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Supplemental Material

Ambient Fine Particulate Matter Air Pollution and Risk of Weight Gain and Obesity in United States Veterans: An Observational Cohort Study

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Figure S5. Association of PM_{2.5} exposure with intra-individual change in BMI and weight in a national cohort of United States Veterans selected from July 1, 2010 through June 31, 2011 and followed until December 31, 2018 (n=3 902 440). (A) BMI, (B) weight. Change is reported as change per year. Linear mixed models were used to obtain rates of change in outcomes associated with PM_{2.5}, where PM_{2.5} was treated as a restricted cubic spline. Models were adjusted for height, weight, and/or BMI, State of residence, age, race, sex, Area Deprivation Index, normalized difference vegetation index, county-level % rural residency, population density, % limited access to healthy food, % access to exercise opportunities, % of adults reporting excessive alcohol consumption and smoking status. There was no missing data, so no imputation was used. Bands represent the 95% confidence interval. 2.205 pounds = 1 kilogram. Values were excluded below the 1st and above the 99th percentiles of the PM_{2.5} distribution, and the 1st percentile serves as the reference value.

References

SUPPLEMENTAL TABLES

Table S1. Contextual variable definitions and data sources.

Variable	Source	Years	Definition
Population Density(Bell et al. 2016)	US Census Bureau's Small Area Income & Poverty Estimates data	2012	Number of people in a county per square mile
Area Deprivation Index(Kind and Buckingham 2018)	American Community Survey from the US Census	2015	A national percentile ranking of census block group socioeconomic status disadvantage. Rankings range from 1 to 100, where 1 indicates the lowest level of disadvantage within the nation, and 100 indicates the highest level of disadvantage. The ranking of each census block group is determined by US Census questions in the theoretical domains of income, education, employment, and housing quality, following methodology by Singh, 2003 and Kind et al., 2014(Kind et al. 2014; Singh 2003). The 17 specific components of the US Census that are used in the ranking are the following: Percent of the block group's population aged ≥ 25 years with < 9 years of education, Percent aged ≥ 25 years with greater than or equal to a high school diploma, Percent of employed persons ≥ 16 years of age in white-collar occupations, Median family income, Income disparity (defined by Singh as the log of $100 \times$ ratio of number of households with $< \$10,000$ income to number of households with $\$50,000+$ income), Median home value, Median gross rent, Median monthly mortgage, Percent owner-occupied housing units (home ownership rate), Percent of civilian labor force population ≥ 16 years of age unemployed (unemployment rate), Percent of families below the poverty level, Percent of population below 150% of the poverty threshold, Percent of single-parent households with children < 18 years of age, Percent of occupied housing units without a motor vehicle, Percent of occupied housing units without a telephone, Percent of occupied housing units without complete plumbing (log), and Percent of occupied housing units with more than one person per room (crowding). The 2015 Area Deprivation Index was created by University of Wisconsin School of Medicine and Public Health using 2011-2015 American Community Survey data.
Rurality(Kind and Buckingham 2018)	US Census Population Estimates	2010	Percent of county population living in a rural area. This is defined as the number of county residents living in a census tract with a population under 2,500, divided by the total county population.
Alcohol Use(Kind and Buckingham 2018)	Behavioral Risk Factor Surveillance System	2006-2012	Percent of adults that report excessive alcohol consumption within the county. Excessive alcohol consumption is defined as a woman either consuming more than four alcoholic drinks during a single occasion or drinking more than one drink on average per day, or a man either consuming more than five alcoholic drinks during a single occasion or drinking more than two drinks on average per day. The number of people who report excessive alcohol consumption within the county is divided by the total number of adult Behavioral Risk Factor Surveillance System survey respondents in the county.

Diet(Kind and Buckingham 2018)	USDA Food Environment Atlas	2010	Percentage of the county population who are low income and do not live close to a grocery store. Living close to a grocery store is defined differently in rural and nonrural areas; in rural areas, it means living less than 10 miles from a grocery store; in nonrural areas, less than one mile. Low income is defined as having an annual family income of less than or equal to 200 percent of the federal poverty threshold for the family size. The number of county residents who are both low income and do not live close to a grocery store is divided by the 2010 US Census county population.
Exercise(Kind and Buckingham 2018)	OneSource Global Business Browser, Delorme map data, ESRI, & US Census Tigerline Files	2010 & 2019	Percentage of the population with access to places for physical activity. Access to places for physical activity is defined as living in census blocks with adequate access to at least one location for physical activity. Adequate access is defined as census blocks where the border is a half-mile or less from a park, or 1 mile or less from a recreational facility in urban census blocks and 3 miles or less in rural census blocks in 2019. Parks include local, state, and national parks. Recreational facilities include YMCAs as well as businesses including a wide variety of facilities such as gyms, community centers, dance studios, and pools, identified by the following Standard Industry Classification codes: 799101, 799102, 799103, 799106, 799107, 799108, 799109, 799110, 799111, 799112, 799201, 799701, 799702, 799703, 799704, 799707, 799711, 799717, 799723, 799901, 799908, 799958, 799969, 799971, 799984, or 799998. The number of county residents with access to places for physical activity is divided by the 2010 resident county population.
Normalized Difference Vegetation Index(Vermote 2019)	National Oceanic and Atmospheric Administration	2010	0.05 by 0.05-degree resolution grid. Normalized Difference Vegetation Index measures surface vegetation by comparing red and near-infrared spectral bands and ranges from -1 (water), to 0 (bare ground), and maximally 1 (dense vegetation).

Table S2. PM_{2.5} distribution by year of follow-up in a national cohort of United States Veterans selected from July 1, 2010 through June 31, 2011 and followed until December 31, 2018 (n=3 902 440).

Year	PM _{2.5} (µg/m ³)						
	0 th Percentile	10 th Percentile	25 th Percentile	50 th Percentile	75 th Percentile	90 th Percentile	100 th Percentile
2010	2.40	6.36	7.80	9.17	10.43	11.75	20.21
2011	2.40	5.92	7.87	9.46	10.85	12.38	18.67
2012	2.40	6.42	8.13	9.52	10.76	11.99	19.33
2013	2.40	6.21	7.57	8.74	9.94	11.24	17.65
2014	2.40	6.13	7.23	8.29	9.41	10.70	20.48
2015	2.40	5.81	7.14	8.36	9.51	10.78	18.56
2016	2.40	5.67	6.78	7.85	9.08	10.32	17.72
2017	2.40	4.78	6.29	7.53	8.62	9.67	16.97
2018	2.40	4.96	6.07	7.32	8.57	9.71	21.38

Abbreviations: PM_{2.5}, ambient fine particulate matter.

Table S3. Model parameters of the top three best-fitting models for each outcome based on the Shape Constrained Health Impact Function (SCHIF) in a national cohort of United States Veterans selected from July 1, 2010 through June 31, 2011 and followed until December 31, 2018 (n=3 902 440).

Outcome	Model	Weight	Mu	Coefficient	Standard error	Tau	Model function ^a
Obesity	Model-1	66.3%	4.983	0.038	0.0068	0.1	log(pm25)*logit
	Model-2	19.0%	5.823	0.032	0.0043	0.1	log(pm25)*logit
	Model-3	14.7%	3.327	0.051	0.0050	0.1	log(pm25)*logit
Weight gain	Model-1	50.3%	4.986	0.027	0.0026	0.1	log(pm25)*logit
	Model-2	48.8%	3.369	0.036	0.0036	0.1	log(pm25)*logit
	Model-3	0.01%	5.827	0.004	0.0022	0.1	log(pm25)*logit

Models are ordered by best fit. The best fitting model in each set was the optimal model, and the ensemble estimates shown in Figure 1 for each outcome were log-likelihood-weighted averages of the estimates from the three models shown for each outcome. The parameter space of our algorithm search for modeling risk of obesity included: taus of 0.1 to 0.2, mu's of 1.671, 3.327, 4.983, 5.823, 7.159 and 9.872 $\mu\text{g}/\text{m}^3$, and a range of 3.327 to 14.655 $\mu\text{g}/\text{m}^3$. The parameter space of our algorithm search for modeling risk of a 10-lbs. higher weight from baseline weight included: taus of 0.1 to 0.2, mu's of 1.752, 3.369, 4.986, 5.827, 7.185, and 9.925 $\mu\text{g}/\text{m}^3$, and a range of 3.369 to 14.645 $\mu\text{g}/\text{m}^3$. Models were adjusted for height, weight, and/or BMI, State of residence, age, race, sex, Area Deprivation Index, normalized difference vegetation index, county-level % rural residency, population density, % limited access to healthy food, % access to exercise opportunities, % of adults reporting excessive alcohol consumption, and smoking status. Model formulae are included in the manuscript.

^a Model function indicates what functional form the model used

Table S4. Weight gain by cumulative average PM_{2.5} exposure in a national cohort of United States Veterans selected from July 1, 2010 through June 31, 2011 and followed until December 31, 2018 (n=3 902 440).

Year of follow-up	PM _{2.5} 10 th Percentile		PM _{2.5} 25 th Percentile		PM _{2.5} 50 th Percentile		PM _{2.5} 75 th Percentile		PM _{2.5} 90 th Percentile	
	Average PM _{2.5} in the Year Prior (µg/m ³)	Cumulative Weight Gain by End of Time Period ^a (lbs.) (95% CI)	Average PM _{2.5} in the Year Prior (µg/m ³)	Cumulative Weight Gain by End of Time Period ^a (lbs.) (95% CI)	Average PM _{2.5} in the Year Prior (µg/m ³)	Cumulative Weight Gain by End of Time Period ^a (lbs.) (95% CI)	Average PM _{2.5} in the Year Prior (µg/m ³)	Cumulative Weight Gain by End of Time Period ^a (lbs.) (95% CI)	Average PM _{2.5} in the Year Prior (µg/m ³)	Cumulative Weight Gain by End of Time Period ^a (lbs.) (95% CI)
1	6.45	0.62 (0.62-0.62)	7.99	0.77 (0.77-0.77)	9.39	0.91 (0.91-0.91)	10.50	1.02 (1.02-1.02)	11.72	1.14 (1.13-1.14)
2	6.45	1.25 (1.25-1.25)	8.19	1.57 (1.57-1.57)	9.58	1.84 (1.83-1.84)	10.76	2.06 (2.06-2.06)	11.92	2.29 (2.29-2.29)
3	6.53	1.88 (1.88-1.88)	8.03	2.34 (2.34-2.35)	9.22	2.73 (2.73-2.73)	10.40	3.06 (3.06-3.07)	11.55	3.41 (3.41-3.41)
4	6.39	2.50 (2.50-2.50)	7.52	3.07 (3.07-3.07)	8.62	3.56 (3.56-3.57)	9.74	4.01 (4.00-4.01)	10.88	4.46 (4.46-4.46)
5	6.17	3.10 (3.09-3.10)	7.28	3.78 (3.77-3.78)	8.44	4.38 (4.38-4.38)	9.51	4.93 (4.92-4.93)	10.67	5.49 (5.49-5.50)
6	5.93	3.67 (3.67-3.67)	7.09	4.46 (4.46-4.47)	8.24	5.18 (5.17-5.18)	9.38	5.84 (5.83-5.84)	10.58	6.52 (6.51-6.52)
7	5.41	4.19 (4.19-4.20)	6.71	5.11 (5.11-5.12)	7.81	5.93 (5.93-5.94)	8.90	6.70 (6.69-6.70)	10.07	7.49 (7.49-7.50)
8	5.24	4.70 (4.70-4.70)	6.54	5.74 (5.74-5.75)	7.54	6.66 (6.66-6.67)	8.62	7.53 (7.53-7.54)	9.73	8.43 (8.43-8.44)

Abbreviations: BMI, denotes body mass index; CI, 95% confidence interval; PM_{2.5}, ambient fine particulate matter. 2.205 pounds = 1 kilogram. Percentile groups are defined as participants with a cumulative average exposure at the percentile ± 0.5%, resulting in roughly 39,000 participants at baseline in each group. Results were obtained from linear mixed models. Models were adjusted for height, State of residence, age, race, sex, Area Deprivation Index, normalized difference vegetation index, county-level % rural residency, population density, % limited access to healthy food, % access to exercise opportunities, % of adults reporting excessive alcohol consumption, and smoking status.

^a Average cumulative gain in BMI associated with PM_{2.5} for those in the percentile group during follow-up.

Table S5. BMI gain by cumulative average PM_{2.5} exposure in a national cohort of United States Veterans selected from July 1, 2010 through June 31, 2011 and followed until December 31, 2018 (n=3 902 440).

Year of follow-up	PM _{2.5} 10 th Percentile		PM _{2.5} 25 th Percentile		PM _{2.5} 50 th Percentile		PM _{2.5} 75 th Percentile		PM _{2.5} 90 th Percentile	
	Average PM _{2.5} in the Year Prior (µg/m ³)	Cumulative BMI Gain by End of Time Period ^a (kg/m ²) (95% CI)	Average PM _{2.5} in the Year Prior (µg/m ³)	Cumulative BMI Gain by End of Time Period ^a (kg/m ²) (95% CI)	Average PM _{2.5} in the Year Prior (µg/m ³)	Cumulative BMI Gain by End of Time Period ^a (kg/m ²) (95% CI)	Average PM _{2.5} in the Year Prior (µg/m ³)	Cumulative BMI Gain by End of Time Period ^a (kg/m ²) (95% CI)	Average PM _{2.5} in the Year Prior (µg/m ³)	Cumulative BMI Gain by End of Time Period ^a (kg/m ²) (95% CI)
1	6.45	0.09 (0.09-0.09)	7.99	0.11 (0.11-0.11)	9.39	0.13 (0.13-0.13)	10.50	0.15 (0.15-0.15)	11.72	0.16 (0.16-0.17)
2	6.45	0.18 (0.18-0.18)	8.19	0.23 (0.23-0.23)	9.58	0.27 (0.26-0.27)	10.76	0.30 (0.30-0.30)	11.92	0.33 (0.33-0.33)
3	6.53	0.27 (0.27-0.27)	8.03	0.34 (0.34-0.34)	9.22	0.40 (0.39-0.40)	10.40	0.44 (0.44-0.45)	11.55	0.49 (0.49-0.50)
4	6.39	0.36 (0.36-0.36)	7.52	0.45 (0.44-0.45)	8.62	0.52 (0.51-0.52)	9.74	0.58 (0.58-0.59)	10.88	0.65 (0.64-0.65)
5	6.17	0.45 (0.45-0.45)	7.28	0.55 (0.54-0.55)	8.44	0.64 (0.63-0.64)	9.51	0.71 (0.71-0.72)	10.67	0.80 (0.79-0.80)
6	5.93	0.53 (0.53-0.54)	7.09	0.65 (0.64-0.65)	8.24	0.75 (0.75-0.76)	9.38	0.85 (0.84-0.85)	10.58	0.95 (0.94-0.95)
7	5.41	0.61 (0.60-0.61)	6.71	0.74 (0.74-0.75)	7.81	0.86 (0.85-0.87)	8.90	0.97 (0.96-0.98)	10.07	1.09 (1.08-1.09)
8	5.24	0.68 (0.68-0.69)	6.54	0.83 (0.83-0.84)	7.54	0.97 (0.96-0.97)	8.62	1.09 (1.09-1.10)	9.73	1.22 (1.22-1.23)

Abbreviations: BMI, denotes body mass index; CI, 95% confidence interval; PM_{2.5}, ambient fine particulate matter. 2.205 pounds = 1 kilogram. Percentile groups are defined as participants with a cumulative average exposure at the percentile ± 0.5%, resulting in roughly 39,000 participants at baseline in each group. Results were obtained from linear mixed models. Models were adjusted for height, State of residence, age, race, sex, Area Deprivation Index, normalized difference vegetation index, county-level % rural residency, population density, % limited access to healthy food, % access to exercise opportunities, and % of adults reporting excessive alcohol consumption, and smoking status.

a Average cumulative gain in BMI associated with PM_{2.5} for those in the percentile group during follow-up.

Table S6. Additional sensitivity analyses of survival outcomes in a national cohort of United States Veterans selected from July 1, 2010 through June 31, 2011 and followed until December 31, 2018 (n=3 902 440).

Model	Hazard Ratio per 10 µg/m ³ of PM _{2.5} (95% CI)	
	Obesity (BMI ≥ 30 kg/m ²) ^b	Weight Gain (10 lbs.) ^c
Within-city analyses ^a	1.20 (1.16-1.24)	1.18 (1.15-1.20)
Stratified by baseline age, race, sex, and BMI	1.05 (1.03-1.07)	1.07 (1.06-1.08)

Abbreviations: BMI, body mass index; CI, 95% confidence interval; PM_{2.5}, ambient fine particulate matter. 2.205 pounds = 1 kilogram.

Cox proportional hazard models provided hazard ratios. Models were adjusted for height, weight, and/or BMI, State of residence, age, race, sex, Area Deprivation Index, rural residency, population density, normalized difference vegetation index, county level % limited access to healthy food, % access to exercise opportunities, % adults reporting excessive alcohol consumption, and smoking status.

^a In a cohort of those who lived in a metropolitan statistical area (n=3 066 141)

^b Baseline body measurement was BMI

^c Baseline body measurement was height and weight

Table S7. Analyses of additional survival outcomes in a national cohort of United States Veterans selected from July 1, 2010 through June 31, 2011 and followed until December 31, 2018 (n=3 902 440).

	Overweight/Obese^a (BMI ≥ 25 kg/m²)	Weight Gain (20 lbs.)	BMI Gain (1 kg/m²)	BMI Gain (3 kg/m²)	BMI Growth (5%)	Weight Growth (5%)
# of outcomes (%)	281 728 (33.73)	762 314 (19.53)	2 074 044 (53.15)	716 958 (18.37)	1 643 251 (42.11)	1 644 225 (42.13)
Sequential Model Adjustments	Hazard Ratio per 10 µg/m³ of PM_{2.5} (95% CI)					
Unadjusted	1.00 (0.98-1.01)	1.29 (1.28-1.30)	1.10 (1.10-1.11)	1.28 (1.27-1.30)	1.17 (1.16-1.17)	1.17 (1.16-1.17)
+Baseline height, weight, and/or BMI (Model 1)	1.14 (1.13-1.16) ^b	1.27 (1.26-1.29) ^c	1.10 (1.09-1.10) ^b	1.27 (1.26-1.28) ^b	1.15 (1.14-1.15) ^b	1.15 (1.14-1.15) ^c
Model 1 + state of residence	1.25 (1.23-1.28)	1.45 (1.43-1.47)	1.17 (1.16-1.18)	1.43 (1.41-1.45)	1.25 (1.24-1.26)	1.24 (1.23-1.26)
Model 1 + state of residence + age, sex, and race	1.04 (1.02-1.06)	1.18 (1.16-1.20)	1.01 (1.01-1.02)	1.17 (1.15-1.19)	1.05 (1.04-1.06)	1.05 (1.04-1.06)
Model 1 + state of residence + age, sex, and race + contextual characteristics ^d	1.05 (1.02-1.07)	1.20 (1.19-1.22)	1.03 (1.02-1.04)	1.21 (1.19-1.23)	1.07 (1.06-1.09)	1.08 (1.07-1.09)
Model 1 + state of residence + age, sex, and race + contextual characteristics ^d + smoking status	1.04 (1.01-1.06)	1.18 (1.16-1.20)	1.03 (1.02-1.04)	1.18 (1.16-1.20)	1.06 (1.05-1.07)	1.07 (1.05-1.08)

Abbreviations: BMI, body mass index; CI, 95% confidence interval; PM_{2.5}, ambient fine particulate matter. 2.205 pounds = 1 kilogram.

Cox proportional hazard models provided hazard ratios. Models were sequentially adjusted using the corresponding covariates listed below.

There was no missing data, so no imputation was used.

a In a cohort of those not overweight or obese at baseline (n=835 212)

b Baseline body measurement was BMI

c Baseline body measurement was height and weight

d Contextual characteristics include county-level Area Deprivation Index, normalized difference vegetation index, county-level % rural residency, population density, % limited access to healthy food, % access to exercise opportunities, and % of adults reporting excessive alcohol consumption

Table S8. Additional sensitivity analyses of intra-individual change in BMI and weight in a national cohort of United States Veterans selected from July 1, 2010 through June 31, 2011 and followed until December 31, 2018 (n=3 902 440).

Model	Intra-individual increase per 10 $\mu\text{g}/\text{m}^3$ of $\text{PM}_{2.5}$ per year (95% CI)	
	BMI (kg/m^2)	Weight (lbs.)
Cohort with a measurement of weight at least 6.5 years after beginning of follow-up ^a	0.139 (0.137-0.142)	0.962 (0.947-0.977)

Abbreviations: BMI, body mass index; CI, 95% confidence interval; $\text{PM}_{2.5}$, ambient fine particulate matter. 2.205 pounds = 1 kilogram.

Linear mixed models provided levels of intra-individual change. Models were adjusted for height, State of residence, age, race, sex, Area Deprivation Index, normalized difference vegetation index, county-level % rural residency, population density, % limited access to healthy food, % access to exercise opportunities, % of adults reporting excessive alcohol consumption, and smoking status.

^a In a cohort of those who had a recorded weight after at least 6.5 years of follow-up (n=1 955 448)

SUPPLEMENTAL FIGURES

Figure S1. Cohort construction flowchart of a national cohort of United States Veterans selected from July 1, 2010 through June 31, 2011 and followed until December 31, 2018 (n=3 902 440).

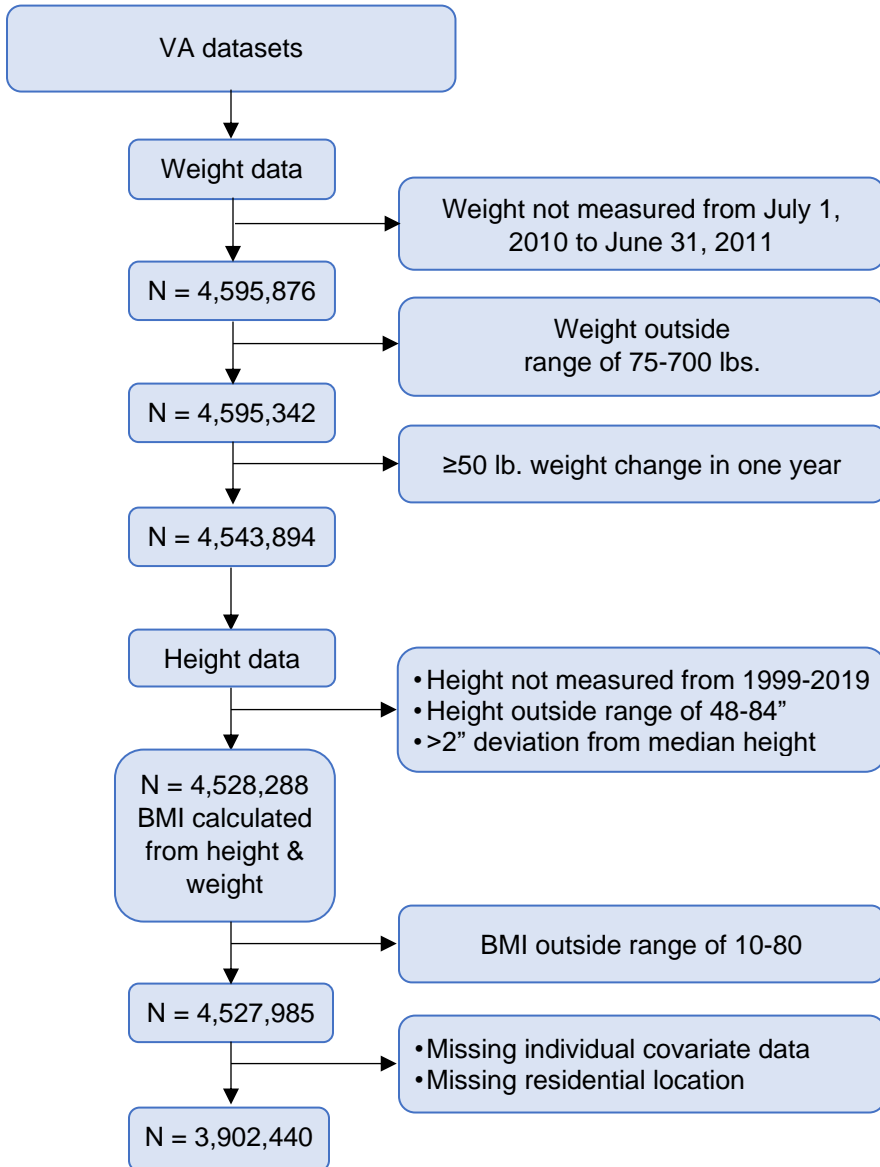


Figure S2. Conceptual framework of the association of PM_{2.5} with obesity and weight gain.

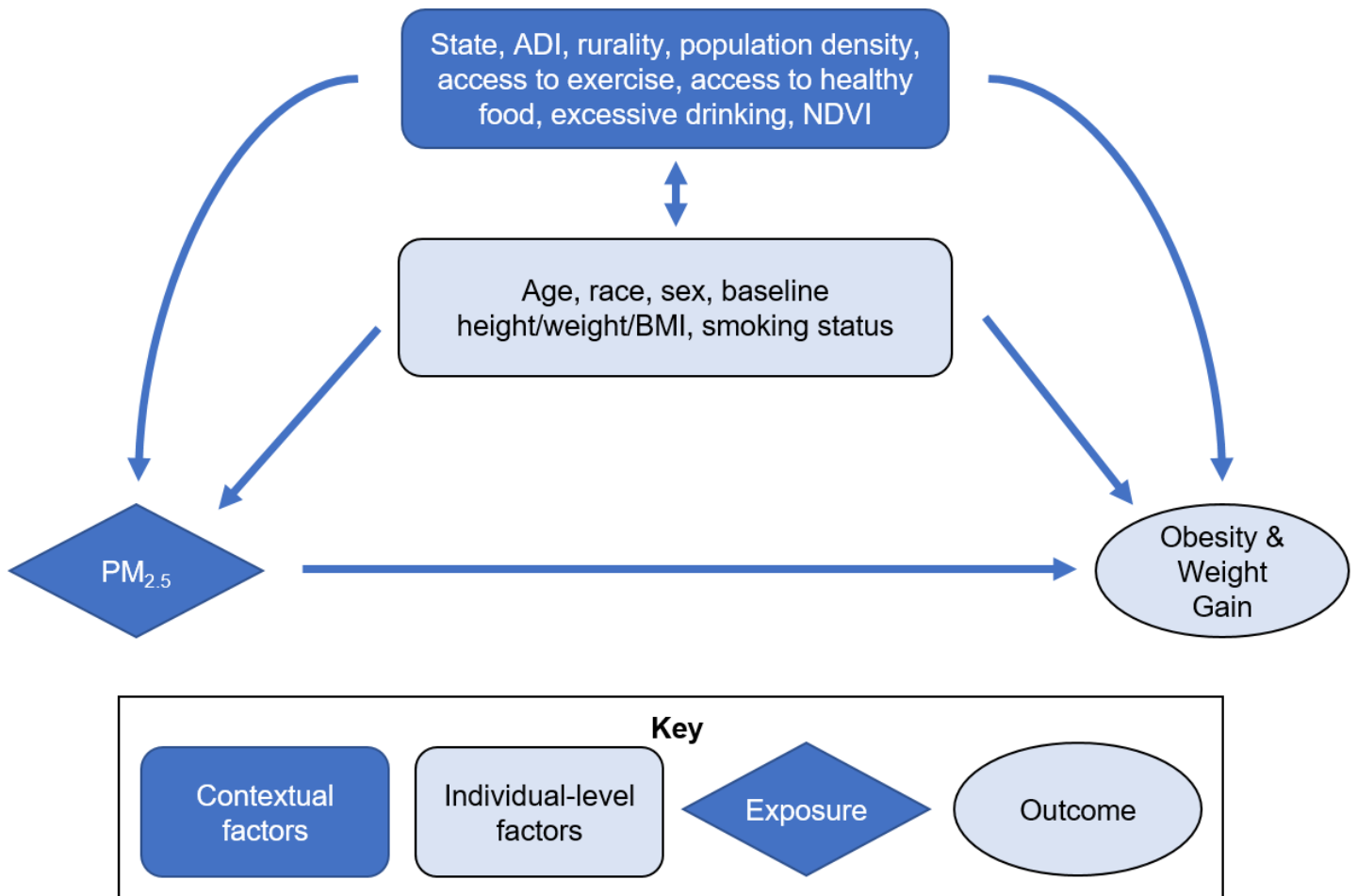


Figure S3. PM_{2.5} distribution by year of follow-up in a national cohort of United States Veterans selected from July 1, 2010 through June 31, 2011 and followed until December 31, 2018 (n=3 902 440). Area indicates the distribution of PM_{2.5} for subjects in the cohort during each year of follow-up. Distributions are weighted by participant time in cohort in that year.

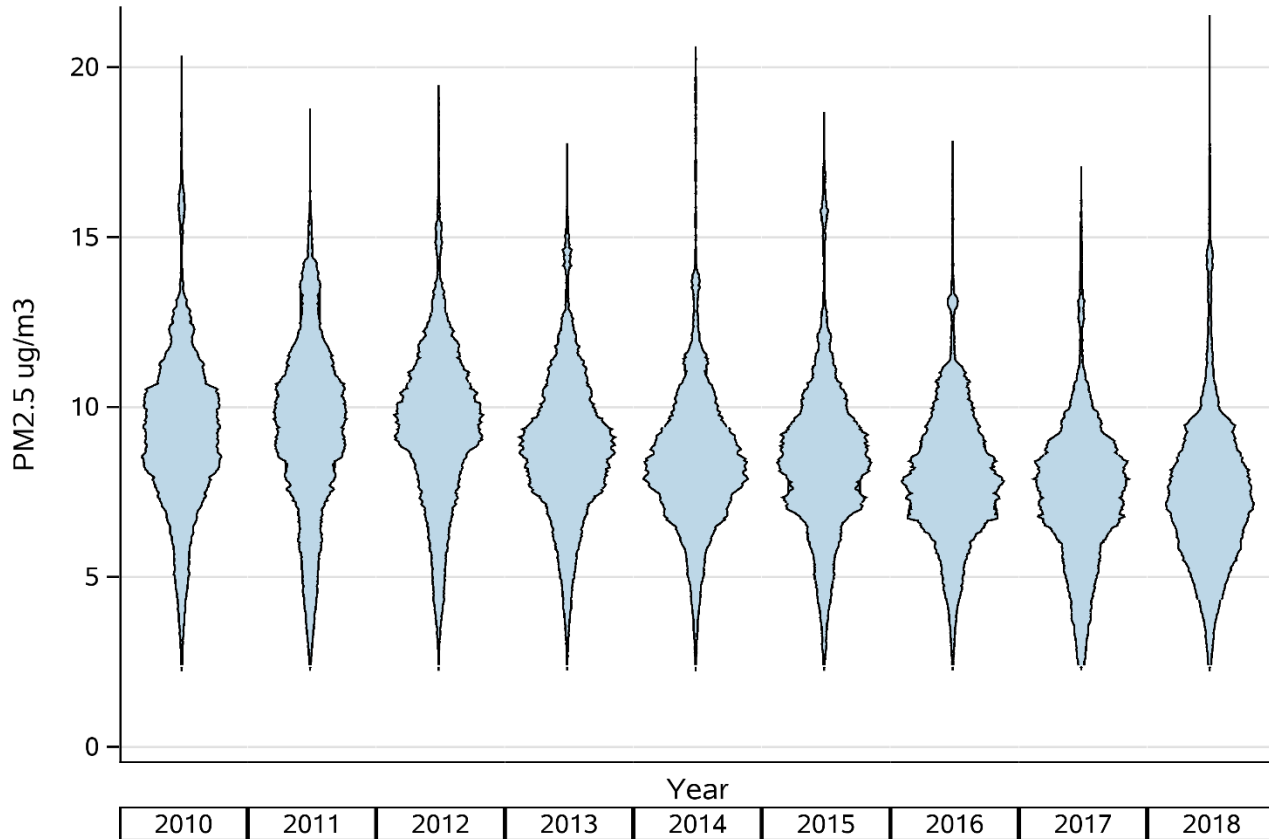
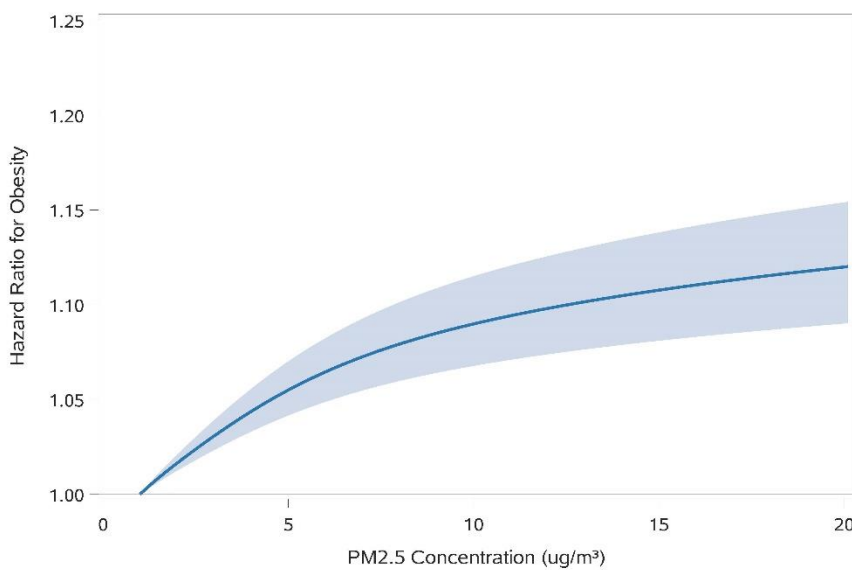


Figure S4. Association of PM_{2.5} exposure with risk of obesity and gain in weight based on the optimal model in a national cohort of United States Veterans selected from July 1, 2010 through June 31, 2011 and followed until December 31, 2018 (n=3 902 440). (A) Obesity, (B) 10 lbs. gain in weight. A Shape Constrained Health Impact Function (SCHIF) modeling approach was used. Models were adjusted for height, weight, and/or BMI, State of residence, age, race, sex, smoking status, Area Deprivation Index, normalized difference vegetation index, county-level % rural residency, population density, % limited access to healthy food, % access to exercise opportunities, and % of adults reporting excessive alcohol consumption. Lines represent the estimated difference in risk associated with a given PM_{2.5} concentration compared to with the reference concentration of 1 µg/m³ (in consideration of the log-linear form). Bands represent the 95% confidence interval. 2.205 pounds = 1 kilogram. Model parameters of the optimal model are reported in Table S3.

A)



B)

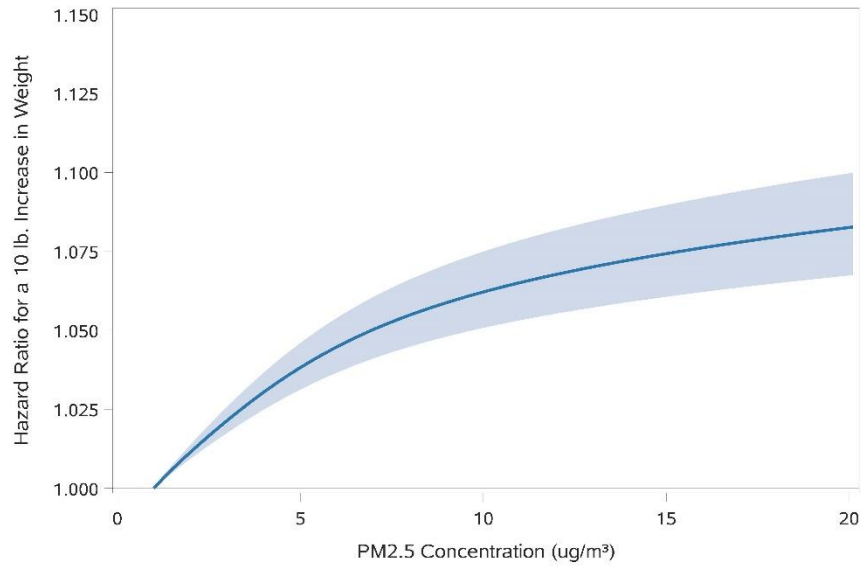
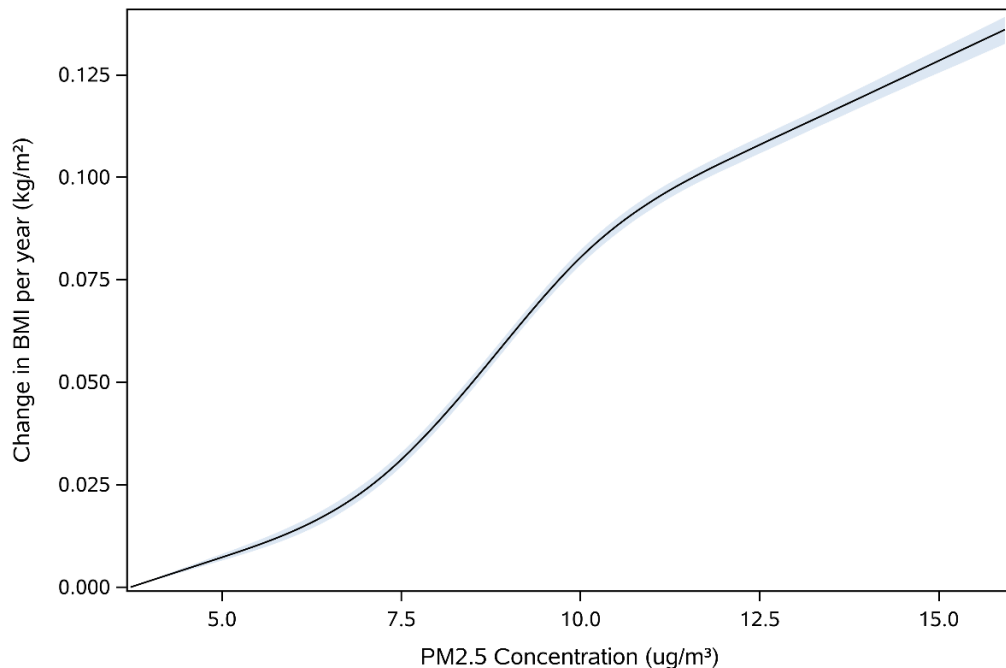
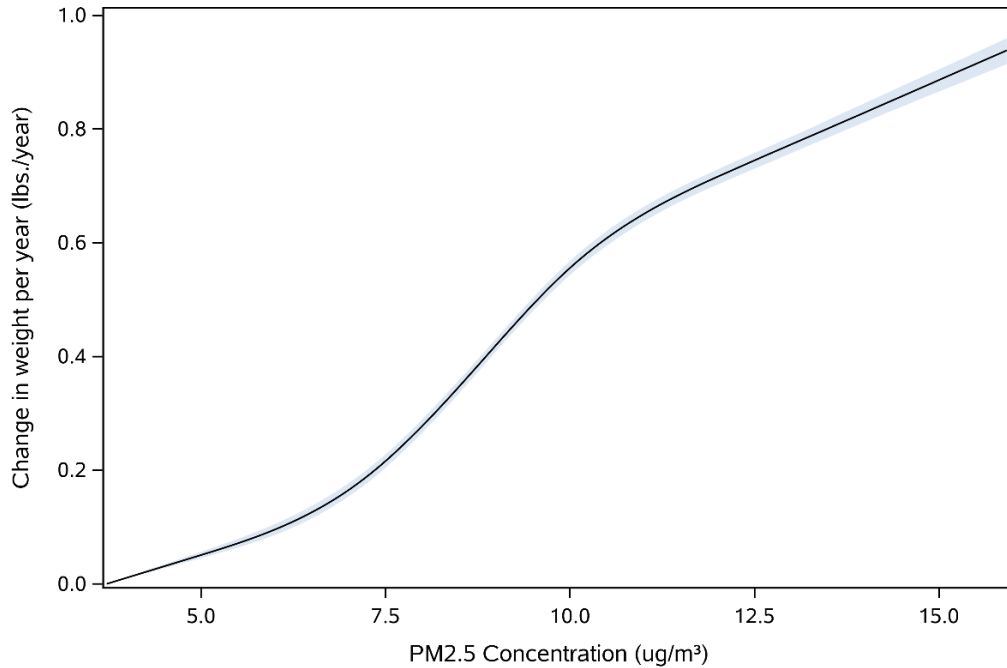


Figure S5. Association of PM_{2.5} exposure with intra-individual change in BMI and weight in a national cohort of United States Veterans selected from July 1, 2010 through June 31, 2011 and followed until December 31, 2018 (n=3 902 440). (A) BMI, (B) weight. Change is reported as change per year. Linear mixed models were used to obtain rates of change in outcomes associated with PM_{2.5}, where PM_{2.5} was treated as a restricted cubic spline. Models were adjusted for height, weight, and/or BMI, State of residence, age, race, sex, Area Deprivation Index, normalized difference vegetation index, county-level % rural residency, population density, % limited access to healthy food, % access to exercise opportunities, % of adults reporting excessive alcohol consumption and smoking status. There was no missing data, so no imputation was used. Bands represent the 95% confidence interval. 2.205 pounds = 1 kilogram. Values were excluded below the 1st and above the 99th percentiles of the PM_{2.5} distribution, and the 1st percentile serves as the reference value.

A)



B)



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