

Early-life Exposure to Air Pollution and Cognitive Decline: The Role of Socioeconomic Status
as a Confounder

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Abstract

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Background: Cognitive decline and dementia are major public health concerns as the U.S. population ages. Identifying early-life environmental risk factors may clarify life course determinants of dementia.

Methods: We linked Health and Retirement Study (HRS) participants ($n = 6571$) to their county of residence in the 1940 U.S. Census and estimated early-life exposures to ambient and source-specific air pollution. Exposures included residential proximity to fossil fuel power plants, oil and gas wells, automobile emissions, and all-source fine particulate matter ($PM_{2.5}$). Predicted dementia probability was derived from validated HRS algorithms between 2000–2020. We fit generalized linear mixed-effects models and random subject intercepts, stratified by individual-level race (i.e., Black or White), to estimate associations between exposures and dementia

probability trajectories. Models were sequentially adjusted for demographics, early-life socioeconomic conditions, and county-level contextual covariates.

Results: In time-on-study models, no consistent associations were observed between early-life exposure to power plant emissions, oil and gas well density, or automobile emissions and predicted probability of dementia. Higher early-life PM_{2.5} concentrations were modestly associated with increased dementia probability, though estimates attenuated following adjustment for socioeconomic covariates. Analyses stratified by race revealed generally higher dementia risk among Black participants compared with White participants, but associations between exposures and outcomes were imprecise and inconsistent across models. Secondary analyses evaluating the role of socioeconomic status suggested partial confounding of the PM_{2.5}–dementia relationship, with attenuation of effect estimates after adjustment for county-level indicators of education, employment, and housing.

Conclusion: Results provide preliminary evidence that early-life air pollution exposures may contribute to racial disparities in dementia risk. Findings underscore the need for life course approaches to dementia prevention and highlight the importance of addressing structural inequities in early-life environments.

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Introduction

Cognitive decline and dementia are increasingly recognized as major public health concerns, particularly as the global population ages and life expectancy continues to rise.^{1,2} Alzheimer's Disease and Alzheimer's Disease-Related Dementias (AD/ADRD) impose significant burdens on individuals, their families, and the healthcare system. This burden highlights the need to identify and mitigate modifiable risk factors across the lifespan.³ While aging remains the primary risk factor for cognitive impairment, emerging evidence suggests that environmental exposures, particularly air pollution, may also contribute to neurodegenerative processes.⁴⁻⁶ Fine particulate matter (PM_{2.5}), a common pollutant generated by industrial activities, traffic, and power generation, has been linked to systemic inflammation, oxidative stress, and vascular dysfunction, all of which may accelerate cognitive decline and dementia pathology.⁷⁻⁹ Inhaled PM_{2.5} may translocate to the brain via the olfactory bulb and is associated with elevated neuroinflammatory markers, suggesting plausible biological pathways.^{7,10} In the United States, approximately 6.9 million adults aged 65+ are living with AD/ADRD, with numbers projected to rise as the population ages.³

Research has shown that exposure to air pollution during early-life developmental periods may be especially consequential for cognitive health trajectories.^{4,10} Early-life exposure to PM_{2.5} has been associated with adverse neurodevelopmental outcomes, including impaired cognition and educational attainment, which are themselves associated with dementia.¹¹⁻¹³ Additionally, early exposures can increase the lifetime risk for cardiovascular disease and vascular dementia, known contributors to cognitive decline.^{13,14} Despite this growing body of evidence, the long-term cognitive consequences of early-life air pollution exposure remain understudied, particularly in the context of adult cognitive aging and dementia risk. It remains uncertain whether early-life

exposure accelerates cognitive aging per se or reduces baseline cognitive reserve, advancing the apparent onset of impairment.¹⁵

A critical element in understanding the cognitive impacts of early-life air pollution exposure is the role of socioeconomic status (SES). Residential segregation, systemic inequities in environmental protections, and historical patterns of industrial siting have resulted in lower SES populations experiencing disproportionately high levels of air pollution.^{14,15} Lower SES has also been independently linked to faster cognitive aging through pathways such as access to education, healthcare, and chronic stress exposures.¹⁶⁻¹⁸ However, the extent to which SES confounds the relationship between early-life air pollution and late-life cognitive decline remains unclear. Unmeasured confounding by SES may obscure or exaggerate observed associations between air pollution and cognitive outcomes, leading to misinterpretation of the underlying risk pathways and hindering the development of effective interventions.^{19,20}

Addressing these gaps in knowledge requires approaches that integrate environmental exposures and social determinants of health across the life course. In this study, we aim to investigate the relationship between early-life residential exposure to multiple sources of PM_{2.5} - including total ambient and power-plant related sources, fossil fuel power plants, oil and gas wells, and automobile emissions - and cognitive decline in older adulthood, while explicitly accounting for early-life SES as a potential confounder. Leveraging the nationally representative Health and Retirement Study (HRS) linked to historical participant residential location based on 1940 U.S. census data, we leverage more refined estimates of historical air pollution exposure and accurate adjustment for early-life neighborhood-level SES than before. By linking PM_{2.5} exposure data from sophisticated climate models and emissions databases to HRS participants' 1940 county of residence, we can estimate the burden of early-life air pollution exposures during a potentially

critical developmental window. This approach also allows for comparison of distinct emission sources: fossil fuel power plants and oil/gas wells as proxies for industrial activity, and automobile-related emissions as a marker of traffic-related pollution, which together provide a more comprehensive assessment of environmental burdens relevant to cognitive health. The study further differentiates between all-source PM_{2.5} and emissions specifically attributable to coal-fired power plants, which were disproportionately located near and impact the air quality of low-income communities and communities of color,²¹ enabling an examination of the unique contributions of industrial sources to cognitive health disparities.

This research is significant for several reasons. First, it addresses a crucial gap in understanding whether and which early-life environmental exposures contribute to cognitive decline and dementia risk in older adulthood. Second, it incorporates the social context of exposure by evaluating SES as a confounding factor (**Figure 1**), a key component for accurately quantifying the environmental risks and for informing interventions. Third, by including power plant-related emissions, the study underscores the historical legacy of industrial pollution in shaping present-day health disparities, particularly among marginalized populations.

The findings from this study have the potential to inform more equitable public health interventions that address both environmental and social determinants of cognitive health. If early-life air pollution exposure is indeed significantly associated with late-life cognitive decline, and if SES meaningfully confounds this relationship, strategies to improve cognitive outcomes in aging populations may require dual approaches: reducing environmental exposures in early life and addressing broader socioeconomic disparities. Importantly, SES itself has been shown to independently contribute to cognitive decline through mechanisms such as limited access to education, health care, and economic stability, even in the absence of environmental

exposures.¹⁶⁻¹⁸ Thus, while SES is treated analytically as a confounder in this study, reducing socioeconomic disparities remains a critical target for dementia prevention. By leveraging historical exposure data and a robust cohort of older adults, this study will provide critical insights into the interplay of air pollution, socioeconomic factors, and cognitive aging. Ultimately, these findings can guide policy efforts and community-level interventions aimed at reducing the burden of dementia and promoting health equity throughout the life course.

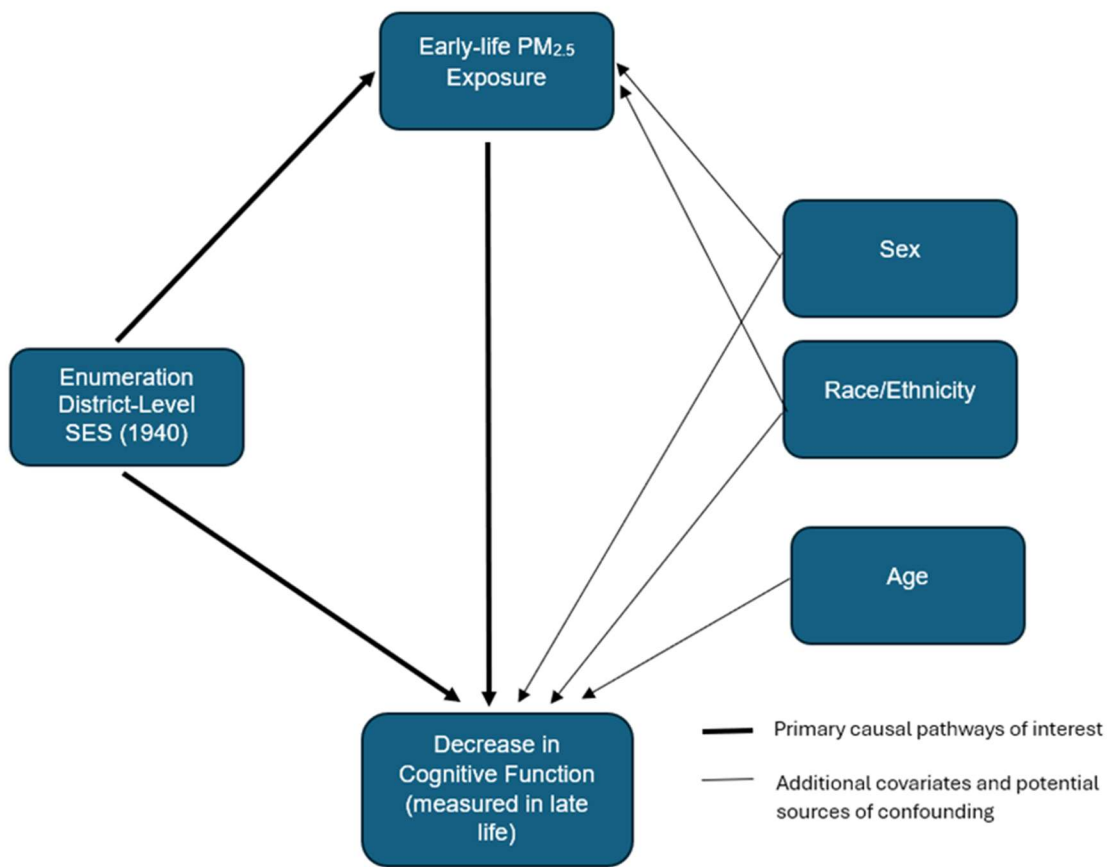


Figure 1 – Directed Acyclic Graph (DAG) illustrating the hypothesized relationships among early-life air pollution exposure, enumeration district-level socioeconomic status, and later-life cognitive decline, as well as other covariates accounted for in this analysis.

Methods

Study Design and Population

This study utilizes a retrospective longitudinal cohort design, leveraging data from the HRS using now-public 1940 U.S. census data to examine the relationship between early-life air pollution exposure and cognitive decline in older adulthood. The HRS is a nationally representative, biennial panel survey of U.S. adults over the age of 50, initiated in the early 1990s to investigate aging-related health and socioeconomic outcomes.¹

Participants were eligible for inclusion if they could be linked to their household's 1940 Census record and were subsequently followed in HRS biennial waves through 2020. Linkage was completed by the Minnesota Population Center and the HRS research team using historical residence information, permitting identification of the county of residence in 1940 for a subset of participants.¹⁴ This linkage provides unique spatial resolution into early-life environments during a sensitive developmental period.⁵ Although exposures were assigned at the county level, socioeconomic measures were drawn from 1940 Census enumeration districts (EDs). EDs are smaller geographic units than counties and were designed by the Census Bureau to organize fieldwork for enumerators.¹⁵

The analytic sample was restricted to participants with (1) available early-life residence data, (2) at least one valid predicated dementia probability score after age 70, and (3) complete information on covariates of interest. The study population was stratified by race (Black vs. White) given well-documented differences in both environmental exposures and dementia risk.²³

Exposure Assessment

Air pollution exposure during early life was quantified for multiple emission sources, including both total ambient PM_{2.5} and specific fossil-fuel-related exposures. All exposures were assigned at the county level based on 1940 census residence.

1. Total Ambient PM_{2.5}

Total ambient PM_{2.5} concentrations were estimated using archived outputs from the Coupled Model Intercomparison Project Phase 6 (CMIP6), a global climate modeling framework.² CMIP6 integrates historical emissions inventories from the Community Emissions Data System (CEDS) with climate model projections to estimate aerosol concentrations. PM_{2.5} is defined in these models as the sum of surface-level dry aerosol mass mixing ratios, including black carbon, sulfate, organic aerosol, sea salt, and dust.

Given inter-model variability, ensemble averages were constructed across eleven CMIP6 models. These ensemble values were aggregated first to a 36-km grid and then to county-level averages to align with participant residence data in 1940.

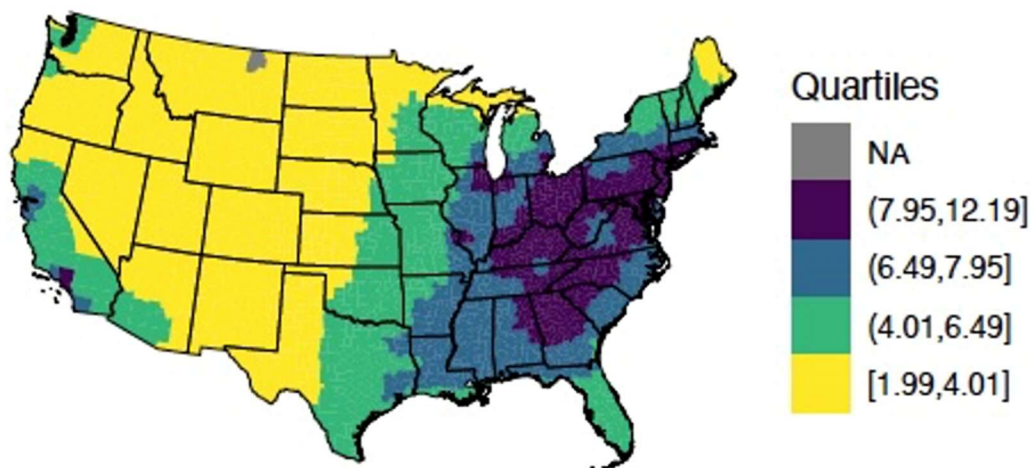


Figure 2 – Total PM_{2.5} concentrations in $\mu\text{g}/\text{m}^3$ (in quartiles) in 1940

2. Fossil Fuel Power Plant Density

Fossil fuel power plant-related exposures were estimated using inverse distance weighting. The location of 2,033 fossil fuel power plants (coal, petroleum, gas) were obtained from the US Energy Information Administration (Form EIA-860M)²² and the US Environmental Protection Agency's Clean Air Markets Division²³ for 1940. The exposure was assigned as the inverse distance-weighted (IDW) sum of all fossil fuel power plants for each county.

3. Oil and Gas Well Density

Oil and gas well locations were extracted from Enverus²⁴ and exposure was assessed using IDW averages of well locations, generating a county-level proxy of fossil fuel extraction activity.

4. Automobile Emissions

Historical mobile source emissions were represented by county-level totals of carbon monoxide (CO), hydrocarbons (HC), and nitrogen oxides (NO_x), expressed in tons per year.

5. Summary of Exposure Measures

Each participant's early-life exposure was assigned in 1940 and meant to capture the period near birth to age 10. This time window reflects critical neurodevelopmental periods during which air pollution may exert long-lasting cognitive effects.

Outcome Assessment

The primary outcome was the predicted probability of dementia (range 0-1) among HRS participants, calculated using the Giannattasio-Power algorithm.^{7,8} This algorithm integrates multiple cognitive test scores with sociodemographic and health data to generate wave-specific

dementia probability estimates. Predictions were available beginning in 2000 for participants aged 70 or older and continued biennially through 2020. All available waves with predictions were used for each participant, yielding repeated measures of dementia probability.

A secondary outcome was the composite cognitive functioning score (0-27), derived from HRS-administered cognitive batteries including episodic memory, mental status, and executive function domains. This measure provides an alternate marker of cognitive decline, validated against full neuropsychological testing.^{9,10}

Covariate Assessment

Covariates were chosen based on established literature linking demographic, socioeconomic, and geographic factors to both air pollution exposure and dementia risk.

- Demographics: sex, race and ethnicity, baseline age, and parental education (maternal and paternal education $\leq 8^{\text{th}}$ grade, binary).
- Geographic: indicator for residing in the South in 1940 (“South1940”), and county-level population density derived from the 1940 US census.
- Socioeconomic: county-level covariates from the 1940 US census, including proportion of population with ≤ 8 years of education , unemployment among Black individuals aged 14+, and median rental cost.

Statistical Modeling

The primary outcome was the predicted probability of dementia (range 0-1) among Black and White participants in the Health and Retirement Study (HRS). All available waves with predictions were included for each participant.¹⁶

We employed generalized linear mixed-effects models (GLMMs) using the glmmTMB package in R, with a random subject-level intercept. This approach accounts for the bounded nature of the dementia probability outcome and clustering of repeated measures within individuals.

Time-on-study was used as the primary time scale, with baseline defined as the first wave with an available dementia prediction and follow-up time defined as the number of waves since Baseline. Natural cubic splines (knots at 2, 5, 9, and 13 waves) were used to flexibly capture non-linear trajectories of dementia probability over follow-up.

Exposures were entered individually, and analyses were stratified by race. SES was incorporated sequentially as a potential confounder through covariate adjustment, rather than an interaction term with air pollution exposures.

Covariates were incorporated sequentially across four models:

1. Base model (time-on-study): $\text{outcome} \sim \text{ns}(\text{time}) \times \text{exposure} + \text{baseline age} + \text{South1940} + (1|\text{subject})$
2. Model 2 (demographics): Model 1 + sex + parental education (maternal and paternal education ≤ 8 th grade)
3. Model 3 (geographic): Model 2 + county-level population density (1940 Census)
4. Fully-adjusted model (socioeconomic): Model 3 + county-level socioeconomic covariates (proportion ≤ 8 years education, unemployment among Black adults, and median rent)

Descriptive analyses summarized distributions of exposures, outcomes, and covariates prior to modeling. All analyses were conducted separately for Black and White participants to allow for effect modification by race.

As a sensitivity analysis, we repeated models using chronological age as the time scale, with natural cubic splines specified at ages 72, 74, 79, 84, and 88.

Results

Study Sample Characteristics

Table 1 presents the demographic, socioeconomic, and baseline health characteristics of the study cohort, stratified by race. Black participants (N = 666) were more likely than White participants (N = 5,905) to have parents with ≤ 8 years of education (maternal: 67% vs. 47%; paternal: 76% vs. 54%), to reside in the South in 1940 (81% vs. 27%), and to report lower educational attainment at baseline (mean 10 vs. 12 years). Baseline household income was also markedly lower among Black participants (\$18,643 vs. \$35,000). In terms of baseline health, Black participants reported poorer self-rated health, with 42% rating their health as fair or poor compared with 28% of White participants. Mean predicted dementia probability at baseline was higher among Black participants (20%) compared to White participants (10%). Follow-up time and the number of dementia probability predictions were similar across groups.

Table 1. Descriptive characteristics of study participants by race.

	Black participants N = 666	White participants N = 5905
Demographic characteristics		
Birth year [mean (SD)]	1928 (9)	1927 (8)
Age in 1940, years [mean (SD)]	11 (9)	12 (8)
Age at baseline, years [mean (SD)]	75 (6)	75 (6)
Female, n (%)	412 (62)	3273 (55)
Mother education \leq 8 th grade, n (%)	447 (67)	2787 (47)
Father education \leq 8 th grade, n (%)	504 (76)	3194 (54)
Census region at birth, n (%)		
Midwest	38 (6)	2328 (39)
Northeast	43 (6)	1411 (24)
South	578 (87)	1603 (27)
West	<5	496 (8)
Missing	<5	67 (1)
Residence region in South in 1940, n (%)	540 (81)	1593 (27)
Education attainment \geq 12 years, n (%)	306 (46)	4529 (77)
Education attainment, n (%)		
Less than HS	341 (51)	1294 (22)
GED	28 (4)	223 (4)

HS graduate	154 (23)	2147 (36)
Some college	91 (14)	1140 (19)
College and above	52 (8)	1101 (19)
Education attainment, years [mean (SD)]	10 (4)	12 (3)
Married/partnered at baseline, n (%)	267 (40)	3692 (63)
Household size-adjusted income at baseline, dollars [mean (SD)]	18643 (20911)	35000 (47764)
Self-rated health at baseline, n (%)		
Excellent	31 (5)	644 (11)
Very good	124 (19)	1693 (29)
Good	230 (35)	1918 (32)
Fair	185 (28)	1102 (19)
Poor	96 (14)	548 (9)
Ever smoked at baseline, n (%)	367 (55)	3309 (56)
County-level characteristics in 1940		
Population density, population per sq mile [mean]	2574	2406
Median rent, dollars [mean]	11	17
Population with $\leq 8^{\text{th}}$ grade education, proportion [mean]	0.64	0.59
Unemployed among Black 14+ population, proportion [mean]	0.09	0.13
Fossil fuel powerplant IDW, 10^{-4} [mean]	5.21	5.91
Oil and/or gas well IDW, 10^{-3} [mean]	2.56	6.85

Automobile emissions (HC, CO, NOx), 10 ² tons/year [mean]	14.77	14.68
PM2.5 mean across models, ug/m ³ [mean]	7.81	7.27
Follow-up characteristics		
Predicted dementia probability at baseline, % [mean (SD)]	20 (30)	10 (24)
Follow-up time, years [mean (SD)]	8 (5)	9 (6)
Number of predictions [mean (SD)]	5 (3)	5 (3)

Early Life Environmental Exposures

Spatial distributions of the four primary exposures are shown in **Figure 3**. Power plant inverse distance weighted (IDW) scores were highest in the Midwest and Southeast, while oil and gas wells were concentrated in Texas, Oklahoma, and Appalachia. Automobile emissions were greatest in large metropolitan areas, and PM_{2.5} concentrations were elevated in the industrial Midwest and Northeast. These patterns highlight regional differences in environmental exposures during the early-life period of study participants.

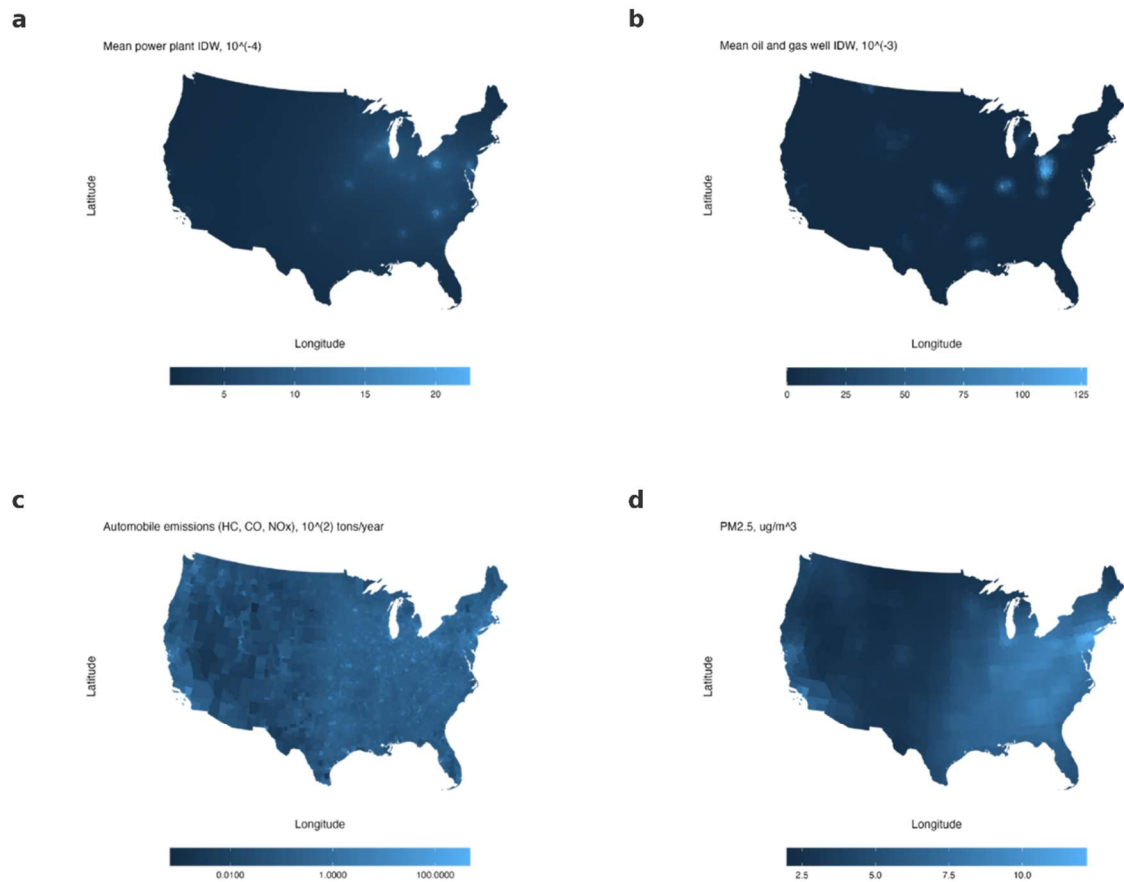


Figure 3. Spatial distribution of historical environmental exposures across U.S. counties.

Panels illustrate county-level variation in the four primary exposure measures used in the analysis. **(a)** Mean power plant inverse distance weighted (IDW) score, reflecting intensity of fossil fuel power plant activity. Highest concentrations are observed in the Midwest and Eastern seaboard. **(b)** Mean oil and gas well IDW score, capturing density of historical well locations. Elevated levels are evident in Texas, Oklahoma, Appalachia, and parts of the Mountain West. **(c)** Automobile emissions, represented by county-level totals of carbon monoxide (CO), hydrocarbons (HC), and nitrogen oxides (NO_x) in tons per year. Emissions cluster in metropolitan areas, particularly the Midwest and Northeast. **(d)** PM_{2.5} concentration, estimated at

the county level, with higher concentrations in the industrial Midwest, Northeast, and select West Coast regions.

Associations Between Early-Life Exposures and Dementia

Fully adjusted models estimated dementia probability trajectories from ages 70-90 and across 20 years of follow-up, comparing participants at the minimum versus 90th percentile of each exposure. Using age as the time scale (**Figure 4**), predicted dementia probabilities rose steadily with age among both Black and White participants, but exposure-related contrasts were generally small and imprecise. For example, among Black participants, higher PM_{2.5} exposure was associated with modestly elevated dementia probabilities from ages 70-80, though confidence intervals were wide. Among White participants, most exposures showed negligible differences in dementia probability across exposure levels.

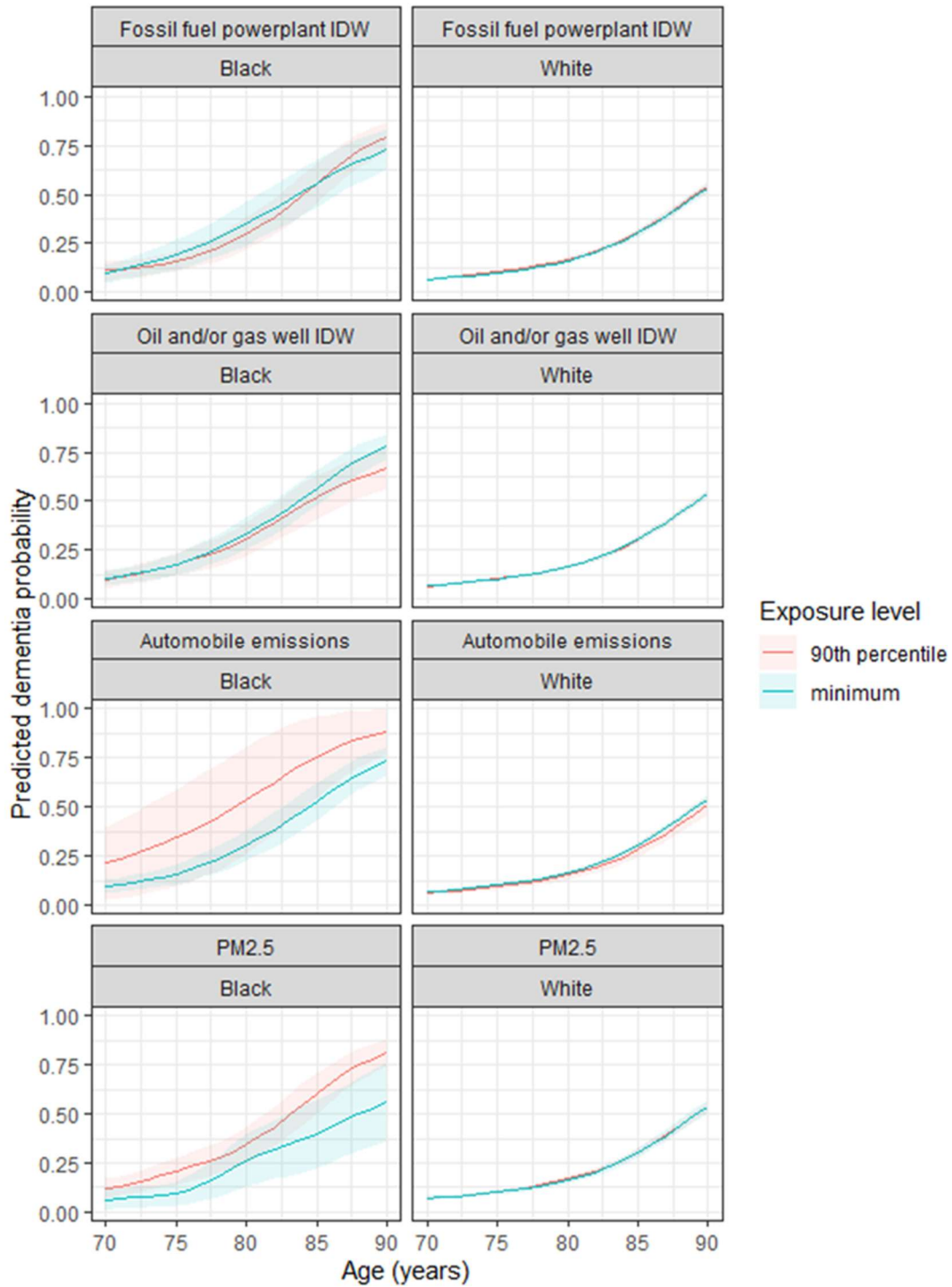


Figure 4. Predicted dementia probability trajectories by age (fully adjusted models). Dementia probability (0-1 scale) plotted against age (70-90 years) for participants at the minimum (blue)

and 90th percentile (red) of each exposure. Curves are shown separately for Black and White participants.

When using time on study as the time scale (**Figure 5**), patterns were consistent: dementia probabilities increased over follow-up, with minimal separation between exposure levels. Some evidence of higher dementia probability at elevated PM_{2.5} levels was observed among Black participants at 10-15 years of follow-up, but estimates were imprecise

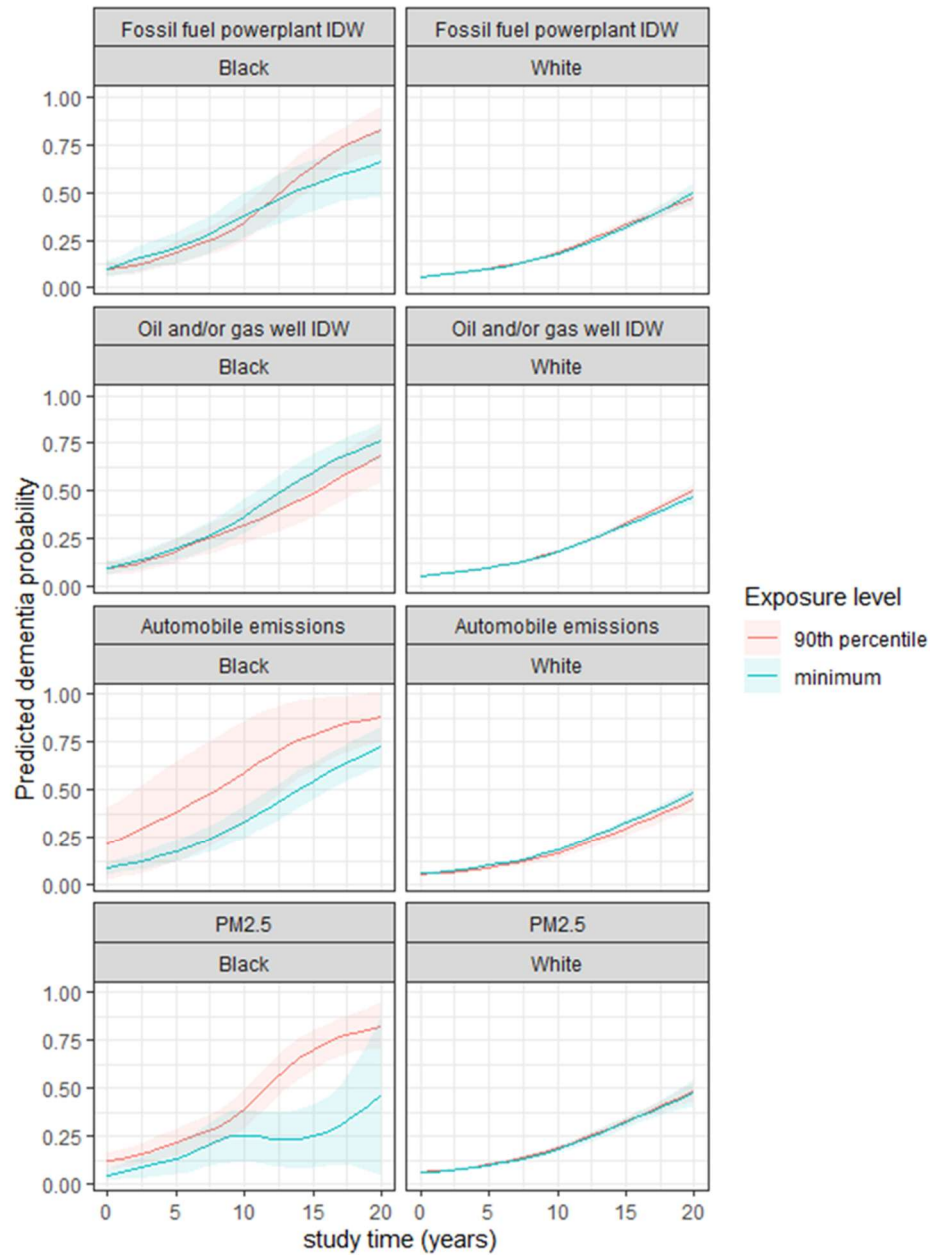


Figure 5. Predicted dementia probability trajectories by time on study (fully adjusted models). Dementia probability (0-1 scale) plotted against follow-up time (0-20 years) for participants at the minimum (blue) and 90th percentile (red) of each exposure. Curves are shown separately for Black and White participants.

Exposure Contrasts Over 5-Year Intervals

Tables 2 and 3 present estimated differences in mean dementia probability across 5-year intervals comparing the minimum versus 90th percentile of each exposure.

With age as the time scale (**Table 2; Figure 6**), contrasts were close to zero in most strata, with wide confidence intervals. Among Black participants, higher PM_{2.5} was associated with increased dementia probability between ages 75-80 (difference: 0.046, 95% CI: 0.002, 0.091), though estimates at later ages were null. For White participants, no consistent associations were observed.

Table 2: Estimated differences in dementia probability across 5-year age intervals, comparing minimum versus 90th percentile of exposure (fully adjusted models).

Age over follow-up	Fossil fuel powerplant IDW		Oil and/or gas well IDW		Automobile emissions		All-source PM _{2.5}	
	Black	White	Black	Black	Black	White	Black	White
70-75	-0.049 (-0.129, 0.03)	0.003 (-0.008, 0.015)	0.005 (-0.036, 0.046)	0.002 (-0.003, 0.006)	0.062 (-0.007, 0.130)	-0.004 (-0.009, 0.001)	0.058 (-0.030, 0.147)	0.008 (-0.008, 0.024)

75-80	-0.017 (-0.113, 0.079)	0.004 (-0.010, 0.018)	-0.027 (-0.076, 0.023)	0.001 (-0.004, 0.006)	0.046 (0.002, 0.091)	-0.003 (-0.012, 0.005)	-0.034 (-0.173, 0.105)	0.006 (- 0.013,0. 025)
80-85	0.048 (-0.067, 0.163)	-0.006 (-0.027, 0.015)	-0.022 (-0.097, 0.054)	-0.002 (-0.009, 0.005)	-0.005 (-0.078, 0.069)	-0.009 (-0.023, 0.005)	0.127 (-0.049, 0.302)	-0.006 (- 0.034,0. 021)
85-90	0.067 (-0.054, 0.188)	0.003 (-0.027, 0.033)	-0.060 (-0.149, 0.029)	0.004 (-0.007, 0.015)	-0.073 (-0.171, 0.025)	-0.010 (-0.020, 0.000)	0.039 (-0.159, 0.237)	-0.005 (-0.045, 0.034)

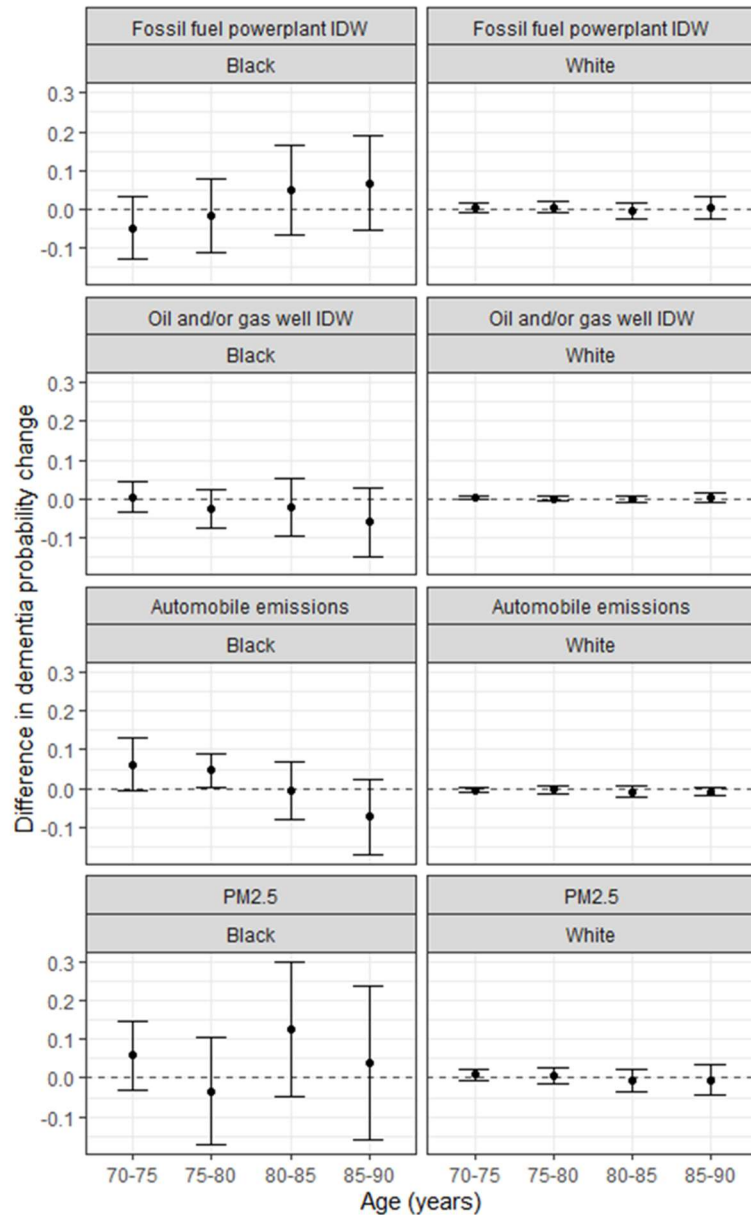


Figure 6. Estimated difference in mean dementia probability by 5-year age interval (fully-adjusted models). Difference in dementia probability between the 90th percentile and minimum exposure, with 95% confidence intervals, for ages 70-75, 75-80, 80-85, and 85-90. Separate estimates shown for Black and White participants.

With time on study as the time scale (**Table 3; Figure 7**), associations were again largely null, though higher PM_{2.5} among Black participants was associated with elevated dementia probability

at 5-10 years of follow-up (difference: 0.054, 95% CI: 0.019, 0.090) and 10-15 years (difference: 0.317, 95% CI: 0.125, 0.508). No consistent associations were observed among White participants for any exposure

Table 3: Estimated differences in dementia probability across 5-year intervals of follow-up time, comparing minimum versus 90th percentile of exposure (fully adjusted models).

Time on study	Fossil fuel powerplant IDW		Oil and/or gas well IDW		Automobile emissions		All-source PM _{2.5}	
	Black	White	Black	Black	Black	White	Black	White
0-5	-0.025 (-0.087, 0.037)	0.000 (-0.008, 0.008)	-0.008 (-0.040, 0.025)	0.000 (-0.002, 0.003)	0.077 (-0.002, 0.155)	-0.004 (-0.010, 0.002)	0.014 (-0.066, 0.094)	0.002 (-0.009, 0.013)
5-10	-0.012 (-0.117, 0.093)	0.004 (-0.012, 0.020)	-0.040 (-0.097, 0.016)	0.002 (-0.004, 0.007)	0.054 (0.019, 0.090)	-0.007 (-0.017, 0.004)	0.052 (-0.096, 0.199)	0.005 (-0.016, 0.026)
10-15	0.131 (-0.009, 0.270)	0.004 (-0.023, 0.032)	-0.061 (-0.150, 0.028)	0.005 (-0.005, 0.015)	-0.017 (-0.105, 0.072)	-0.011 (-0.025, 0.002)	0.317 (0.125, 0.508)	-0.001 (-0.036, 0.034)
15-20	0.074 (-0.174, 0.322)	-0.038 (-0.109, 0.033)	0.040 (-0.093, 0.173)	0.030 (0.002, 0.059)	-0.089 (-0.177, -0.002)	-0.002 (-0.020, 0.017)	-0.095 (-0.568, 0.377)	0.000 (-0.094, 0.095)

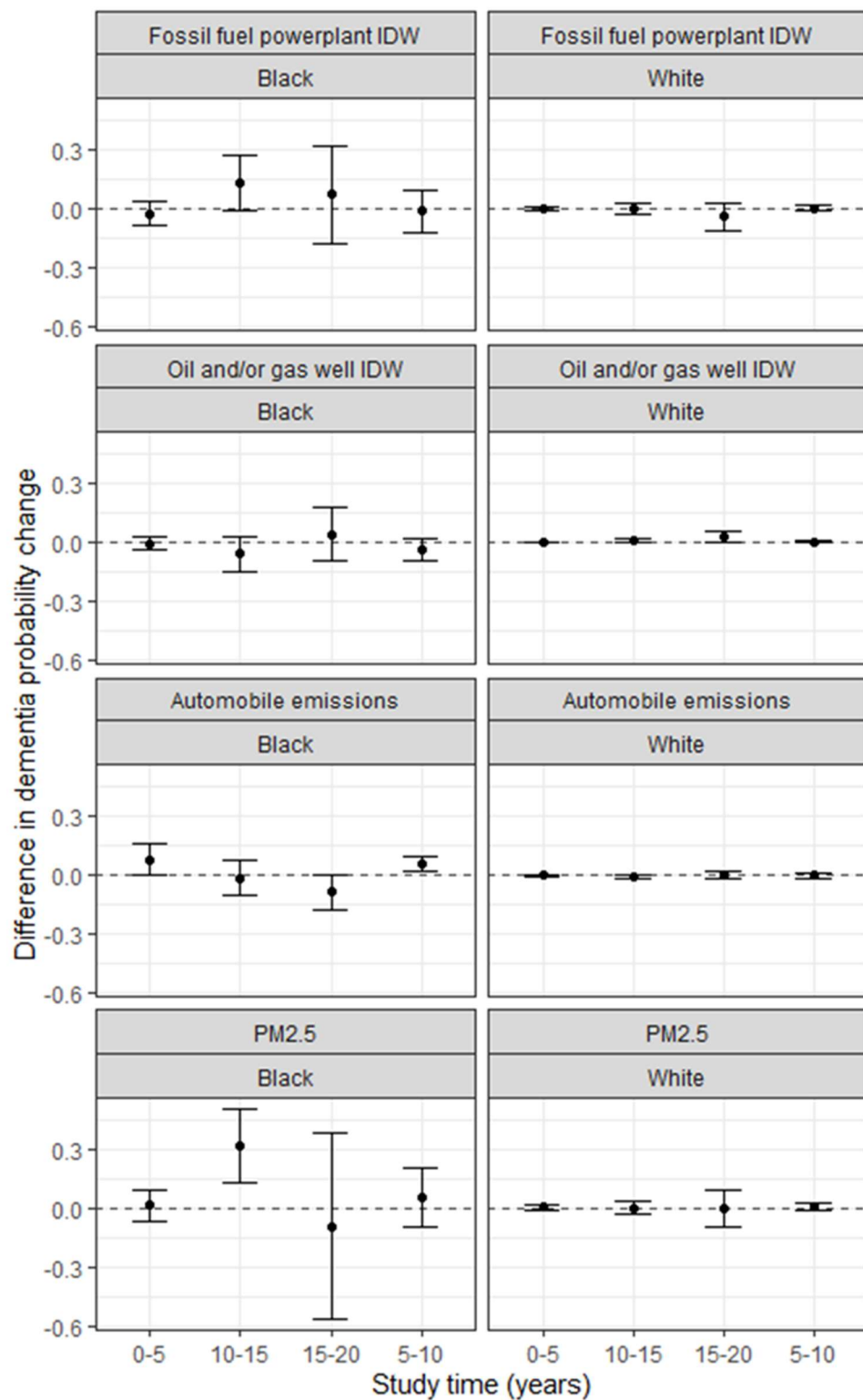


Figure 7. Estimated Differences in mean dementia probability by 5-year intervals of time on study (fully adjusted models). Differences in dementia probability between the 90th percentile and minimum exposure, with 95% confidence intervals, for 0-5, 5-10, 10-15, and 15-20 years of follow-up. Separate estimates shown for Black and White participants.

Confounding by Socioeconomic Status

In secondary analyses, adjustment for county-level SES covariates attenuated associations between PM_{2.5} and dementia among Black participants. For example, the positive associations observed between ages 75-80 (**Table 2**) and 5-15 years of follow-up (**Table 3**) diminished after full adjustment, suggesting that socioeconomic factors explain for of the apparent PM_{2.5}-dementia relationship. Among White participants, adjustment for SES did not meaningfully alter results.

Discussion

Summary of Findings

In this study, we examined whether early-life exposure to fossil fuel-related air pollution was associated with increased dementia probability in older adulthood among participants in the Health and Retirement Study. Overall, we observed largely null associations across multiple exposure metrics and time scales. However, among Black participants, higher PM_{2.5} exposure was modestly associated with increased dementia probability in models using both and time-on-study as time scales. These associations were attenuated after adjusted for county-level socioeconomic characteristics, suggesting that socioeconomic disadvantage confounds the relationship between early life PM_{2.5} exposure and cognitive decline.

Our findings highlight that early-life exposures may not have a strong direct effect on dementia risk in this cohort, but that SES disparities remain a key driver of cognitive health inequities.

These results are consistent with a growing body of literature showing that social determinants of health, including socioeconomic and structural inequalities, contribute to dementia risk independently and in conjunction with environmental exposures.^{11,16,21}

Comparison with Prior Literature

Our largely null findings are consistent with several cohort studies that have reported weak or inconsistent associations between late-life air pollution exposure and dementia risk.^{6,7,20} For example, large-scale analyses in U.S Medicare data identified modest associations of PM_{2.5} with Alzheimer's disease incidence, though effect sizes were small and sensitive to model specification.^{6,20} European cohort studies have similarly observed mixed results, with associations present in some but not all cohorts.^{7,20}

Few prior investigations have examined early-life exposures in relation to late-life cognitive outcomes. A registry-based study out of Sweden found that air pollution exposure during childhood and adolescence was associated with lower cognitive function in later adulthood, supporting the hypothesis of sensitive developmental windows.²² However, most work to date has focused on mid- or late-life exposure, underscoring the novelty of our approach.

Our results also align with a large body of research documenting racial and socioeconomic disparities in dementia risk. Numerous studies demonstrate that Black older adults in the U.S experience disproportionately higher dementia incidence compared with White adults, attributable in part to structural and social determinants of health.^{10,11,16,21} Prior work has further shown that neighborhood-level SES confounds observed associations between air pollution and cognitive outcomes.^{14,17} The attenuation of PM_{2.5} associations in our fully adjusted models is consistent with these findings, highlighting the central role of socioeconomic context.

Strengths and Limitations

Strengths

Key strengths of this study include the use of a large, nationally representative cohort with linkage to historical Census data, enabling life course-oriented analyses. We applied validated measures of dementia probability, leveraged multiple exposure metrics for fossil fuel-related pollution, and stratified analyses by race to highlight disparities.^{12,13}

Limitations

Several Limitations warrant consideration. First, exposures were assigned at the county level using inverse distance weighting and historical emissions inventories, which may introduce exposure misclassification.^{23,24} Second, dementia probability was predicted rather than clinical

adjudicated, though this measure has shown strong concordance with gold-standard diagnoses.¹⁵ Third, residual confounding is possible, particularly from unmeasured individual-level SES factors and health behaviors. Finally, despite long follow-up, selective survival may bias associations, particularly in racially stratified analyses.^{10,11}

Implications

Our results suggest that addressing socioeconomic disparities may be a more impactful strategy for reducing dementia inequities than focusing solely on early-life air pollution exposure. While null findings for pollution should be interpreted cautiously, they underscore the importance of considering the broader social and structural context in dementia prevention efforts.

For theory, these findings support life course models that emphasize cumulative socioeconomic disadvantage as a central determinant of cognitive aging.^{9,11} For public health practice, interventions targeting education, employment, and neighborhood resources in early life may yield long-term benefits for cognitive health.^{10,17} For future research, replication with finer-scale exposure assessment, examination of other early-life exposures, and integration of biomarkers of neurodegeneration may help clarify potential pathways linking environmental exposures and dementia risk.^{8,22}

Conclusion

In this study, we found little evidence that early-life exposure to fossil-fuel related air pollution was independently associated with late-life dementia risk. Modest associations observed among Black participants for PM_{2.5} were attenuated after adjustment for socioeconomic context, underscoring the importance of structural and social determinants of health.

These findings highlight the central role of socioeconomic disparities in shaping cognitive aging outcomes and reinforce the need for life course approaches that integrate both environmental and social exposures. Future research should continue to investigate sensitive developmental windows, incorporate richer measures of early-life context, and evaluate interventions that address inequities in order to reduce the burden of dementia.

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Supplementary Materials

Figure S1. Correlation plot of county-level covariates, including the environmental exposures

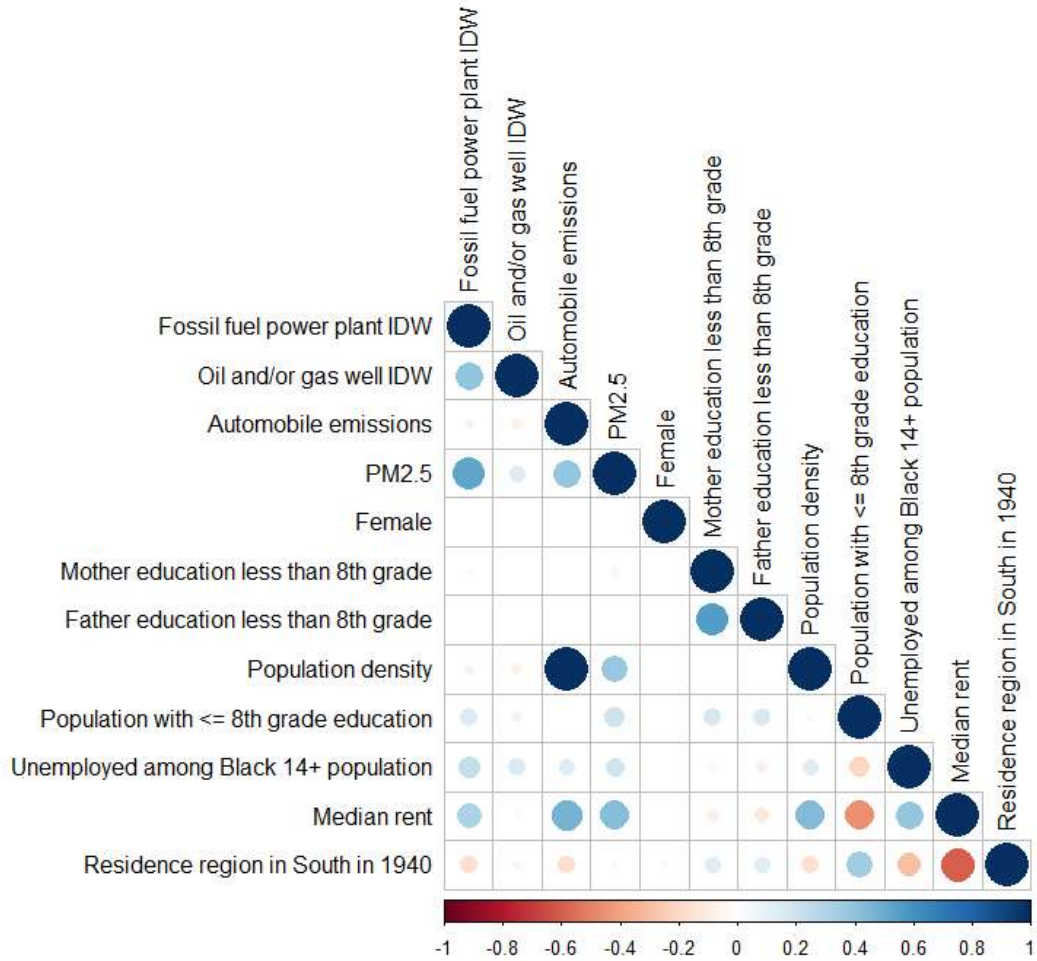


Table S1-4. Model coefficients

Each table reports coefficients from the fully adjusted generalized linear beta models for the four exposures, stratified on race (White/Black) and using age or time on study as the time scale.

Table S1. Regression coefficients from the fully adjusted model among Black participants using age as the timescale

	Mean power plant IDW	Mean oil and gas well IDW	Automobile emissions (HC, CO, NOx)	PM2.5
Intercept	-2.62 (-3.59,-1.65)	-2.38 (-2.87,-1.89)	-2.54 (-3.04,-2.05)	-3.25 (-5.30,-1.20)
Exposure	0.04 (-0.12,0.20)	0.00 (-0.04,0.04)	0.03 (-0.01,0.07)	0.10 (-0.16,0.36)
Spline term 1	1.09 (0.29,1.90)	0.71 (0.39,1.02)	0.71 (0.40,1.02)	0.29 (-1.51,2.09)
Spline term 2	1.73 (0.68,2.78)	1.40 (0.98,1.82)	1.40 (0.98,1.81)	2.08 (-0.29,4.46)
Spline term 3	2.54 (1.63,3.45)	2.22 (1.86,2.59)	2.23 (1.88,2.59)	2.29 (0.24,4.34)
Spline term 4	3.81 (2.77,4.85)	4.40 (3.93,4.86)	4.26 (3.80,4.71)	3.31 (0.97,5.65)
Spline term 5	5.03 (2.85,7.21)	4.84 (3.91,5.77)	4.39 (3.46,5.33)	4.86 (-0.18,9.90)
Spline term 6	4.68 (2.35,7.00)	4.45 (3.29,5.60)	3.73 (2.55,4.92)	4.99 (-0.97,10.94)
Female	0.08 (-0.12,0.27)	0.06 (-0.13,0.26)	0.07 (-0.12,0.27)	0.08 (-0.11,0.28)
Maternal education <= 8th grade	-0.02 (-0.25,0.22)	-0.02 (-0.25,0.22)	-0.03 (-0.27,0.20)	0.00 (-0.24,0.23)

	Mean power plant IDW	Mean oil and gas well IDW	Automobile emissions (HC, CO, NOx)	PM2.5
Paternal education <= 8th grade	0.03 (- 0.22,0.29)	0.04 (- 0.21,0.29)	0.06 (- 0.20,0.31)	0.06 (- 0.19,0.32)
County level population density	0.01 (- 0.10,0.12)	0.01 (- 0.10,0.12)	-1.86 (- 4.04,0.32)	-0.01 (- 0.12,0.10)
County level population proportion with <= 8th grade education	-0.79 (- 1.83,0.25)	-0.81 (- 1.84,0.21)	-1.01 (- 2.05,0.04)	-1.27 (-2.36,- 0.17)
County level unemployed proportion among Black 14+ population	-1.32 (- 3.53,0.89)	-1.25 (- 3.43,0.93)	-1.27 (- 3.44,0.91)	-1.30 (- 3.48,0.88)
County level median rent	-0.01 (- 0.03,0.01)	-0.02 (- 0.04,0.00)	-0.02 (- 0.04,0.00)	-0.03 (- 0.05,0.00)
Residence region in South in 1940	-0.10 (- 0.51,0.30)	-0.13 (- 0.54,0.27)	-0.02 (- 0.43,0.38)	-0.09 (- 0.49,0.30)
Exposure:Spline term 1	-0.07 (- 0.22,0.07)	0.01 (- 0.03,0.04)	0.00 (0.00,0.01)	0.06 (- 0.17,0.28)
Exposure:Spline term 2	-0.07 (- 0.26,0.12)	-0.01 (- 0.06,0.04)	0.00 (- 0.01,0.01)	-0.09 (- 0.39,0.21)
Exposure:Spline term 3	-0.06 (- 0.22,0.10)	0.00 (- 0.04,0.05)	0.00 (- 0.01,0.01)	-0.01 (- 0.27,0.25)
Exposure:Spline term 4	0.08 (- 0.10,0.26)	-0.05 (- 0.11,0.00)	0.00 (- 0.01,0.01)	0.12 (- 0.17,0.42)
Exposure:Spline term 5	-0.06 (- 0.44,0.31)	-0.03 (- 0.13,0.08)	0.03 (0.00,0.06)	-0.02 (- 0.65,0.62)
Exposure:Spline term 6	-0.06 (- 0.40,0.27)	-0.01 (- 0.14,0.12)	0.06 (0.01,0.11)	-0.08 (- 0.83,0.68)

Table S2. Regression coefficients from the fully adjusted model among Black participants using time on study as the timescale

	Mean power plant IDW	Mean oil and gas well IDW	Automobile emissions (HC, CO, NOx)	PM2.5
Intercept	-1.63 (-2.16,-1.10)	-1.59 (-1.97,-1.22)	-1.75 (-2.13,-1.37)	-2.67 (-3.55,-1.78)
Age at baseline centered at 75	0.15 (0.13,0.16)	0.15 (0.13,0.16)	0.15 (0.13,0.16)	0.15 (0.13,0.16)
Exposure	0.00 (-0.06,0.06)	0.00 (-0.02,0.01)	0.04 (0.00,0.08)	0.13 (0.03,0.23)
Spline term 1	0.89 (0.42,1.36)	0.87 (0.67,1.07)	0.87 (0.68,1.07)	1.14 (0.08,2.20)
Spline term 2	1.67 (1.15,2.19)	1.46 (1.24,1.69)	1.45 (1.23,1.67)	2.46 (1.28,3.64)
Spline term 3	2.09 (1.38,2.81)	2.45 (2.14,2.75)	2.34 (2.04,2.64)	0.76 (-0.95,2.48)
Spline term 4	3.20 (2.40,4.00)	3.49 (3.14,3.85)	3.40 (3.06,3.75)	2.88 (1.04,4.72)
Spline term 5	2.50 (1.42,3.58)	3.30 (2.82,3.79)	3.27 (2.81,3.74)	2.58 (-0.04,5.19)
Female	0.08 (-0.11,0.28)	0.07 (-0.12,0.27)	0.09 (-0.11,0.28)	0.09 (-0.11,0.28)
Maternal education <= 8th grade	0.00 (-0.24,0.24)	0.01 (-0.23,0.25)	0.00 (-0.24,0.24)	0.02 (-0.22,0.26)
Paternal education <= 8th grade	0.04 (-0.22,0.29)	0.03 (-0.22,0.29)	0.05 (-0.21,0.30)	0.06 (-0.19,0.31)
County level population density	0.02 (-0.09,0.13)	0.02 (-0.09,0.13)	-1.99 (-4.17,0.19)	0.00 (-0.11,0.11)

	Mean power plant IDW	Mean oil and gas well IDW	Automobile emissions (HC, CO, NOx)	PM2.5
County level population proportion with <= 8th grade education	-0.83 (- 1.87,0.21)	-0.91 (- 1.94,0.12)	-1.04 (- 2.08,0.01)	-1.31 (-2.41,- 0.22)
County level unemployed proportion among Black 14+ population	-1.13 (- 3.35,1.08)	-1.17 (- 3.36,1.02)	-1.10 (- 3.28,1.09)	-1.13 (- 3.31,1.05)
County level median rent	-0.02 (- 0.04,0.00)	-0.02 (- 0.04,0.00)	-0.02 (- 0.04,0.00)	-0.03 (- 0.05,0.00)
Residence region in South in 1940	-0.12 (- 0.52,0.29)	-0.14 (- 0.55,0.27)	-0.04 (- 0.44,0.36)	-0.11 (- 0.51,0.29)
Exposure:Spline term 1	0.00 (- 0.08,0.08)	0.00 (- 0.02,0.02)	0.00 (0.00,0.00)	-0.03 (- 0.17,0.10)
Exposure:Spline term 2	-0.05 (- 0.14,0.05)	-0.01 (- 0.03,0.02)	0.00 (- 0.01,0.00)	-0.13 (- 0.28,0.02)
Exposure:Spline term 3	0.06 (- 0.07,0.19)	-0.03 (- 0.06,0.01)	0.01 (0.00,0.01)	0.21 (- 0.01,0.43)
Exposure:Spline term 4	0.04 (- 0.10,0.18)	-0.03 (- 0.06,0.00)	0.00 (- 0.01,0.01)	0.07 (- 0.16,0.31)
Exposure:Spline term 5	0.15 (- 0.05,0.34)	-0.01 (- 0.05,0.03)	0.00 (- 0.02,0.01)	0.09 (- 0.25,0.43)

Table S3. Regression coefficients from the fully adjusted model among White participants using age as the timescale

Percentile	Mean power plant IDW	Mean oil and gas well IDW	Automobile emissions (HC, CO, NOx)	PM2.5
Intercept	-2.89 (-3.13,-2.64)	-2.90 (-3.02,-2.77)	-2.91 (-3.03,-2.79)	-2.76 (-3.13,-2.38)
Exposure	0.00 (-0.04,0.03)	0.00 (-0.01,0.00)	0.00 (-0.01,0.00)	-0.02 (-0.07,0.03)
Spline term 1	0.49 (0.27,0.71)	0.51 (0.41,0.62)	0.54 (0.43,0.64)	0.37 (0.02,0.71)
Spline term 2	0.87 (0.58,1.16)	0.94 (0.80,1.08)	0.96 (0.82,1.10)	0.71 (0.26,1.17)
Spline term 3	1.59 (1.34,1.84)	1.60 (1.48,1.72)	1.61 (1.49,1.72)	1.44 (1.05,1.83)
Spline term 4	3.33 (3.06,3.61)	3.37 (3.23,3.50)	3.42 (3.29,3.56)	3.35 (2.93,3.77)
Spline term 5	4.78 (4.15,5.41)	4.72 (4.42,5.03)	4.75 (4.46,5.05)	4.42 (3.46,5.39)
Spline term 6	5.49 (4.72,6.27)	5.23 (4.88,5.59)	5.21 (4.85,5.57)	5.21 (4.04,6.38)
Female	0.03 (-0.02,0.08)	0.03 (-0.02,0.08)	0.03 (-0.02,0.08)	0.03 (-0.02,0.08)
Maternal education <= 8th grade	0.16 (0.10,0.22)	0.16 (0.10,0.22)	0.16 (0.10,0.22)	0.16 (0.10,0.22)
Paternal education <= 8th grade	0.14 (0.08,0.20)	0.14 (0.08,0.20)	0.14 (0.08,0.20)	0.14 (0.08,0.20)
County level population density	-0.03 (-0.06,0.00)	-0.03 (-0.07,0.00)	0.18 (-0.17,0.52)	-0.03 (-0.07,0.00)

Percentile	Mean power plant IDW	Mean oil and gas well IDW	Automobile emissions (HC, CO, NOx)	PM2.5
County level population proportion with <= 8th grade education	0.32 (0.01,0.63)	0.37 (0.09,0.65)	0.38 (0.10,0.66)	0.34 (0.01,0.66)
County level unemployed proportion among Black 14+ population	0.18 (- 0.09,0.44)	0.19 (- 0.08,0.46)	0.19 (- 0.07,0.46)	0.18 (- 0.08,0.45)
County level median rent	0.00 (- 0.01,0.00)	0.00 (- 0.01,0.00)	0.00 (- 0.01,0.00)	0.00 (- 0.01,0.00)
Residence region in South in 1940	0.19 (0.12,0.26)	0.19 (0.12,0.26)	0.19 (0.12,0.26)	0.18 (0.11,0.26)
Exposure:Spline term 1	0.01 (- 0.03,0.04)	0.00 (0.00,0.01)	0.00 (0.00,0.00)	0.02 (- 0.02,0.07)
Exposure:Spline term 2	0.02 (- 0.03,0.06)	0.00 (0.00,0.01)	0.00 (0.00,0.00)	0.03 (- 0.03,0.09)
Exposure:Spline term 3	0.00 (- 0.04,0.04)	0.00 (0.00,0.01)	0.00 (0.00,0.00)	0.02 (- 0.03,0.07)
Exposure:Spline term 4	0.01 (- 0.03,0.05)	0.00 (0.00,0.01)	0.00 (0.00,0.00)	0.01 (- 0.05,0.06)
Exposure:Spline term 5	-0.01 (- 0.10,0.09)	0.00 (- 0.01,0.02)	0.00 (- 0.01,0.00)	0.04 (- 0.08,0.17)
Exposure:Spline term 6	-0.05 (- 0.16,0.07)	0.00 (- 0.02,0.01)	0.00 (- 0.01,0.01)	0.00 (- 0.15,0.15)

Table S4. Regression coefficients from the fully adjusted model among White participants using time on study as the timescale

Percentile	Mean power plant IDW	Mean oil and gas well IDW	Automobile emissions (HC, CO, NOx)	PM2.5
Intercept	-2.29 (-2.39,-2.20)	-2.26 (-2.32,-2.20)	-2.26 (-2.32,-2.20)	-2.27 (-2.41,-2.13)
Age at baseline centered at 75	0.14 (0.14,0.15)	0.14 (0.14,0.15)	0.14 (0.14,0.15)	0.14 (0.14,0.15)
Exposure	0.01 (-0.01,0.02)	0.00 (0.00,0.00)	0.00 (-0.01,0.00)	0.00 (-0.02,0.02)
Spline term 1	0.64 (0.51,0.78)	0.62 (0.56,0.69)	0.63 (0.56,0.69)	0.62 (0.41,0.83)
Spline term 2	1.14 (1.00,1.29)	1.12 (1.04,1.19)	1.12 (1.05,1.19)	1.08 (0.85,1.30)
Spline term 3	1.85 (1.66,2.04)	1.91 (1.82,2.01)	1.92 (1.83,2.01)	1.90 (1.61,2.19)
Spline term 4	2.81 (2.59,3.03)	2.72 (2.60,2.83)	2.76 (2.65,2.87)	2.72 (2.38,3.06)
Spline term 5	2.83 (2.54,3.12)	2.63 (2.49,2.77)	2.68 (2.54,2.82)	2.68 (2.23,3.12)
Female	0.04 (-0.01,0.09)	0.04 (-0.01,0.09)	0.04 (-0.01,0.09)	0.04 (-0.01,0.09)
Maternal education <= 8th grade	0.16 (0.11,0.22)	0.17 (0.11,0.22)	0.17 (0.11,0.22)	0.16 (0.11,0.22)
Paternal education <= 8th grade	0.14 (0.08,0.20)	0.14 (0.08,0.20)	0.14 (0.08,0.20)	0.14 (0.08,0.20)
County level population density	-0.03 (-0.06,0.01)	-0.03 (-0.06,0.00)	0.20 (-0.13,0.54)	-0.03 (-0.06,0.00)

Percentile	Mean power plant IDW	Mean oil and gas well IDW	Automobile emissions (HC, CO, NOx)	PM2.5
County level population proportion with <= 8th grade education	0.31 (0.01,0.61)	0.37 (0.09,0.64)	0.38 (0.11,0.66)	0.34 (0.02,0.65)
County level unemployed proportion among Black 14+ population	0.16 (- 0.10,0.42)	0.17 (- 0.09,0.44)	0.18 (- 0.08,0.44)	0.17 (- 0.09,0.43)
County level median rent	0.00 (- 0.01,0.00)	0.00 (- 0.01,0.00)	0.00 (- 0.01,0.00)	0.00 (- 0.01,0.00)
Residence region in South in 1940	0.19 (0.12,0.26)	0.19 (0.12,0.26)	0.19 (0.12,0.26)	0.18 (0.11,0.26)
Exposure:Spline term 1	0.00 (- 0.02,0.02)	0.00 (0.00,0.00)	0.00 (0.00,0.00)	0.00 (- 0.03,0.03)
Exposure:Spline term 2	0.00 (- 0.02,0.02)	0.00 (0.00,0.01)	0.00 (0.00,0.00)	0.01 (- 0.02,0.04)
Exposure:Spline term 3	0.01 (- 0.02,0.04)	0.00 (- 0.01,0.00)	0.00 (0.00,0.00)	0.00 (- 0.04,0.04)
Exposure:Spline term 4	-0.01 (- 0.04,0.02)	0.01 (0.00,0.01)	0.00 (0.00,0.00)	0.00 (- 0.04,0.05)
Exposure:Spline term 5	-0.02 (- 0.07,0.02)	0.01 (0.00,0.02)	0.00 (0.00,0.00)	0.00 (- 0.06,0.06)