Environ Health Perspect

DOI: 10.1289/EHP14418

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Supplemental Material

Associations between Fine Particulate Matter Components, Their Sources, and Cognitive Outcomes in Children Ages 9–10 Years Old from the United States

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Figure S4. Weights of PM components, clustered by source factor groups, contributing to significant grouped mixture effects on neurocognitive outcomes in 9–10-year-old participants from the ABCD Study cohort (n=8,589), 2016-2018. A) Weights for associations seen for general cognitive ability and crustal (negative association), industrial (negative association), and traffic (positive association) related components. B) Weights for association seen for learning & memory and ammonium nitrate-related components (negative association). C) Weights for associations seen for executive function and traffic (negative association) and biomass burning (positive association) related components. Abbreviations: NO_3^- for nitrate; NH_4^+ for ammonium; OC for organic carbon; EC for elemental carbon; Zn for zinc; K for potassium; Si for silicon; Pb for lead; Ni for nickel; Fe for iron; Cu for copper; Ca for calcium; Br for bromine. Numeric data for Supplemental Figure 4 can be found in Excel Table S10.

References

Additional File- Excel Document

Supplemental Methods

Distributed acyclic graph (DAG), selection of confounders, and identified minimally sufficient dataset: Using variables identified based on the literature and a directed acyclic graph (DAG) approach,[1,2] we have identified a single minimal sufficient adjustment sets of variables that, when controlled for, are expected to block biasing pathways in our final analyses. To identify this final minimal sufficient list, we first started by included several a priori observed and unobserved confounders that were known to predict neurobehavioral development and may also influence where people live (and thus residential air pollution exposure (**Supplemental Figure 1**)). This included the following variables: **1)** Demographics: Child's age, sex and race/ethnicity; **2)** Socioeconomic Position (SES): Parent report of parental education, family income, parental employment status, marital status; **3)** Perceived Neighborhood Safety: Neighborhood safety [3,4] calculated as an average score derived from three questions of the ABCD Parent Neighborhood quality/Crime Survey Modified from PhenX (NSC); **4)** Urban vs. Rural classification: Determined and assigned by the 2010 Census Urban and Rural Classification; **5)** Noise Exposure: estimated ambient anthropomorphic sound levels using a U.S. wide geospatial model [5] that sources from 479 site locations and estimated at a 1-km grid across the U.S.; **6)** Parental Factors: Biological maternal age; **7)** Child's Pubertal development [6]; **8)** Secondhand Smoke Exposure: Through parent-report, information is obtained during the 6-months prior to each visit and during the pregnancy; and **9)** Lifestyle Factors: Physical activity of the child and average screen time use. We also considered unobserved variables: Parent Race/Ethnicity (Racialization) is an unmeasured variable which is included in the DAG to represent the many economic, cultural, and societal factors present in the United States that may impact where people live and the situation in which children grow and develop, which is likely to have effects on cognitive development. Greenspace Access is another unmeasured variable that is often a direct result of a person's residential location, may influence the severity of air pollution exposure in a geographic area[7], and may have downstream effects on cognitive development. Finally, residential address is included as an unmeasured variable, as the air pollution assigned to each study participant is assigned to that participant's residential address, but this study does not utilize the actual geolocation of each subject or any spatial analyses with this geolocation.

Next, we created a DAG using DAGgitty [8], a software designed to assist in the creation and interpretation of causal diagrams. DAGgitty uses color-coding of variables and arrows to clarify how variables interrelate to each other and to the exposure and outcome to identify biasing pathways. Our team worked together to use field-specific background knowledge, familiarity with published literature, and intuition to draw the DAG presented in **Supplemental Figure 1A**, which aims to create a complete picture of the variables available within ABCD that may be relevant. Beyond three variables identified (Child's age, sex, and race/ethnicity) as important *a priori* demographic factors in all models, our analysis in DAGitty produced a single minimal sufficient adjustment set (i.e. white circles in **Supplemental Figure 1A** and simplified in **Supplemental Figure 1B**). Details on the color-coding system used by DAGgity is provided in the **Supplemental Figure 1A** legend key.

Supplemental Results

Supplemental Table 1. Comparison of ABCD Study Cohort and analytic sample demographics

Variables	Study Sample (N=8,589)	ABCD Sample (N=11,876)
Age (months)		
Mean (SD)	119 (7.4)	119 (7.5)
Sex at birth		
Female	4086 (47.6 %)	5680 (47.8%)
Male	4503 (52.4 %)	6196 (52.2%)
Race/Ethnicity		
Asian	208 (2.4 %)	252 (2.1%)
Black	1252 (14.6 %)	1784 (15.0%)
Hispanic	1822 (21.2 %)	2411 (20.3%)
Other[a]	891 (10.4 %)	1247 (10.5%)
White	4416 (51.4 %)	6180 (52.0%)
Total household income		
<$50k	2338 (27.2 %)	3223 (27.1%)
>=$50k & <$100k	2233 (26 %)	3071 (25.9%)
>=$100k	3289 (38.3 %)	4564 (38.4%)
Don't Know or Refuse	729 (8.5 %)	1016 (8.6%)
Urbanicity		
Urbanized Area	7633 (88.9 %)	9856 (83.0%)
Urban Cluster	259 (3 %)	372 (3.1%)
Rural	697 (8.1 %)	966 (8.1%)
Neighborhood Safety		
Mean (SD)	3.87 (0.97)	3.89 (0.98)
Physical Activity (hours/week)		
Mean (SD)	3.5 (2.3)	3.49 (2.3)
Screen times (hours/day)		
Mean (SD)	2.94 (2.21)	2.96 (2.4)

Values shown are either mean (standard deviation) or N (% frequency). [a] "Other" race/ethnicity category includes subjects who were parent-identified as American Indian/Native American, Alaska Native, Native Hawaiian, Guamanian, Samoan, Other Pacific Islander, Asian Indian, Chinese, Filipino, Japanese, Korean, Vietnamese, Other Asian, or Other Race ((participants that were identified in more than one category or multi-racial).

Supplemental Table 2. Prediction performance metrics (root mean square error) from ensemble models of $PM_{2.5}$ components, as previously reported[9] .

Component	Model RMSE
EC	0.09 (µg/m^3)
NH_4^+	0.09 (µg/m^3)
NO_3^-	0.07 (µg/m^3)
OC	0.18 (µg/m^3)
SO_4^{2-}	0.28 (µg/m^3)
Br	0.18 (ng/m^3)
Ca	2.86 (ng/m^3)
Cu	1.35 (ng/m^3)
Fe	4.99 (ng/m^3)
K	4.77 (ng/m^3)
Ni	0.45 (ng/m^3)
Pb	0.34 (ng/m^3)
Si	10.15 (ng/m^3)
V	0.73 (ng/m^3)
Zn	1.82 (ng/m^3)

Supplemental Table 3. Grouped Weighted quantile sum results showing cumulative associations between groups of PM components, based on six identified source factors, and neurocognitive performance in 9–10-year-old participants from the ABCD Study cohort (n=8,589), 2016-2018 also adjusting for exposure to ozone.

Outcome	WQS mixture group membership	Estimate	Std Error	p-value
General Cognitive Ability	**Ca, Si (Crustal)**	-2.51×10^{-2}	**1.18×10^{-2}**	**0.0329****
	SO_4^{2-}, V (coal-burning power plants)	-1.73×10^{-3}	9.41×10^{-3}	0.8539
	OC, K, Br (Biomass Burning)	-4.04×10^{-3}	1.01×10^{-2}	0.6887
	EC, Cu, Fe (Traffic)	**2.38×10^{-2}**	**7.43×10^{-3}**	**0.0013*****
	NH_4^+, NO_3^- (Ammonium Nitrates)	-1.21×10^{-2}	1.11×10^{-2}	0.2724
	Pb, Ni, Zn (Industrial)	**-1.89×10^{-2}**	**8.84×10^{-3}**	**0.0325****
Learning & Memory	Ca, Si (Crustal)	-1.45×10^{-2}	1.18×10^{-2}	0.2173
	SO_4^{2-}, V (coal-burning power plants)	9.33×10^{-3}	8.82×10^{-3}	0.2901
	OC, K, Br (Biomass Burning)	8.70×10^{-3}	9.82×10^{-3}	0.3753
	EC, Cu, Fe (Traffic)	-3.78×10^{-2}	9.46×10^{-3}	0.6893
	NH_4^+, NO_3^- (Ammonium Nitrates)	**-3.34×10^{-2}**	**1.10×10^{-2}**	**0.0021*****
	Pb, Ni, Zn (Industrial)	-6.74×10^{-4}	9.41×10^{-3}	0.5024
Executive Function	Ca, Si (Crustal)	-1.88×10^{-2}	1.31×10^{-2}	0.1511
	SO_4^{2-}, V (coal-burning power plants)	-7.85×10^{-4}	8.49×10^{-3}	0.9367
	OC, K, Br (Biomass Burning)	**2.88×10^{-2}**	**1.16×10^{-2}**	**0.0128****
	EC, Cu, Fe (Traffic)	**-2.19×10^{-2}**	**1.08×10^{-2}**	**0.0433****
	NH_4^+, NO_3^- (Ammonium Nitrates)	-1.74×10^{-2}	1.24×10^{-2}	0.1574
	Pb, Ni, Zn (Industrial)	-4.44×10^{-4}	1.04×10^{-2}	0.9594

[a]Estimates are per 1-unit increase in the grouped WQS index, interpreted as approximately 1 decile increase in source factor groups. Results from Grouped WQS regression models wherein the 15 PM components grouped into six source factors, adjusting for age, sex, race and ethnicity, overall household income, perceived neighborhood safety, urbanicity, physical activity, and daily screen average hours and site and exposure to annual levels of ozone. Abbreviations: SO_4^{2-} for sulfate; NO_3^- for nitrate; NH_4^+ for ammonium; OC for organic carbon; EC for elemental carbon; Zn for zinc; V or vanadium; K for potassium; Si for silicon; Pb for lead; Ni for nickel; Fe for iron; Cu for copper; Ca for calcium; Br for bromine. †PMF identified ammonium sulfates components (SO_4^{2-}, V, and NH_4^+) were reduced to SO_4^{2-}, V (likely reflecting coal-burning power plants) to reduce overlap of NH_4^+ in GQWS analysis. Bolded values reflect p<0.05.

Supplemental Table 4. Associations between each $PM_{2.5}$ source factor and cognitive outcome in 9–10-year-old participants from the ABCD Study cohort (n=8,588), 2016-2018 also adjusting for exposure to ozone.

	General Cognitive Ability			**Learning & Memory**			**Executive Function**		
Source	***b***	**Std Error**	**p value**	***b***	**Std Error**	**p value**	***b***	**Std Error**	**p value**
Crustal	-2.70×10^{-2}	2.67×10^{-2}	0.3119	-2.48×10^{-2}	2.70×10^{-2}	0.9269	-5.58×10^{-2}	2.98×10^{-2}	0.0613
Ammonium Sulfates	6.53×10^{-3}	4.61×10^{-2}	0.8872	6.68×10^{-3}	4.65×10^{-2}	0.1511	1.15×10^{-1}	5.14×10^{-2}	0.0246
Biomass Burning	-8.07×10^{-3}	4.90×10^{-2}	0.8693	-2.34×10^{-2}	4.95×10^{-2}	0.6360	2.78×10^{-2}	5.47×10^{-2}	0.6114
Traffic	1.29×10^{-2}	2.69×10^{-2}	0.6322	-3.29×10^{-2}	2.72×10^{-2}	0.2261	-5.95×10^{-2}	3.00×10^{-2}	0.0473
Ammonium Nitrates	-5.09×10^{-2}	3.39×10^{-2}	0.1336	**-1.29×10^{-1}**	**3.42×10^{-2}**	**0.0001*** **	1.65×10^{-3}	3.78×10^{-2}	0.9652
Industrial	8.09×10^{-3}	3.75×10^{-2}	0.8290	2.16×10^{-2}	3.78×10^{-2}	0.5680	-3.95×10^{-2}	4.18×10^{-2}	0.3446

Linear regression models, adjusted for age, sex, race and ethnicity, overall household income, neighborhood safety, urbanicity, physical activity, daily screentime average hours and site. Estimates include unstandardized beta coefficients (b), standard errors, and p-values. Bolded values reflected models passing Bonferroni correction (p=0.008).

Supplemental Table 5. Weighted Quantile Sum (WQS) regression results examining the mixture of 15 PM components on neurocognitive performance in 9–10-year-old participants from the ABCD Study cohort (n=8,580), 2016-2018, also adjusting for parental education.

Outcome	Estimate[a]	Std Error	p-value
General Cognitive Ability	-1.843×10^{-2}	9.66×10^{-3}	0.0642
Learning & Memory	-4.313×10^{-2}	1.402×10^{-2}	**0.0024**
Executive Function	-2.661×10^{-2}	1.445×10^{-2}	0.0577

[a]Estimates are per 1-unit increase in the WQS index, reflecting as approximately 1 decile increase in all PM components. WQS regression models of the 15 PM components, adjusting for age, sex, race and ethnicity, overall household income, perceived neighborhood safety, urbanicity, physical activity, and daily screen average hours, site and parental education. Bolded values reflect p<0.05.

Supplemental Table 6. Grouped Weighted quantile sum results showing cumulative associations between groups of PM components, based on six identified source factors, and neurocognitive performance in 9–10-year-old participants from the ABCD Study cohort (n=8,580), 2016-2018, including parental education as an additional covariate.

Outcome	WQS mixture group membership	Estimate[a]	Std Error	p-value
General Cognitive Ability	Ca, Si (Crustal)	-2.06×10^{-2}	1.14×10^{-2}	0.0709
	SO_4^{2-}, V (portion of Ammonium Sulfates†)	-2.95×10^{-3}	9.15×10^{-3}	0.7471
	OC, K, Br (Biomass Burning)	-1.28×10^{-2}	9.82×10^{-3}	0.1920
	EC, Cu, Fe (Traffic)	$\mathbf{2.51 \times 10^{-2}}$	$\mathbf{7.48\times 10^{-3}}$	**0.0007*** **
	NH_4^+, NO_3^- (Ammonium Nitrates)	-7.44×10^{-3}	1.08×10^{-2}	0.4917
	Pb, Ni, Zn (Industrial)	-1.34×10^{-2}	8.86×10^{-3}	0.1304
Learning & Memory	Ca, Si (Crustal)	-1.21×10^{-2}	1.16×10^{-2}	0.2969
	SO_4^{2-}, V (portion of Ammonium Sulfates†)	1.04×10^{-2}	8.36×10^{-3}	0.2129
	OC, K, Br (Biomass Burning)	8.03×10^{-3}	9.81×10^{-3}	0.4184
	EC, Cu, Fe (Traffic)	-3.76×10^{-3}	9.56×10^{-3}	0.6942
	NH_4^+, NO_3^- (Ammonium Nitrates)	$\mathbf{-3.00 \times 10^{-2}}$	$\mathbf{1.09 \times 10^{-2}}$	**0.0061*** **
	Pb, Ni, Zn (Industrial)	-7.62×10^{-3}	9.46×10^{-3}	0.4209
Executive Function	Ca, Si (Crustal)	-1.93×10^{-2}	1.33×10^{-2}	0.1461
	SO_4^{2-}, V (portion of Ammonium Sulfates†)	8.23×10^{-4}	8.78×10^{-3}	0.9253
	OC, K, Br (Biomass Burning)	$\mathbf{2.91 \times 10^{-2}}$	$\mathbf{1.15 \times 10^{-2}}$	**0.0495***
	EC, Cu, Fe (Traffic)	$\mathbf{-2.13 \times 10^{-2}}$	$\mathbf{1.08 \times 10^{-2}}$	**0.0397***
	NH_4^+, NO_3^- (Ammonium Nitrates)	-1.59×10^{-2}	1.24×10^{-2}	0.1981
	Pb, Ni, Zn (Industrial)	-2.08×10^{-3}	1.04×10^{-2}	0.8407

[a]Estimates are per 1-unit increase in the grouped WQS index, interpreted as approximately 1 decile increase in source factor groups. Results from Grouped WQS regression models wherein the 15 PM components grouped into six source factors, adjusting for age, sex, race and ethnicity, overall household income, perceived neighborhood safety, urbanicity, physical activity, and daily screen average hours, site and parental education. Abbreviations: SO_4^{2-} for sulfate; NO_3^- for nitrate; NH_4^+ for ammonium; OC for organic carbon; EC for elemental carbon; Zn for zinc; V or vanadium; K for potassium; Si for silicon; Pb for lead; Ni for nickel; Fe for iron; Cu for copper; Ca for calcium; Br for bromine. †PMF identified ammonium sulfates components (SO_4^{2-}, V, and NH_4^+) were reduced to SO_4^{2-}, V (likely reflecting coal-burning power plants) to reduce overlap of NH_4^+ in GQWS analysis. Bolded values reflect $p<0.05$.

Supplemental Table 7. Associations between each $PM_{2.5}$ source factor and cognitive outcome in 9–10-year-old participants from the ABCD Study cohort (n=8,580), 2016-2018, including parental education as an additional covariate.

	General Cognitive Ability			**Learning & Memory**			**Executive Function**		
Source	***b***	**Std Error**	**p value**	***b***	**Std Error**	**p value**	***b***	**Std Error**	**p value**
Crustal	-2.01×10^{-2}	2.60×10^{-2}	0.4391	-1.09×10^{-3}	2.68×10^{-2}	0.9674	-5.49×10^{-2}	2.98×10^{-2}	0.0655
Ammonium Sulfates	-5.33×10^{-3}	4.48×10^{-2}	0.9053	5.91×10^{-2}	4.62×10^{-2}	0.2009	1.13×10^{-1}	5.13×10^{-2}	0.0272
Biomass Burning	-2.70×10^{-2}	4.78×10^{-2}	0.5733	-2.31×10^{-2}	4.92×10^{-2}	0.6379	2.52×10^{-2}	5.47×10^{-2}	0.6455
Traffic	4.33×10^{-2}	2.63×10^{-2}	0.0992	-2.13×10^{-2}	2.71×10^{-2}	0.4308	-5.29×10^{-2}	3.01×10^{-2}	0.0787
Ammonium Nitrates	-1.73×10^{-2}	3.31×10^{-2}	0.6001	**-1.11×10^{-01}**	**3.40×10^{-2}**	**0.0010****	1.03×10^{-2}	3.79×10^{-2}	0.7849
Industrial	8.38×10^{-3}	3.65×10^{-2}	0.8182	2.11×10^{-2}	3.75×10^{-2}	0.5734	-3.79×10^{-2}	4.17×10^{-2}	0.3639

Linear regression models, adjusted for age, sex, race and ethnicity, overall household income, neighborhood safety, urbanicity, physical activity, daily screentime average hours, site and parental education. Estimates include unstandardized beta coefficients (b), standard errors, and p-values. Bolded values reflected models passing Bonferroni correction (p=0.008).

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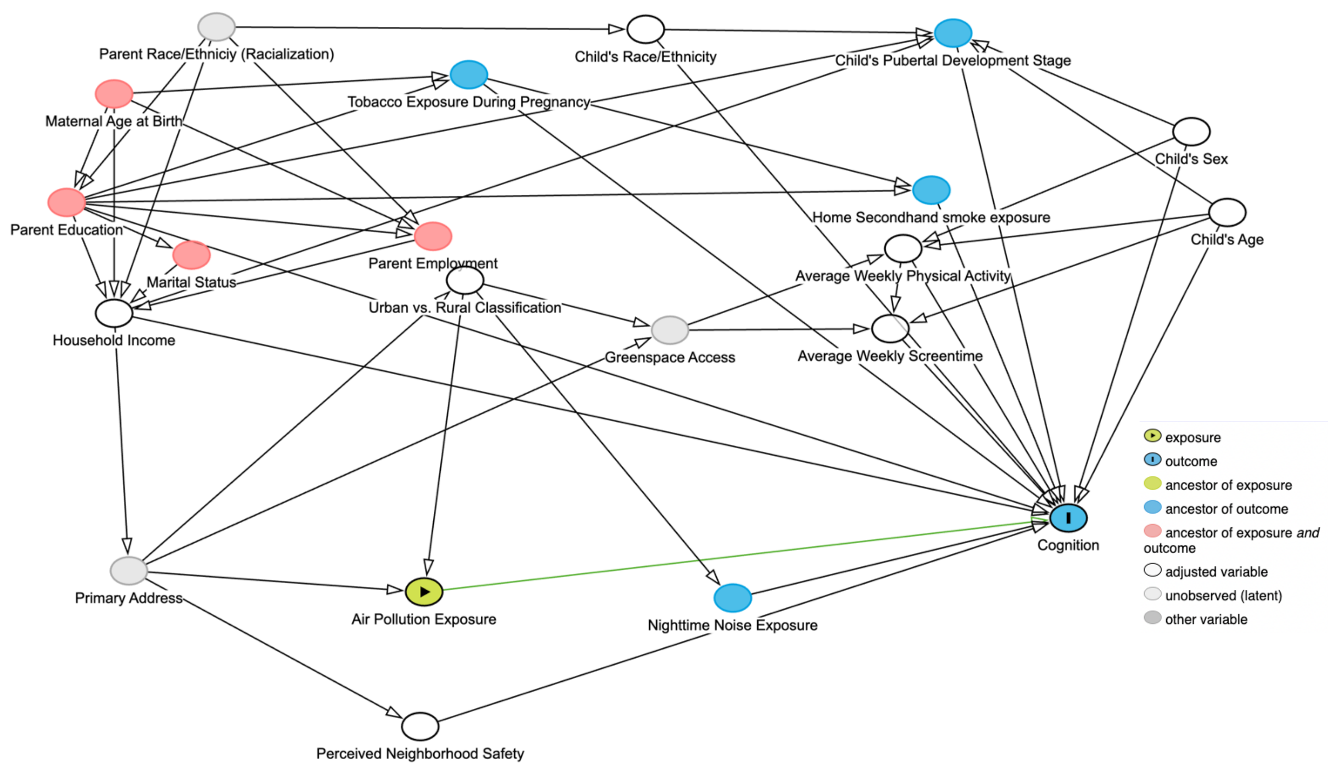
A)



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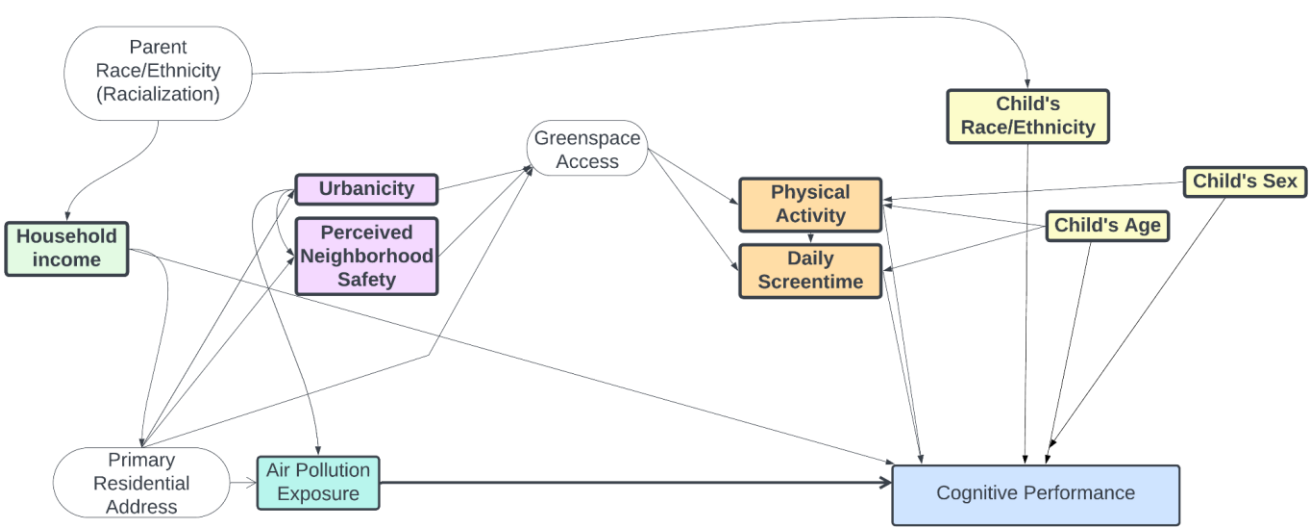

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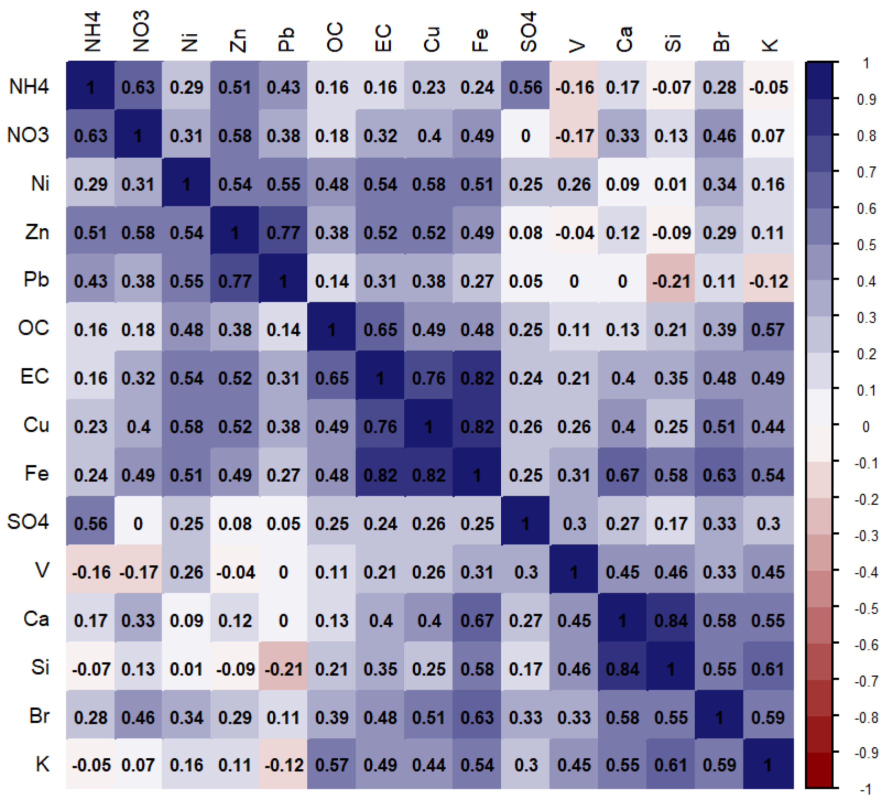

Abbreviations: SO_4^{2-} for sulfate; NO_3^- for nitrate; NH_4^+ for ammonium; OC for organic carbon; EC for elemental carbon; Zn for zinc; V or vanadium; K for potassium; Si for silicon; Pb for lead; Ni for nickel; Fe for iron; Cu for copper; Ca for calcium; Br for bromine. Numeric data for Supplemental Figure 2 can be found in Excel Table S8.

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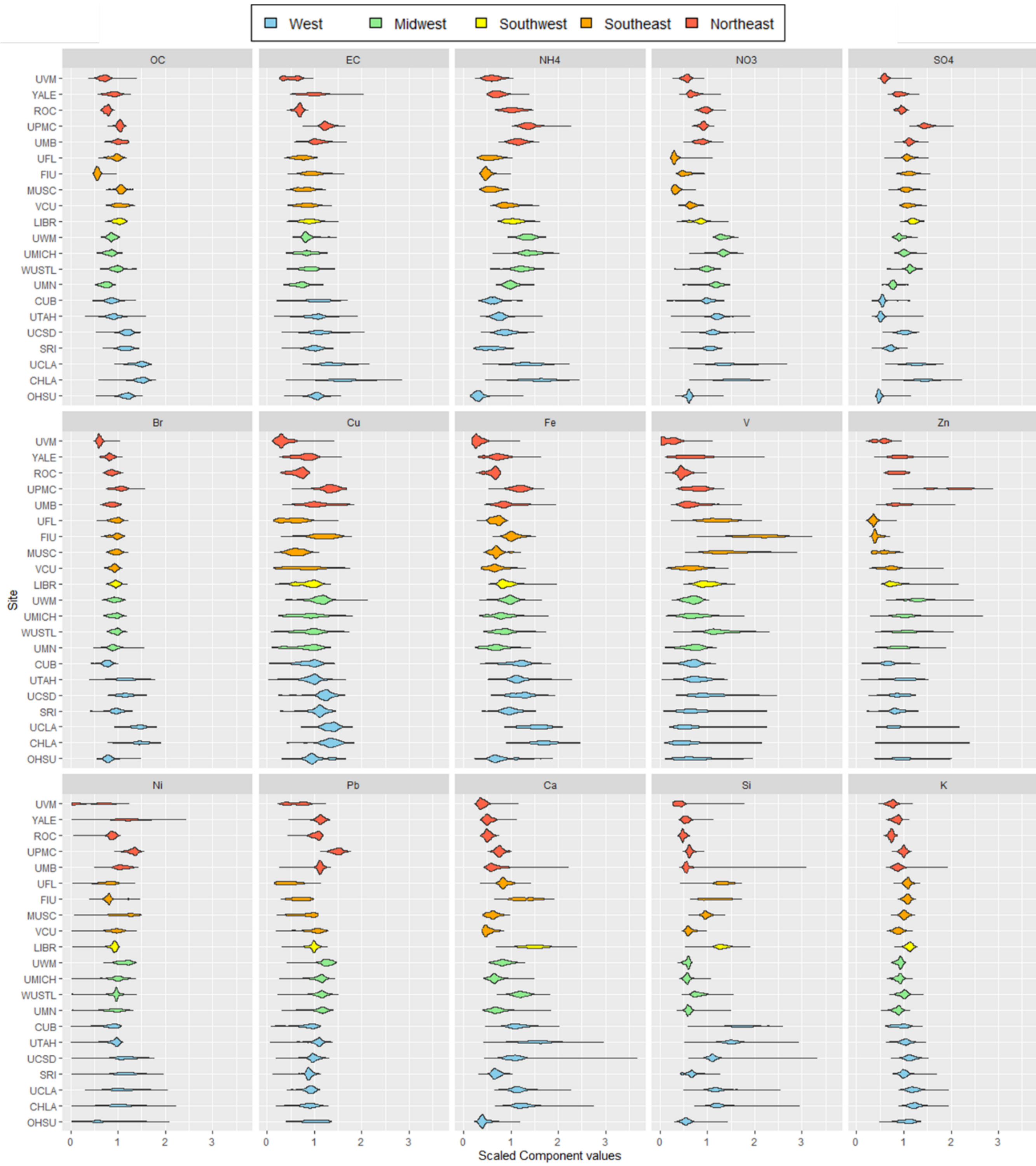

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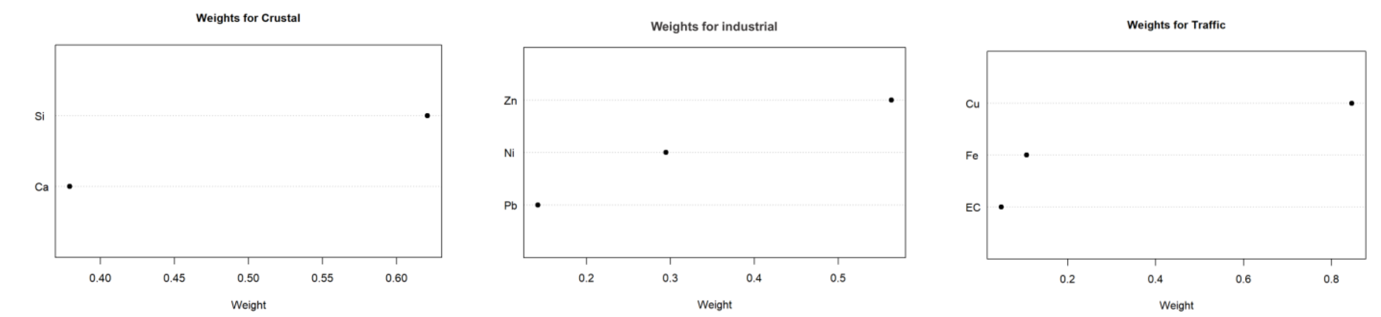
A)



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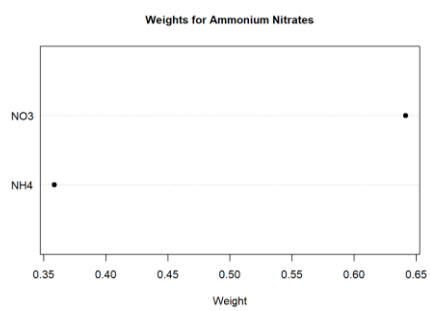

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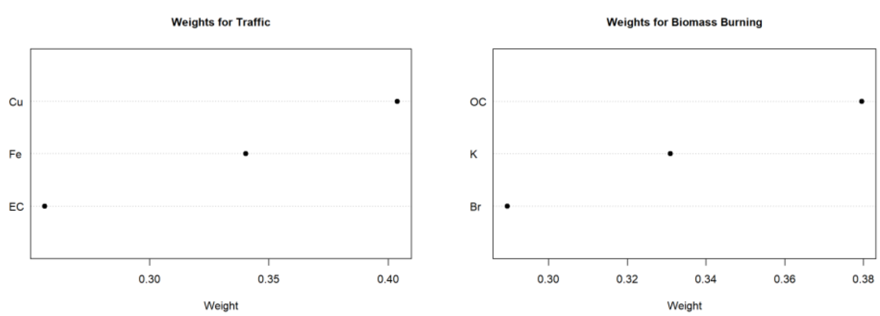

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