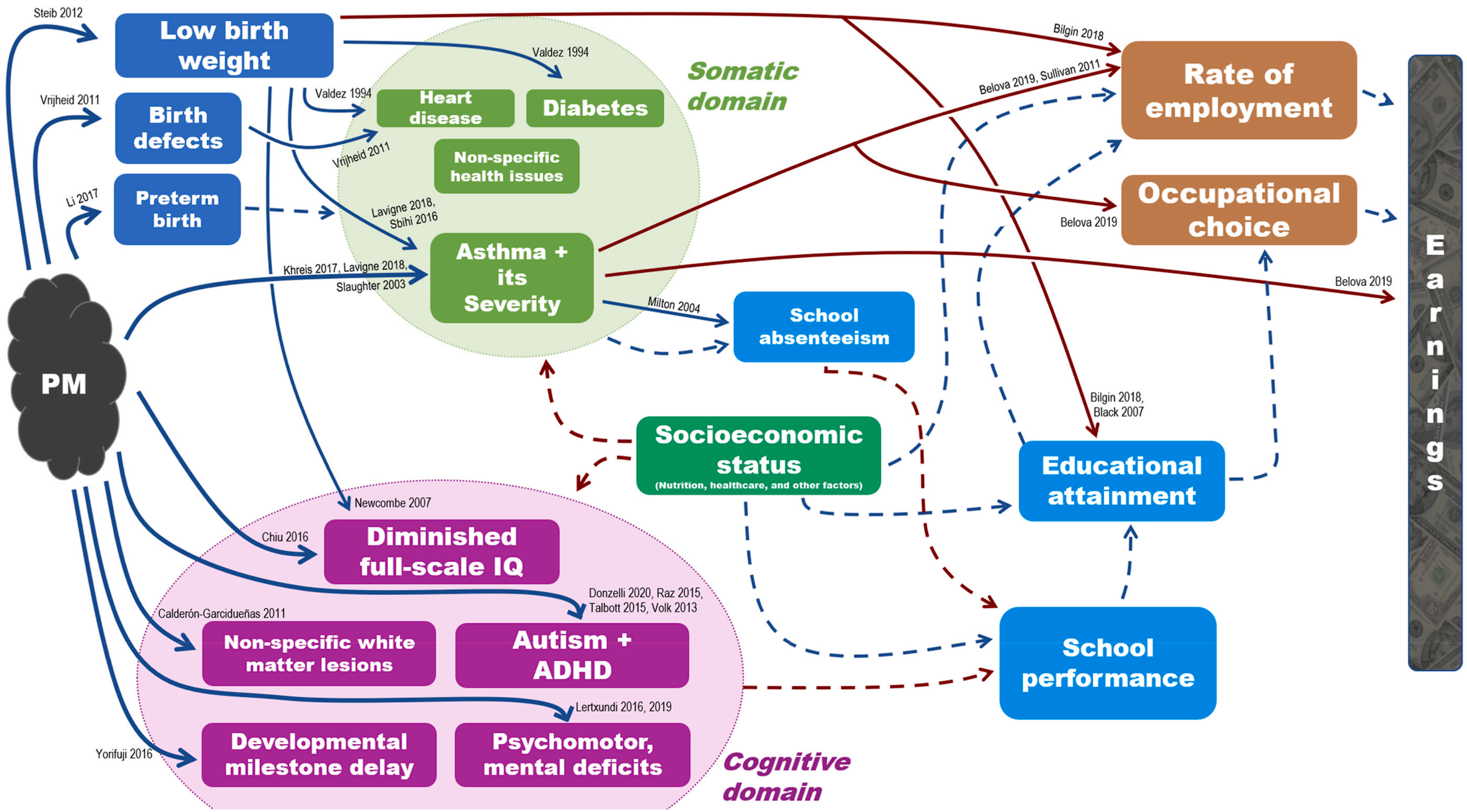

Fig. 1. Directed acyclic graph (DAG) detailing the theoretical link between early-life exposures to $PM_{2.5}$ and earnings in adulthood. Blue arrows represent a positive association, red arrows indicate a negative association. Solid arrows represent an association supported by literature cited in this article, dashed arrows represent an association with strong theoretical support. This figure is intended to highlight potential pathways and may not include all pathways.

established their earning potential—relative to that of all other Americans born the same year (Chetty et al., 2018). Children who move are tracked based on the address of the parent at the time of filing their tax returns, and adulthood income estimates for such children are weighted by the proportion of their childhood that is spent in different tracts.

$PM_{2.5}$ data were not widely collected by the U.S. EPA until 1999, well after the childhood period of the cohort. To obtain exposures relevant to the prenatal/early-life period for this cohort, we applied estimated historic levels of $PM_{2.5}$ generated using a chemical transport model that incorporates emission inventories for several PM-constituent pollutants and meteorological data. Meng et al. (2019) estimated these $PM_{2.5}$ concentrations across North America for 1981–2016. By assessing the ratio of the chemical transport model estimates to that of $PM_{2.5}$ data estimated by satellite imagery on a much finer spatial scale, the researchers downscaled their 1989–2016 estimates to $0.01^\circ \times 0.01^\circ$ resolution. These downscaled estimates were then adjusted using a geographic-weighted regression that leveraged available $PM_{2.5}$ data, the ratio of PM_{10} to $PM_{2.5}$, urban land cover, subgrid elevation differences, and simulated composition of various PM-related aerosols. $PM_{2.5}$ values between 1981 and 1988 were then iteratively inferred, year-by-year backwards from 1989, based on ratios between $PM_{2.5}$ and monitored PM_{10} and TSP measurements (Meng et al., 2019). We used area-weighting to apportion each $0.01^\circ \times 0.01^\circ$ grid-cell's $PM_{2.5}$ estimate to Census tracts based on area-weighted averaging using the R sp package. Census tract $PM_{2.5}$ concentrations were represented in our models as an average of the 1981–1983 estimates.

Covariates for our regression models were obtained from Opportunity Insights (Opportunity Insights, 2019) and the U.S. Census Bureau's 2010 Summary File for each Census tract (U.S. Census Bureau, 2010). Data were linked using 11-digit Federal Information Processing Standard (FIPS) codes.

2.2. Statistical analysis

The association between estimated adult income percentile and prenatal/early-life concentrations of $PM_{2.5}$ was estimated using mixed-effects regression as our baseline model. This model adjusted for two community factors that are among the strongest determinants of later-life earnings in previous research: tract-level median household income and the proportion of parents who are single in the tract (Chetty et al., 2018), both from 1990, the earliest year available with the same census tract geographies as were used to estimate earnings. The model also adjusted for population density, which has a positive association with airborne particulates. Additional variables in the model include the income percentile of the child's parents (P1, P25, P50, P75, and P100), race/ethnicity of the child (non-Hispanic White, non-Hispanic Black, Hispanic), urbanicity of the Census tract, the Census-designated U.S. region to account for large scale spatial trends, and US county (modelled as a random effect).

To more closely explore whether the relationship between childhood particulate pollution and adulthood earnings is modified by familial income, we ran separate models stratified by parental income. Due to differing dynamics of air pollution and earning potential in urban and rural areas (Kundu and Stone, 2014), models were also stratified by urbanicity (urban, rural, mixed) (U.S. Census Bureau, 2010). Thus, fifteen models, accounting for each combination of the five percentiles for parental income and the three urbanicity categories, were implemented to explore associations between air pollution and income percentile across the dimensions of class mobility and urbanicity. These stratified models include the same covariates as the baseline mixed-effects model. Robustness of results were explored in two ways: i) to account for children who moved geographically during their childhood and experienced environments with different pollution profiles, we adjusted for moving with a model in which the dependent variable considers incomes for the subset of those who as adults live in the same commuting zone as they did when they were children, and ii) to assess the extent to which air pollution may influence earnings independent of those effects driven by hinderances at school, we included school performance in an additional set of mixed-effect models. School performance was modelled using tract-level 3rd grade math test scores from 2013, which were estimated using a land-area-weighted average of school district test scores and were available for 99.5% of the 2010 US Census tracts in our study. Lastly, to assess the potential for residual confounding, we ran a linear model assessing the relationship between 1981 and 1983 $PM_{2.5}$ and adult earnings for children of all races/ethnicities.

To estimate the impact of $PM_{2.5}$ on income as adults for the 1978–1983 birth cohort, we fit regressions analogous to the stratified models but without race/ethnicity (using the pooled earnings estimate for all races). We used coefficients from these models to predict the earnings outcomes for children under a "low pollution" scenario, where any $PM_{2.5}$ values exceeding the current U.S. annual ambient standard were instead capped at that standard (12 $\mu g/m^3$) (U.S. EPA, 2012). In other words, we estimated what the earnings would have been if all children were exposed to $PM_{2.5}$ levels that met current U.S. EPA's regulations. We compared aggregate cohort earning outcomes under the hypothetical "low pollution" scenario to those under the baseline scenario, which reflects actual conditions, using information provided by Opportunity Insights on the number of children in each tract and the fraction of children whose parents earned income below the national median. For this analysis, the earnings of children with parents with income below the median income were estimated as the average of the expected earnings for children raised by parents in the P1, P25, and P50 income percentiles, while the earnings for children with above-median income parents were estimated as the average of expected earnings for children with parents in the P50, P75, and P100 income percentiles.

Statistical analyses were performed using R version 3.6.1 (R Core Team, 2019).

Table 1
Estimated child income percentiles and $PM_{2.5}$ by tract and population characteristics.

Tract & Population Characteristics	Number of Census Tracts	Median Adult Income Percentile (Q1, Q3)[a]	Median Childhood $PM_{2.5}$ $\mu g/m^3$ (Q1, Q3)[b]
Total	71,904	49.6 (43.9, 55.6)	21.6 (17.4, 25.5)
Parental Income Percentile			
1st percentile *(poorest)*	c	36.8 (32.1, 42.2)	c
25th percentile	c	43.9 (40.5, 47.9)	c
50th percentile	c	49.6 (46.7, 52.9)	c
75th percentile	c	55.6 (52.4, 58.7)	c
100th percentile *(richest)*	c	65.5 (60.9, 69.7)	c
Urbanicity (for Children of Median Parental Income)			
Urban	45,017	50.0 (46.8, 53.4)	23.5 (19.4, 26.9)
Mixed	18,886	49.2 (46.6, 52.0)	18.5 (15.2, 22.8)
Rural	8001	49.1 (46.4, 52.3)	17.3 (12.8, 21.6)
Region (for Children of Median Parental Income)			
Midwest	16,968	49.9 (46.8, 53.1)	22.2 (17.5, 25.5)
Northeast	13,410	52.4 (49.5, 55.7)	23.7 (19.4, 26.3)
South	26,041	48.0 (45.5, 51.0)	21.8 (18.4, 24.7)
West	15,485	49.8 (47.4, 52.6)	18.0 (13.7, 24.2)

[a] Median percentile (relative to other children born in the same year) in the national distribution of individual income (i.e. just own earnings) measured as mean annual earnings in 2014–2015, for children of any race (pooled estimate) (Chetty et al., 2018).

[b] Quartiles of tract-level averages, 1981–1983.

[c] Earnings estimates, when available for a given Census tract, are calculated for every parental income percentile. Thus, the universe of Census tracts is the same for all parental income percentiles and their median air pollution levels are identical. The air pollution levels provided for the 1st percentile represent the medians, 1st quartiles, and 3rd quartiles for the entire dataset.

3. Results

Table 1 provides Census-tract-level summary statistics for median adult income percentiles and ambient $PM_{2.5}$ concentrations in childhood by parental income percentile, urbanicity, and region. Estimates for adult income percentile are available for 71,904 contiguous U.S. Census tracts, representing 99.3% of tracts in the contiguous U.S. The median tract-level $PM_{2.5}$ for 1981–1983 for the entire dataset was 21.6 μg/m^3, far exceeding the current U.S. EPA annual standard (12 μg/m^3). Adult income percentiles were largely a function of parental income; children raised by the richer parents (P100) were estimated to have a median adulthood income nearly 30-percentile points higher than the adulthood income for children raised by the poorest parents ($65,000 vs. $27,600 in 2015 USD).

Nearly two-thirds (62.6%) of Census tracts in the dataset were categorized as 'urban.' The median adult income percentile was negligibly higher for children raised in urban communities compared to those raised in 'mixed' and 'rural' tracts. Childhood $PM_{2.5}$ levels, however, were much higher in urban tracts: median $PM_{2.5}$ levels were 23.5, 18.5, and 17.3 μg/m^3 for urban, mixed, and rural locations, respectively. In fact, the median urban $PM_{2.5}$ level exceeded the 75th percentile $PM_{2.5}$ for mixed and rural locations (22.8 μg/m^3 and 21.6 μg/m^3, respectively). Among the four U.S. geographic regions, adult income percentiles were predicted to be the highest for children raised in the Northeast (median income percentile 52.4) and the lowest for children raised in the South (median percentile 48.0). The Northeast had the highest regional median $PM_{2.5}$ concentration by a considerable margin. The West had the lowest median $PM_{2.5}$ concentrations of any region by nearly 4 μg/m^3.

Table 2 displays selected results for the baseline regression. There is a significant negative association between prenatal/early-life $PM_{2.5}$ concentrations and adult income percentile; all other characteristics equal, a child raised in a tract with 75th percentile $PM_{2.5}$ would be expected to achieve an income percentile 0.51 points lower in adulthood than a child raised in a tract with 25th percentile $PM_{2.5}$. Children raised by richer parents had higher projected incomes. Children raised in urban areas had 0.21 percentile points higher projected incomes than those in rural areas. Results for all model covariates are shown in Table A1 in the Appendix.

Table 2
Selected baseline regression results [a].

Dependent variable: Expected Adult Income Percentile	
Intercept	39.767***
	(0.148)
Childhood [$PM_{2.5}$][b]	−0.063***
μg/m^3	(0.006)
Parent $: 1st %ile	Ref.
Poorest	–
Parent $: 25th %ile	6.500***
	(0.038)
Parent $: 50th %ile	11.211***
	(0.038)
Parent $: 75th %ile	16.092***
	(0.038)
Parent $: 100th %ile	25.685***
Wealthiest	(0.038)
Urbanicity: Rural	Ref.
	–
Urbanicity: Mixed	−0.312***
	(0.058)
Urbanicity: Urban	0.208***
	(0.068)
Observations	693,845

Note: *p < 0.05 **p < 0.01 ***p < 0.001.

[a] Selected results. Model additionally controls for race, region, share of single parents, median household income, population density, and county (random effect).

[b] Univariate effect without control variables: 0.060 (0.003), $p < 0.001$.

Fig. 2 shows the association between childhood $PM_{2.5}$ exposure and adult earnings from stratified models. For all fifteen strata of urbanicity and parental income, the association between early-life ambient $PM_{2.5}$ and adult income was negative. Children born in tracts with more particulate pollution had poorer adult income outcomes. For each urbanicity category, the negative association between $PM_{2.5}$ and income percentile was largest for children born to the poorest parents and generally lessened with increasing parental income. This suggests that higher-income families are less sensitive to the potential impacts of air pollution. The relationship between childhood $PM_{2.5}$ and adult outcomes was highest for rural Census tracts, and effect estimates diminished with increasing urbanicity. Estimated $PM_{2.5}$ effects in rural Census tracts were considerable; all other characteristics equal, a child born to parents of median income would be expected to earn an income in adulthood 3.37 percentile points lower if born in a tract with 75th percentile $PM_{2.5}$ relative to a tract with 25th percentile $PM_{2.5}$. Accounting for differences in pollution, an equivalent child in an urban environment would be expected to have a 0.28 lower income percentile in adulthood if raised in the more polluted Census tract. For children raised by parents of median household income, an increase of 1 μg/m^3 of prenatal/early-life ambient $PM_{2.5}$ was associated with a 0.38 decrease in adult income percentile for rural children. In mixed and urban Census tracts, a 1 μg/m^3 increase in $PM_{2.5}$ was associated with 0.24 and 0.04 decreases in income percentile, respectively. Prenatal/early-life levels of ambient $PM_{2.5}$ were not significantly associated with adult income percentile for children born in rural or urban communities to the extreme richest parents (those with incomes in the 100th income percentile). Complete model results are presented in the Appendix, Table A2.

Results from the stratified models are supported by sensitivity analyses (Appendix Tables A3 and A4). To control for the effect of movers, we ran a series of stratified models in which the dependent variable was recharacterized as the expected adult income for the subset of the cohort who, as adults, resided in the same commuting zone of their childhood. While the magnitude of the association between childhood $PM_{2.5}$ and adult earnings outcomes was somewhat smaller in this analysis compared to our base models, findings were generally comparable (childhood $PM_{2.5}$ had a significant negative association with adult earnings that was most pronounced for more rural and lower income populations). In separate sensitivity analysis, we adjusted for tract-level measure of school performance in our mixed effects models. Though the effect size of the association between childhood $PM_{2.5}$ and adult earnings decreased slightly in these school-performance-adjusted models in rural and urban communities, and increased slightly for mixed urbanicity communities, results for the estimated effect of $PM_{2.5}$ were similar to those in the baseline model.

For policy relevance and context, we ran a set of models analogous to the stratified model to estimate how adult earnings outcomes for children might differ under a hypothetical scenario - if the ambient $PM_{2.5}$ levels in the early 1980s had not exceeded the current federal annual standard (12 μg/m^3). By incorporating the number of children in each tract with parents above and below median income, these predictions can be extrapolated to median predicted incomes for children of different income and urbanicity backgrounds for the entire 1978–1983 birth cohort. Median income estimates under the baseline scenario and predicted incomes under the "low pollution" scenario (capping $PM_{2.5}$ levels at 12 μg/m^3) are shown in Fig. 3. For all classes of children except for urban children raised by richer parents, adult median income levels are anticipated to have been higher under the low pollution scenario. Based on these predictions, we estimate that 2014–2015 earnings for the 1978–1983 birth cohort would have been approximately $7.18 billion higher under the low pollution scenario than they were in actuality. The share of this income growth differs sharply between children raised by parents above and below median income; under the low pollution scenario, lower-income children, as a group, are anticipated to earn $5.69 billion more annually as adults (an average increase of roughly $562/

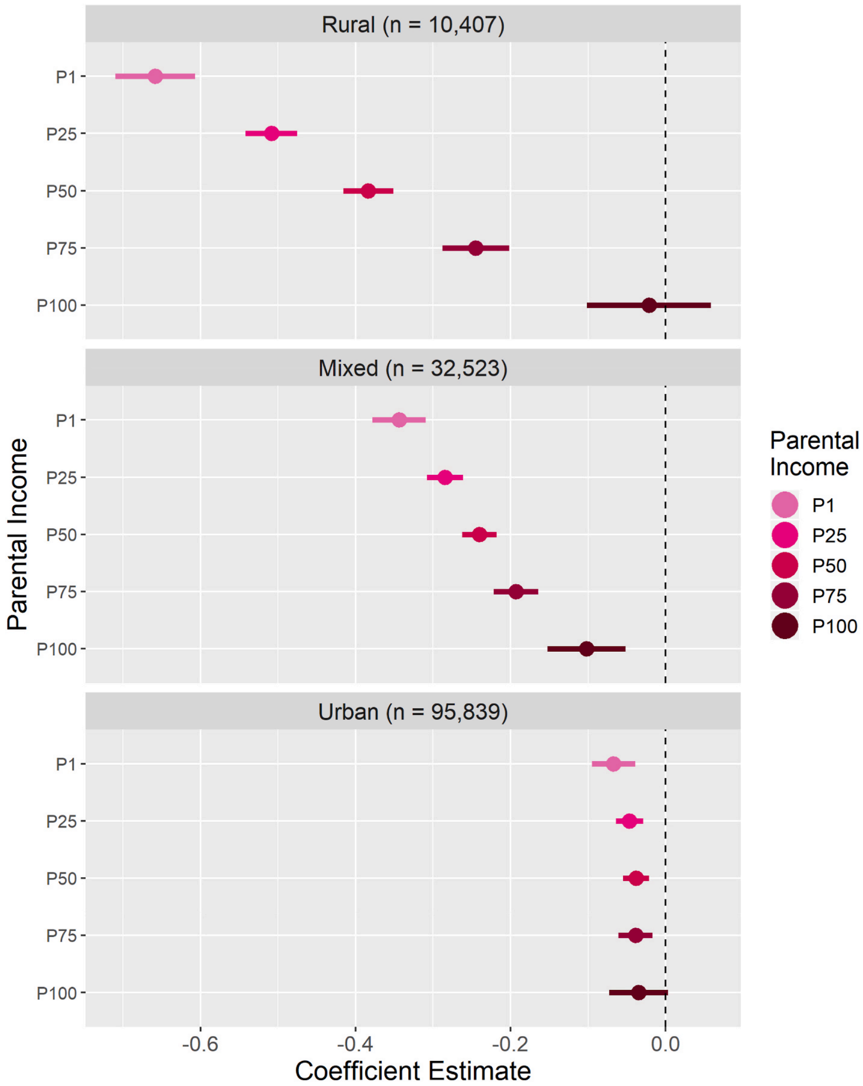

Fig. 2. Coefficient estimates for mixed-effect stratified models predicting associations between childhood $PM_{2.5}$ exposure (1981–1983) and adult earnings (2014–2015 individual income). Models control for U.S. region, race/ethnicity, Census-tract level median household income, proportion of single parents, population density, and U.S. county (a random effect). A coefficient estimate of −0.5 would indicate that a 1 μg/m^3 increase in childhood $PM_{2.5}$ concentration is associated with a 0.5 percentile decrease in adult income. For complete model results, refer to Table A2.

person), while richer children are anticipated to earn $1.49 billion more annually as adults (an average increase of roughly $147/person). This suggests that improvements in air pollution have a disproportionately larger benefit for lower-income families.

4. Discussion

There are multiple possible explanations for differing burden of pollution by class. Richer populations, including children, have higher baseline health status. Wealthier families can provide better nutrition for their children, bolstering their resistance to health stressors, and live in more secure, better ventilated housing, limiting indoor infiltration of air pollutants. Adequate medical treatment may be too costly for low-income families who may lack health insurance, or may represent a financial burden that deprives children of enrichment activities. Children from lower-income families may additionally experience greater degrees of psychosocial stress, which may act synergistically with air pollution in inducing health deficits (Clougherty et al., 2014; Shankardass et al., 2009). This concept is supported by research suggesting that air pollution is associated with more consequential outcomes for lower-income people; for example, lower-income Southern California adolescents, relative to richer counterparts, experience 150% greater declines in IQ following $PM_{2.5}$ exposure (P. Wang et al., 2017). Lastly, to the extent that air pollution varies across a Census tract, lower-income families may be more likely to be located in areas with elevated pollution. Low-income families have less capacity to move (DeLuca and Jang-Trettien, 2020), such as away from polluted areas, and, historically, sociopolitical systems have encouraged development of toxic industry in economically-disadvantaged and disenfranchised areas (Collins et al., 2016; Evans and Kantrowitz, 2003).

With respect to urbanicity, the negative associations between childhood $PM_{2.5}$ and adult incomes were largest in rural areas, and were substantially smaller in magnitude in urban environments. One possible explanation for these results is the different chemical composition of $PM_{2.5}$ in rural versus urban areas, which relates to different pollution sources, e.g., higher contribution from transportation in urban settings, agriculture in rural areas. Indeed, earlier work has shown that the chemical structure of particles varies dramatically (Bell et al., 2007), with multiple studies demonstrating that $PM_{2.5}$ with different chemical composition can invoke different health responses (Chung et al., 2015; Dominici et al., 2015; Y. Wang et al., 2017). Another potential explanation, consistent with the National Institute of Health's recognition that rural populations are vulnerable to environmental exposures (Collins and Pérez-Stable, 2021), is that rural populations may be more

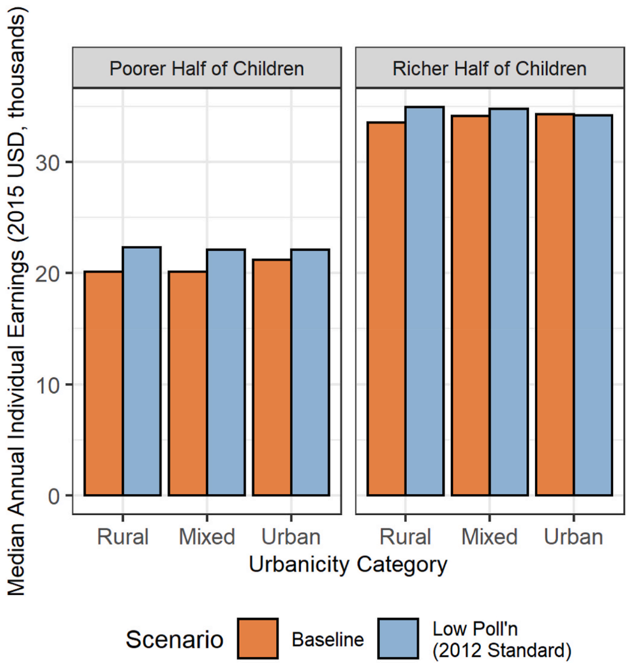

Fig. 3. Predicted adult 2014–2015 median incomes under a baseline (pollution levels as they were in 1981–1983) scenario and a hypothetical low pollution scenario ($PM_{2.5}$ capped at 12 μg/m^3, the current federal annual standard) for different subpopulations.

sensitive to PM. Relative to urban residents, people in rural communities are more likely to smoke and consume tobacco products, spend more time near gas-powered equipment, and use wood for heating (Matz et al., 2015), as well as suffer from an alcohol use disorder (Borders and Booth, 2007) or obesity (Befort et al., 2012), all of which could exacerbate the detrimental effects of air pollution. Additionally, structural factors related to educational and employment opportunities in rural areas may make residents more vulnerable to the health impacts of particles. For instance, asthma has large adverse associations with both employment and earnings in 'primary occupations,' such as farming, construction, and material moving, which represent a greater share of the labor opportunities in rural settings (Belova et al., 2020). Urban environments have generally better access to healthcare, such as to physicians and specialists (Rosenblatt and Hart, 2000), independent of income. Alternatively, ambient pollution levels may better approximate actual exposure in rural, relative to urban, communities; rural populations spend more time outside and are more likely to work outside relative to urban counterparts (Matz et al., 2015), and some urban environments may feature improved ventilation in homes (Hulin et al., 2010). Results may also reflect nonlinearities in the concentration-response curve, with a larger relative response at lower concentrations in rural environments. Lastly, findings could relate to unmeasured confounding variables that trends positively with urbanicity, childhood $PM_{2.5}$ concentrations, and expected adult income (e.g., transportation infrastructure, prevalence of non-agricultural employment). If such features are more common in urban environments, correlate positively with PM, and favorably influence earnings outcomes, their omission from the regression models could contribute to the observed PM-income trend. Further research is needed to understand how these factors and others may mediate the relationship between early-life particulate exposure and income in adulthood, and to explore the various pathways and exposure-response function through which air quality impacts income potential.

We explored the extent to which earnings would have been elevated, theoretically due to better human capital formation and labor productivity associated with improved health across the life course, under a hypothetical scenario in which $PM_{2.5}$ concentrations in 1981–1983 did not exceed the national annual standard of 12 μg/m^3. Extrapolating our model results across the 20.5 million children in the cohort, we estimate that annual adult earnings for this cohort would have been $7.2 billion higher in 2014–2015. The majority of these benefits ($5.7 billion, 79%) would be claimed by people raised by parents earning less than the national median income (50% of the population). These results align with our findings that particulate matter has the largest negative association with later-life earnings for the poorest children, and with prior research that indicates that health and social consequences of particulates, such as the severity and academic detriment of childhood asthma, are more pronounced in low-income populations (Currie and Lin, 2007; Fowler et al., 1992; O'Brien et al., 2018). By having disproportionate benefits to lower-income households, abatement of particulate pollution could benefit income equity in the United States. Under the baseline condition, median incomes for children raised by parents earning more than the national median were roughly $13,300 higher than those of children raised by poorer parents. Under the hypothetical "low pollution" scenario, that difference would be reduced by roughly 10%.

Strengths of our study include its fine spatial scale and its robustness to both selection and misclassification bias. The Opportunity Insights study includes 96.2% of American children born between 1978 and 1983 (omitting only those whose parents' tax returns could not be linked to census tract), representing a nearly complete cohort. Additionally, the diversity of the agencies compiling the data and the temporality of our data suggests it would be unlikely that any measurement error of one of our inputs would be correlated with error in another. Our results on childhood air pollution and links to adulthood income potential reaffirm those of O'Brien et al. (2018), who found that county-level concentrations of birth-year ambient particulates were associated with diminished incomes for low-income (parental income at the 25th percentile) but not richer (at the 75th income percentile) children. In our study, across all urbanicity categories, $PM_{2.5}$ had the largest negative associations with earnings for children raised by the poorest families, and the smallest (and often statistically insignificant) associations for children raised by the richest families. These findings were robust and generally consistent with adjustment for school performance or when considering only the children who did not move geographically. Our results are also broadly consistent with a paper by Manduca and Sampson (2021) that examined traffic pollution for one year of exposure. They found children who had higher childhood exposure to air pollution, based on an aggregate indicator of traffic-related pollution and housing-derived lead, were significantly more likely to be incarcerated as adults or have children as teenagers.

Our study has several important limitations. While we present several hypotheses, further research is needed to evaluate the complex mechanisms by which childhood $PM_{2.5}$ exposure negatively affects later-life earnings, including potential mediators (Richiardi et al., 2013). Our finding that earnings of children from low-income families would be higher had their air pollution exposure been lower does not incorporate the real-world complexities such as redistribution of income-generating opportunities (e.g., if these children had higher incomes in adulthood, would other children have lower earnings). While sensitivity analyses adjusting for 3rd grade math scores suggest that air pollution may have consequential effects on earnings beyond those related to school performance, further research with more accurate data on educational attainment, respiratory illness, and mental acuity during childhood for those in the cohort is critical to better understand how these factors might influence adult outcomes. Also, future work is needed on potential confounding variables that could be related to urbanicity, childhood $PM_{2.5}$ concentrations, and expected adult income (e.g., infrastructure, occupation). That said, the consistency of the effect size of $PM_{2.5}$ between our baseline model and a univariate linear regression (the effect of $PM_{2.5}$ increased by roughly 5% after including relevant covariates such as parental income and urbanicity) suggests that our results are robust to issues of residual confounding.

Our data does not provide information on residential histories. Correspondingly, we are neither able to quantify nor disentangle the influence of adolescent and adulthood particulate exposures on earnings. When considering the potential mechanisms for the relationship between particulates and earnings, later-life exposures would have no influence on certain outcomes such as preterm birth, low birth weight, ADHD, or autism spectrum disorder. Adult exposures, we additionally argue, would have negligible effects on educational attainment. The degree to which these later-life exposures are correlated with childhood exposures is also an important question. By adulthood, data suggests that many of the children from this birth cohort had moved: in 94.4% of census tracts, fewer than a third of the children born in a tract lived in that tract as adults. Even if these children are relocating to nearby areas, significant intraurban variability in particulate pollution by tract suggests diminished correlation. Nevertheless, though our findings are robust to the inclusion of sociodemographic covariates, we are unable to completely rule out confounding from later-life exposures, particularly those in adolescence when children are still developing and in school. Future research on the critical exposure windows that mediate the relationship between particulates and earnings is paramount to understand how to best secure the economic success of America's children.

Another limitation is that we rely on estimations; key variables (expected child income percentile, $PM_{2.5}$ concentrations) were estimated via statistical models, rather than observed. In the context of air pollution data, evidence suggests that model predictions are worse for older concentrations (e.g., from the 1980s) than for the last decade (Kim et al., 2018). Nevertheless, these models are effective in capturing overall relative trends of pollution and class mobility, and are the best available for this time period. Our analysis uses averages of estimated $PM_{2.5}$ from 1981 to 1983 as proxies for prenatal/early-life concentrations of air pollutants for children born in 1978–1983. Prenatal and early-life exposures influence health in different ways, and because the class mobility data are reported in aggregate for a 5-year period, we cannot disentangle how exposures at these two time periods might differentially influence child earning outcomes. There is also a slight temporal mismatch between the air pollution data and the mobility birth cohort. However, we expect that these limitations do not meaningfully detract from the research approach because pollution concentrations are generally stable over periods of a few years, especially at the trend-level. A similar temporal mismatch exists between the childhood period of those researched in the present study and some model covariates; tract-level urbanicity (2010), population density (2000), and 3rd grade math scores (2013) correspond to a time-period when the subjects in the cohort have reached adulthood. Because the data in our study were linked using 2010 Census tract geographies, and Census tract geographies can vary over time, we were unable to obtain more temporally accurate measurements for these parameters. For similar reasons, we could not fully investigate potentially interesting demographic covariates (e.g., prevalence of non-agricultural employment, transportation infrastructure), as data from the 1980s was sparse and not geographically consistent with our study area. The lack of data on individual-level covariates also precludes the examination of several interesting scientific questions, such as the influence of parental smoking or obesity on this relationship. Additional work on these issues is warranted. Despite these limitations, the consistency of our results across all of our analyses—assessed with fine particulate matter at the most detailed spatial resolution to date—provides meaningful evidence of the consequential impact of air pollution on childhood development and earnings potential.

5. Conclusion

Our research indicates that after controlling for pertinent economic and geographic covariates, early-life exposures to fine particulate matter are adversely associated with later-life earnings. This negative association is most pronounced for children born to low-income and rural families. While our evidence does not prove causation, they suggest that Americans born between 1979 and 1983, and especially those raised by parents of low income, would have higher incomes if particulate pollution had not exceeded current federal standards. These findings indicate that the benefits of air pollution abatement extend beyond the domain of direct impacts on health and could include a more productive and equitable society. As income estimates become available for later generations, future research should evaluate the relationship between other air pollutants (such as nitrogen oxides and ozone) and earnings potential. Improved data quality may also enable better investigation of the mechanism behind the observed adverse relationship between air pollution and income (e.g., a persistent detriment to knowledge acquisition, pulmonary health, or some other factor).

Credit author statement

Lucien Swetchinski: conceptualization, methodology, formal analysis, writing – original draft, funding acquisition. **Kelvin C. Fong**: methodology, writing - reviewing and editing. **Rachel Morello-Frosch:** conceptualization, writing - reviewing and editing. **Julian D. Marshall:** resources, writing - reviewing and editing. **Michelle L. Bell:** conceptualization, supervision, methodology, writing - reviewing and editing, funding acquisition.

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Declaration of competing interest

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Data availability

The authors do not have permission to share data.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2023.116391.

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