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Ischemic Heart Disease Mortality and Long-Term Exposure to Source-Related Components of U.S. Fine Particle Air Pollution

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ABSTRACT

Background: Fine particulate matter (PM_{2.5}) air pollution exposure has been identified as a global health threat. However, the types and sources of particles most responsible are not yet known. In this work, we sought to identify the causal characteristics and sources of air pollution underlying past published associations in the American Cancer Society's Cancer Prevention Study-II cohort between long-term PM_{2.5} exposure and Ischemic Heart Disease (IHD) mortality.

Methods: Individual risk factor data were evaluated for 445,860 adults in 100 U.S. metropolitan areas followed from 1982 to 2004 for vital status and cause of death. Using Cox proportional hazard models, IHD mortality hazard ratios (HRs) were derived for PM_{2.5}, trace constituents, and pollution source-associated PM_{2.5}, as derived from air monitoring at central stations throughout the nation during 2000-2005.

Results: Associations with IHD mortality varied by PM_{2.5} mass constituent and source. A coal combustion PM_{2.5} IHD HR = 1.05 (95% CI=1.02, 1.08) per $\mu\text{g}/\text{m}^3$, versus an IHD HR = 1.01 (95% CI=1.00, 1.02) per $\mu\text{g}/\text{m}^3$ PM_{2.5} mass, indicated a risk roughly five times higher for coal combustion PM_{2.5} than for PM_{2.5} mass in general, on a per $\mu\text{g}/\text{m}^3$ PM_{2.5} basis. Diesel traffic-related elemental carbon (EC) soot was also associated with IHD mortality (HR = 1.03; 95% CI: 1.00, 1.06 per 0.26 $\mu\text{g}/\text{m}^3$ EC increase). However, PM_{2.5} from both wind-blown soil and biomass combustion were not associated with IHD mortality.

Conclusions: Long-term PM_{2.5} exposures from fossil fuel combustion, especially coal burning, but also from diesel traffic, were associated with increases in IHD mortality in this nationwide population. Results suggest that PM_{2.5} – mortality associations can vary greatly by source, and that the largest IHD health benefits per $\mu\text{g}/\text{m}^3$ from PM_{2.5} air pollution control may be achieved via reductions of fossil fuel combustion exposures, especially from coal-burning sources.

INTRODUCTION

Numerous epidemiologic studies have documented associations between long-term exposure to fine particulate matter mass ($PM_{2.5}$) air pollution and increased mortality in urban populations (e.g., Ozkaynak and Thurston 1987; Dockery et al. 1993; Pope et al. 1995; Krewski et al. 2000; Pope et al. 2002; Eftim et al. 2008; Brook et al. 2010; Ostro et al 2011; Beelen et al. 2014). This association is notably robust for cardiovascular disease mortality, and especially death from ischemic heart disease (IHD, associated with a reduction of blood supply to the heart, potentially leading to heart attack), as found in prior analyses of the American Cancer Society (ACS) Cancer Prevention Study-II (CPS-II) cohort (Pope et al. 2004). Based on such studies, the U.S. EPA has attributed nearly 90% of the economic valuation of human health benefits derived from the U.S. Clean Air Act to reductions in $PM_{2.5}$ (U.S. EPA, 1999), and nearly 1 in 5 U.S. IHD deaths are associated with $PM_{2.5}$ exposure (Fann et al. 2012). Globally, it has been estimated by WHO that roughly 3 million people die each year as a result of outdoor ambient particulate matter air pollution exposures (Lim et al, 2012; WHO, 2014), indicating air pollution to be one of the world's largest single environmental health risks, with $PM_{2.5}$ being estimated to account for some 9.4% (6.6–11.8) of all IHD globally (Evans et al. 2013).

Past research has focused primarily on $PM_{2.5}$ mass concentration, so the types and sources of particles most responsible for these adverse health associations are not known, limiting our ability to address this global cardiovascular disease threat. Thus, the National Academy of Science (NAS) and the World Health Organization (WHO) have placed a high priority on determining which constituents and components of the $PM_{2.5}$ mass are most responsible for these reported health effects (NRC 2001; WHO 2007). As noted by the WHO (2007), this would “facilitate targeted abatement policies and more effective control measures to reduce the burden

of disease due to air pollution.”

The present analysis addresses this need by extending the follow-up of one of the largest of the PM_{2.5}-mortality cohort studies that has linked individual risk factor and ambient air pollution with vital status data (Krewski et al. 2000; Pope et al. 2002, Pope et al. 2004), while expanding the scope to consider both PM_{2.5} source-specific components and trace element constituent exposures. Contributions of this analysis include: (1) expansion of the follow-up from 16 to 22 years, increasing the number of deaths considered by more than one-third; (2) substantially expanded PM_{2.5} air pollution exposure data, including new PM_{2.5} composition data; and (3) consideration of source-apportioned PM_{2.5} mass to investigate which pollution sources are most important to PM_{2.5}-IHD mortality associations in this cohort.

METHODS

Study Population

The study population cohort was drawn from the ACS CPS-II, a prospective mortality study of approximately 1.2 million adults (Garfinkel 1985; Krewski et al. 2009). Participants were enrolled by ACS volunteers in the fall of 1982, and resided in all 50 states, the District of Columbia, and Puerto Rico. Enrollment was restricted to persons at least 30 years of age, in households including someone at least 45 years of age, from whom the ACS obtained informed consent. Participants completed surveys, including questions about age, sex, weight, height, smoking history, alcohol use, occupational exposures, diet, education, marital status, and other characteristics. This secondary analysis of the ACS CPS-II dataset was approved by the Ottawa Hospital Research Ethics Board, Canada, and by the IRB at the NYU School of Medicine, NY, NY USA.

Deaths were ascertained through personal inquiries (e.g., direct contact with participants by volunteers) through September 1988, and subsequently via the National Death Index (Calle and Terrell, 1993) through December 31, 2004. Mortality from IHD was studied because this was the category found most associated with PM_{2.5} exposure in past analyses of this cohort (e.g., Pope et al. 2004; Krewski et al. 2009). More than 99% of known deaths were assigned a cause using the International Classification of Diseases, 9th and 10th revision (ICD-9 410-414, ICD 10 I20-I25). The analytic cohort included 445,860 participants having questionnaire, known vital status through 2004, and contextual census data, residing in 100 U.S. metropolitan areas within the contiguous U.S. where the required air pollution data were available, with 34,408 IHD deaths (of a total of 157,572 deaths from all causes) occurring during follow up. Seventy-six of the metropolitan study areas were included in previously published ACS studies (e.g., Pope et al. 2002; Pope et al. 2004).

Particulate Matter Source and Constituent Exposure Estimates

Participants were assigned a metropolitan area of residence based on their enrollment address and 3-digit zip code area. Complete data were available for 100 Metropolitan Statistical Areas (MSAs) (Figure 1). The mean concentrations of PM_{2.5} mass and trace constituents were compiled for 2000-2005 from the Health Effects Institute (HEI) Atmospheric and Environmental Research (AER) database (HEI, 2007), derived from the U.S. EPA Air Quality System that archived Chemical Species Network (CSN) and gaseous criteria pollutant data. The present analysis focuses on further investigations of the PM_{2.5} – IHD association, so gaseous air pollutants, evaluated in past analyses (Krewski et al. 2009), are not considered here, except in the derivation of the source factors (Thurston et al. 2011), as discussed below. These PM_{2.5} constituent data were analyzed to derive estimates of source apportioned PM_{2.5} mass exposure

concentrations using the Absolute Principal Component Analysis (APCA) PM_{2.5} source apportionment method (Thurston and Spengler 1985). Since this process results in orthogonal source components, the source impacts derived have the advantage that they are derived to be as independent of one other as possible. This method involved: (1) a factor analysis of the trace constituents; (2) identification of source-related factors (based on key tracers in each component); (3) adjustment of factor scores into absolute scores; and, (4) a regression of the PM_{2.5} mass data on the source-related components yielding apportionments of PM_{2.5} mass to each source-related factor (Thurston et al. 2011).

These PM_{2.5} mass and speciation data have been previously characterized on a nationwide basis (Bell et al. 2007). Trace elements considered were arsenic (As), calcium (Ca), chlorine (Cl), iron (Fe), lead (Pb), manganese (Mn), nickel (Ni), selenium (Se), vanadium (V), silicon (Si), zinc (Zn), potassium (K), sodium (Na), elemental carbon (EC), organic carbon (OC), and sulfur (S).

In the source apportionment analysis of these trace constituent and mass data (Thurston et al. 2011), the major U.S. PM_{2.5} source categories derived (and their key source-identifier elemental tracers) were: Metals Industry (Pb, Zn); Soil Particles (Ca, Si); Motor Vehicle Traffic (EC); Steel Industry (Fe, Mn); Coal Combustion (As, Se); Oil Combustion (V, Ni); Salt Particles (Na, Cl) and Biomass Burning (K, OC). While these various tracer elements are individually emitted by multiple sources, when they appear together they have been found to be useful for identifying specific source category impacts (e.g., both As and Se for coal) (Thurston et al. 2011). Sulfur (S) is considered individually here, but it is a general marker for fossil fuel sources that could have different predominant origins in different places (e.g., oil or diesel combustion California vs. coal combustion in the Eastern U.S.), so it is not as uniquely associated with any one single

source category, and was therefore not included in the source apportionment model (Thurston et al. 2011). Of traffic emissions, EC is predominantly from diesel vehicles, while nitrogen dioxide (NO₂), also included as a traffic tracer in this source apportionment, is emitted by both diesel and gasoline powered vehicles (Schauer et al. 2006). Nationwide spatial plots of the source-related PM_{2.5} contributions to total PM_{2.5} mass (hereafter referred to source impacts) have been found to support the source-component interpretations in this analysis: ubiquitous sources, such as Traffic and Soil, were found to be spread across the nation, more unique sources (e.g., steel and metals processing) highest in select industrialized cities, coal highest in the Ohio River Valley region, biomass burning highest in the U.S. Northwest, and residual oil combustion highest in the Northeastern U.S. and major seaport cities (Thurston et al. 2011). To provide directly comparable results with past nationwide analyses of this cohort (e.g., Pope et al. 2002; Pope et al. 2004; Krewski et al. 2009), individual site elemental and source apportioned PM_{2.5} exposures were averaged over the concentration values for all monitors in each MSA for the health effects analyses (ranging from 1 to 4 PM_{2.5} speciation monitoring stations per MSA) over the period 2000-2005, with a majority (53%) of participants residing in an MSA with multiple sites.

Statistical Analysis

Standard and multilevel random-effects Cox proportional-hazard (RE-CPH) regression models were applied to estimate mortality in relation to each of the individual indices of PM_{2.5} air pollution. The most extensively adjusted models estimated IHD mortality hazard ratios (HRs) for each PM_{2.5} mass, constituent, and source exposure using Cox proportional hazards (CPH) (Fleming and Harrington, 1991) models that also included spatial random effects and control for contextual socio-economic variables. We also evaluated models with random effects but not contextual variables, models with contextual variables but not random effects, and fixed effect

models adjusted for individual-level variables only. The time axis used in the models was survival time from enrollment date. Survival times were censored at time of death or end of follow-up. To facilitate comparisons with past analyses, we modeled individual $PM_{2.5}$ constituents and sources as continuous variables and report HRs for interquartile range (IQR) increases (equal to the difference between the 25th and 75th percentile) in the estimated mean concentration of each pollutant during 2000-2005. We also report HRs per 1- $\mu\text{g}/\text{m}^3$ increases in each source to facilitate comparisons among sources according to each source's mortality contribution per unit mass. In addition, sensitivity analyses of simultaneous CPH models, including both a source-related $PM_{2.5}$ mass and the remaining $PM_{2.5}$ mass (i.e. $PM_{2.5}$ - source-related $PM_{2.5}$), were conducted for each identified $PM_{2.5}$ source category in order to estimate the source-specific $PM_{2.5}$ IHD impacts, after adjusting for the impact of all other $PM_{2.5}$. Natural Spline (NS) plots, showing concentration-response curves for key source impact categories, were also prepared, using the statistical package R. In R, a model was defined using the function `ns()` of the R "splines" package, in combination with the GAMEPHIT procedure, by including in the model a term the form `ns(x, df = k)`, where `df` is the number of degrees of freedom (Krewski et al., 2009; R Development Core Team 2012). All survival models were stratified by one-year age categories, sex, and race (non-Hispanic White versus other), assigning each sex-race-age category its own baseline hazard.

A total of 42 variables were included to control for individual characteristics that might confound the air pollution-mortality association. The variables included were individual-level risk factors from the CPS II enrollment questionnaire (Garfinkel, 1985), based upon previous ACS- air pollution analyses model specifications (e.g., Krewski et al. 2009), as listed in Table 1. These included active smoking and former smoking (yes/no for each; and cigarettes/day,

duration, and initiation < 18 years among active and former smokers, respectively); ever cigar/pipe smoker (yes/no); passive smoke exposure (hrs./day); possible workplace exposure to PM (yes/no); occupational dirtiness index (7 categories with an indicator of exposure to an increasingly dirty job or not, plus a missing data category); marital status (married, single, or other); education (< high school, high school, or > high school); body mass index (BMI) and BMI²; consumption of beer, wine, and other alcohol (yes, no, or missing, with separate variables for each type of alcohol); quintile of dietary fat consumption; and quintile of combined dietary vegetable, fruit, and fiber consumption.. For the occupational dirtiness index, six enrollment question variables were used to record past occupational exposures to asbestos, chemicals/acids/solvents, coal/stone dust, coal tar/pitch/asphalt, diesel engine exhaust, or formaldehyde, and these were then collapsed into one variable for the statistical analyses by identifying a participant as occupationally exposed if a “1” for “yes” appeared for any one of the six variables (Krewski et al. 2000).

Data on ecologic risk factors representing social and economic variables were obtained from the U.S. Census and other secondary sources at the MSA level (US Bureau of Census, 1993). Six ecologic covariates obtained from the 1990 U.S. Census (median household income, percentage of persons over the age of 16 years who were unemployed, percentage of adults with a post-secondary education, Gini coefficient of income inequality [ranging from 0 to 1, with 0 indicating an equal distribution of income, and 1 indicating that one person has all the income], and percent Black and percent Hispanic population) (U.S. Bureau of the Census, 1993). Models also incorporated an MSA-level random effects adjustment, taking into account residual mortality variation within communities (Krewski et al, 2009).

RESULTS

Key cohort characteristics are tabulated versus PM_{2.5} quintile in Table 1. This is a nationwide cohort, but considers only adults over age 30 at enrollment. It was recruited by volunteers, rather than via random sampling. The average age of the cohort was 56.6 years at enrollment, and the group has more advanced education and a higher percentage of White participants than the general population of the US. The PM_{2.5} constituent and source apportionment exposure data are summarized in Table 2. These data indicate that traffic-related PM_{2.5} has the highest mean concentration averaged across the national cohort (see Thurston et al. 2011), while other, more regionalized sources (e.g., coal-combustion, oil combustion, biomass burning, and soil), have somewhat lower national average PM_{2.5} concentration contributions.

Figure 2 presents the PM_{2.5} - IHD mortality HRs (and 95% Confidence Intervals, CIs) from the RE-CPH model (including individual and contextual variables) for the various PM_{2.5} constituents (i.e., trace elements) and the source components (i.e., PM_{2.5} mass attributed to each source category). The results of all models considered (i.e., CPH with and without Random Effects, with and without contextual variables) are presented in Table 3. As shown in Figure 2 and Table 3, IHD mortality was statistically significantly associated ($p < 0.05$) with PM_{2.5} mass and a variety of PM_{2.5} elements across most models (e.g., Se, S, As, Cl, Pb, EC, Fe), but consistently not with others (e.g., Si, K, Mn, or OC). Estimates based on reduced models (without random effects and/or adjustment for contextual variables) were generally more often statistically significant than the more extensively adjusted model estimates. However, there were some exceptions, e.g., the HR central estimate for S based on the fully adjusted model (1.06; 95% CI: 1.02, 1.11) was statistically significant and also larger than the HR adjusted for individual-level variables only (1.02; 95% CI: 1.00, 1.03) (Table 3).

The source-component results shown in Figure 2 and Table 3 are concordant with the strong associations found for coal combustion's key tracers (Se and As), with consistently statistically significant IHD mortality – PM_{2.5} source category associations across models being found with coal combustion PM_{2.5} (Table 3). Particulate S, which is predominantly formed from sulfur dioxide emissions from various fossil fuel combustion sources, but especially from coal power plant emissions in the U.S. during the period of this study (USEPA, 2000), is also significant in most models. Metals-related factors and mortality were also statistically significant in some models, though the average exposure is very low across the nation (mean = 0.2 µg/m³), consistent with the significant IHD association with Pb, a metal strongly associated with this source factor (Thurston et al. 2011). Coal combustion associated PM_{2.5} yielded an IHD HR = 1.03, CI = 1.01, 1.05, per coal combustion PM_{2.5} IQR = 0.64 µg/m³, while PM_{2.5} mass yielded an IHD HR = 1.03, CI = 1.00, 1.06 per PM_{2.5} mass IQR = 3.1 µg/m³.

When considered on a per 10 µg/m³ PM_{2.5} mass basis, the CI of the estimate, PM_{2.5} HR = 1.09 (CI = 1.00, 1.20), overlaps prior PM_{2.5} - IHD estimates for another subset of this same cohort (e.g., HR = 1.18 (CI = 1.14, 1.21 per 10 µg/m³ PM_{2.5}, from Krewski et al. 2009). When the HR's of the source concentrations (which are much smaller than the total mass) are similarly viewed on a per 1 µg/m³ comparable basis, the coal combustion PM_{2.5} had an IHD HR = 1.05 (CI = 1.02, 1.08) per 1 µg/m³ coal PM_{2.5}, versus a 1 µg/m³ PM_{2.5} HR = 1.01 (CI = 1.00 – 1.02). This indicates that the IHD risk estimate for coal PM_{2.5} is roughly five times higher than that for PM_{2.5} mass in general, per µg/m³. While the overall Traffic-related PM_{2.5} component and the more gasoline engine traffic-related OC were not consistently statistically significantly associated with IHD mortality across the various models, a key tracer of diesel traffic (EC) was positively and statistically significantly associated with IHD in 3 of the 4 models considered (p < 0.05), and

nearly so in the most extensively specified RE-CPH model (HR = 1.03 per $0.3 \mu\text{g}/\text{m}^3$ EC, CI = 1.0, 1.06) (Table 3). However, neither wind-blown crustal/soil nor biomass combustion-related $\text{PM}_{2.5}$ mass were statistically significantly associated with IHD mortality in any model considered.

Results of the sensitivity analysis, with both the individual source-related components of $\text{PM}_{2.5}$ and the “all other” $\text{PM}_{2.5}$ mass for each included simultaneously, are presented in Figure 3. In this analysis, estimates from models of source-related components of $\text{PM}_{2.5}$ (presented in Figure 2 and Table 3) were adjusted for a variable representing the remaining $\text{PM}_{2.5}$ mass (i.e., after subtracting the mass of each respective source-related component from total $\text{PM}_{2.5}$ mass). These results indicate that, even after adjustment for the other $\text{PM}_{2.5}$ mass, the coal-related $\text{PM}_{2.5}$ HR is the source component least changed, and most clearly seen to be still statistically significant (IHD HR = 1.05 (CI=1.02, 1.08) per $1 \mu\text{g}/\text{m}^3$ coal $\text{PM}_{2.5}$). In addition, of all the sources considered here, removal of coal-related $\text{PM}_{2.5}$ from the $\text{PM}_{2.5}$ mass reduces the overall $\text{PM}_{2.5}$ mass HR estimate the most. Indeed, once coal-related $\text{PM}_{2.5}$ is removed, the “other $\text{PM}_{2.5}$ ” HR drops to nearly 1.0 and is clearly non-significant (IHD HR = 1.01, CI=0.93, 1.10 per $10 \mu\text{g}/\text{m}^3$ $\text{PM}_{2.5}$). In these models, diesel traffic-related (IHD HR = 1.01, CI=1.00, 1.03 per $1 \mu\text{g}/\text{m}^3$ $\text{PM}_{2.5}$) and metals-related (IHD HR = 1.09 (CI=1.00, 1.20) per $1 \mu\text{g}/\text{m}^3$ $\text{PM}_{2.5}$) $\text{PM}_{2.5}$ are the only other sources that approach statistical significance. Other sources of $\text{PM}_{2.5}$ are seen from these results to be less important contributors to the overall $\text{PM}_{2.5}$ mass effect, as they are clearly non-significant, and their removal from $\text{PM}_{2.5}$ has a more minor reduction in the $\text{PM}_{2.5}$ mass HR estimate.

The correlations of the source-related components, as calculated from the individual trace element observations, were derived to be orthogonal (independent) from one another (Thurston

et al. 2011), but averaging the daily values over time and metropolitan areas can introduce inter-correlations among the source impacts (e.g., if two source-specific PM_{2.5} impacts are highest in the same city). The inter-correlations of the various source impacts across the metropolitan areas (not shown) indicate that the highest spatial correlations are found between steel impacts and metals concentrations ($r=0.67$), which is likely due to the fact that both are especially high in Birmingham, AL in this dataset (Thurston et al. 2011). The salt and traffic-related PM_{2.5} components also show a relatively high spatial inter-correlation with each other ($r=0.44$), which is likely caused by the common use of salt on roads in winter.

Natural Spline plots of HR's as a function of source-specific mass concentration (Figure 4) are shown for the sources that were most consistently statistically significant across the various models examined (Coal and Traffic), versus those sources most consistently non-significant across the models examined (Soil and Biomass Burning). These are visually seen to be roughly comparable with the Figure 2 RE-CPH HR effect estimates, with Coal Combustion having the steepest slope (i.e., greatest effect per $\mu\text{g}/\text{m}^3$) presented, and a slope consistent with a 5% increase in IHD risk per 1 $\mu\text{g}/\text{m}^3$ increase in PM_{2.5} mass concentration from coal combustion. Also, similar to the RE-CPH results, Crustal/Soil and Biomass Burning PM_{2.5} are indicated by the CIs provided in these natural spline plots to have non-significant associations with IHD mortality.

DISCUSSION

While PM_{2.5} pollution from most industrial and fossil fuel combustion categories had estimates of association with IHD mortality above 1.0, coal combustion PM_{2.5} and its key emission tracer elements (i.e., Se and As) were most strongly and robustly associated with IHD mortality across all the various model specifications considered (e.g., of these source and tracer groupings, they are the only ones that are clearly all statistically significant across the four models considered). In addition, particulate S, known to largely result from fossil fuel combustion, and especially coal combustion (Zhang et al. 2014), was also found to be associated. Notably, the association between IHD mortality per 1- $\mu\text{g}/\text{m}^3$ increase in coal combustion PM_{2.5} was larger than the effect estimate for a 1- $\mu\text{g}/\text{m}^3$ increase in total PM_{2.5} mass. In contrast, IHD mortality was not associated with crustal soil PM_{2.5}, biomass PM_{2.5}, nor with the elemental tracers associated with these source categories. However, our findings do not rule out effects of sources that were not identified by the source apportionment analysis, or effects of region-specific sources and exposures.

The associations between ambient PM_{2.5} air pollution and IHD mortality in our study cohort are consistent with previous reports, though few studies have estimated associations with long-term PM_{2.5} elemental constituents and/or source-specific PM_{2.5} mass components. A previous cross-sectional study of long-term PM_{2.5} sources and all-cause mortality rates in the U.S. during 1980 (Ozkaynak and Thurston 1987) similarly reported associations with metropolitan area-wide sulfates and coal combustion-related particle exposures. Previous analyses of the ACS CPS-II cohort (Pope et al. 1995; Krewski et al. 2000; Pope et al. 2002; Pope et al. 2004) and the Harvard Six City Study cohort (Dockery et al. 1993) also showed associations between sulfates and both all-cause and cardiopulmonary mortality. Long-term exposures to EC and S were significantly

associated with total mortality in a previous analysis of the ACS CPS-II cohort (Smith et al. 2009). A meta-analysis of data from 19 European cohorts indicated that long-term exposure to PM_{2.5} sulfur was associated with natural-cause mortality, and that this association was robust to adjustment for other pollutants and PM_{2.5} mass (Beelen et al. 2015). Sulfate alone, as discussed by Lippmann and Thurston (1996), is an unlikely causal factor for mortality or morbidity from a toxicological perspective, so it may be a contributor to the toxicity of the PM_{2.5} mixture, or serving as a marker for a certain type or source of particulate pollution that needs identification. A study of deaths among U.S. Veterans (Lipfert et al. 2006) employed data from the U.S. EPA CSN fine particle speciation network, finding mortality associations with nitrates, EC, Ni, V, and traffic density. PM_{2.5} constituents derived from fossil fuel combustion and constituents of crustal origin were more strongly associated with mortality in a population of 45,000 California teachers than other PM_{2.5} constituents (Ostro et al. 2010). A follow up of this cohort (Ostro et al. 2015) found statistically significant ($p < 0.05$) associations of IHD with PM_{2.5} mass, nitrate, elemental carbon (EC), copper (Cu), and secondary organics and the sources gas- and diesel-fueled vehicles, meat cooking, and high-sulfur fuel combustion in California. However, individual trace element metals were not associated with CVD mortality in a meta-analysis of 19 European cohorts (Wang et al. 2014). Collectively, these past studies are largely consistent with a finding that the PM_{2.5} association with mortality varies with its elemental composition, but most past studies have not looked at the PM_{2.5} constituent issue from a collective source-specific PM_{2.5} component perspective, which is more readily translatable into air quality policy.

While effects of short-term (day to day) exposures to PM_{2.5} components and sources may differ from effects of long-term exposures, findings from studies of short-term exposures to trace elements and sources have been generally consistent with findings from the present study. For

example, Laden et al (2000) estimated that a $10\text{-}\mu\text{g}/\text{m}^3$ increase in $\text{PM}_{2.5}$ from mobile sources was associated with a 3.4% (95% CI: 1.7, 5.2%) increase in daily mortality in six U.S. cities, and that a $10\text{-}\mu\text{g}/\text{m}^3$ increase in $\text{PM}_{2.5}$ from coal combustion sources was associated with a 1.1% increase (95% CI: 0.3, 2.0%) in mortality. However, daily mortality was not associated with $\text{PM}_{2.5}$ crustal soil particles (Laden et al. 2000). They concluded that combustion particles in the fine fraction from mobile and coal combustion sources, but not fine crustal particles, were associated with increased daily mortality. Using Bayesian hierarchical modeling, Bell (2012) investigated seasonal and temporal variation in $\text{PM}_{2.5}$ composition and the risk of total, cardiovascular, and respiratory hospital admissions for persons ≥ 65 years of age in 202 U.S. counties during 1999 through 2005, finding that mortality effect estimates for particulate matter mass were higher in seasons and counties with higher $\text{PM}_{2.5}$ Ni content. Ito et al. (2006) Applied a Poisson Generalized Linear Model (GLM) to estimate source-specific $\text{PM}_{2.5}$ mass relative risks at lags 0-4 days for total non-accidental, cardiovascular, and cardiorespiratory mortality adjusting for weather, seasonal/temporal trends, and day-of-week for Washington, DC during 1988-1997, finding that the secondary sulfate component had the largest (and most consistently statistically significant across investigative teams) percent excess cardiovascular mortality risk estimates, with primary coal-related $\text{PM}_{2.5}$ being similarly significantly associated, and risk estimates for traffic-related $\text{PM}_{2.5}$, while significant in some cases, were more variable, and soil-related PM showed smaller effect size estimates. These various studies have largely provided results consistent with the findings of this new research, indicating that the mortality risk from $\text{PM}_{2.5}$ can vary by mass composition and source.

Overall, in this new research we found that the $\text{PM}_{2.5}$ source-component associations with IHD mortality were coherent with results from individual key trace constituents used to identify

pollution sources. Model results indicate that, in this dataset, long-term exposures to PM_{2.5} from coal combustion-related PM_{2.5} (a source component most correlated with As and Se) and EC (a tracer element from combustion sources, especially diesel-powered motor vehicles in urban areas) were among those the most robustly associated with increased risk of IHD mortality across the models considered. The fact that IHD mortality risk was more consistently statistically significantly associated with the EC tracer across the models considered than was overall traffic related PM_{2.5}, may suggest that the diesel portion of the traffic component increases risk to IHD more than PM_{2.5} from other vehicles. Soil and biomass burning (and their tracers, Si and Ca, K and OC, respectively) were least often positively significantly associated with IHD mortality across models.

This study has two important strengths. This is the first large nationwide U.S. study to comprehensively examine the characteristics of PM_{2.5} elemental constituents and source-specific components in relation to IHD in a prospective cohort study able to consider detailed individual-level subject risk factor information. Only recently have the availability of data from the CSN and the development of advanced source apportionment methods made studies of the constituents and sources of PM_{2.5} possible. Second, the large population and number of cities considered, combined with the increased long-term follow-up, provide enhanced power to assess increases in risk related to relatively small changes in PM_{2.5} mass and component exposures.

Despite the strengths of this new analysis, there are several attributes of this study that may have limited its ability to detect all effects. One was the use of central site monitors as an indicator of individual exposure, which, even though averaged across available sites in each MSA, could potentially introduce non-differential measurement error across the various sources. Traffic markers such as EC can display significant long-term average concentration spatial

variation on scales of 50-500 m within cities (Henderson et al., 2007), while elevated pollution sources (e.g. power plants with tall stacks) may be more spatially homogeneous. This could potentially bias the effect estimates of localized sources, such as traffic, towards the null hypothesis of no increase in risk. Another concern might be that not all sources varied as much spatially (e.g., between-cities) as others, which may limit the ability of the analysis to identify the impact of those more spatially homogeneous, and less spatially variable, sources, especially the steel industry and salt aerosols (having the smallest overall Standard Deviations in Table 2). However, coal combustion PM_{2.5} exposure had a smaller absolute Standard Deviation across the US than two of the other sources (wood burning and traffic), but still had the most significant association, suggesting that this factor was not a major determinant of source significance in this analysis. Spatial confounding may also remain, despite adjustment for contextual variables defined at the MSA level and the use of random effects models to account for uncontrolled regional variation.

Potential misclassification of the cause of death and changes in participant characteristics (such as smoking status) during the follow up are also sources of potential misclassification. In addition, exposures were classified using PM_{2.5} data from 2000-2005, while follow-up extended from 1982 through 2004; consequently, there could have been some exposure misclassification if concentrations of PM_{2.5} and PM_{2.5} constituents changed over time, and associations with PM_{2.5} sources in 2000-2005 may actually reflect earlier exposures to these sources of PM_{2.5}. Previous analyses of this cohort have shown PM_{2.5} levels at different time-periods to be correlated, with lower levels at the end of the follow-up period, but indicating that areas with the highest exposures in the 1980's were still the most highly exposed in 2000 (Pope et al. 2002). Estimated concentrations of many of the trace element constituents (including Si, Se, Zn, V, and Mn) and

source components (Soil, Coal, Metals, Traffic, and Oil) were correlated with estimates for the early 1980's, at the start of cohort follow up (Thurston et al. 2011), supporting the use of 2000-2005 CSN data to estimate long term exposures. Although residential mobility is generally relatively low in older adults (Mateyka, 2015), exposure misclassification could also have occurred if ACS cohort participants moved to a different area after baseline (Jerrett et al. 2007).

A lack of information on medications (e.g., statins, anti-hypertensives, etc.) could also be a potential confounding factor if they are spatially correlated with air pollution exposures, as statins have been suggested as possibly protective against PM_{2.5} health effects (e.g., Schwartz et al. 2005). Since there may have been regional differences in drug prescribing patterns and adherence, and although adjustment has been made for random effects and for individual- and city-level SES indicators, they may not have been adequate to address this potential source of confounding.

These results also raise the causality question as to whether it is biologically plausible that combustion-related particles, and coal combustion PM_{2.5} in particular, would have a greater cardiovascular toxicity, per unit mass of exposure, than other particles, especially versus those of biomass or soil origins. There is evidence that oxidant stress is involved in the cardiovascular impacts of PM_{2.5}, and it is also known that trace metals, such as those contained in high concentration in fossil fuel combustion-related particles, can cause oxidative stress (Brook et al. 2010), likely contributing to atherosclerosis progression. In addition, NYU's mouse inhalation studies at five US sites across the US showed substantial variations in aortic plaque progression by geographic region that was coherent with the regional variation in annual IHD mortality in the ACS-II cohort, with both the human and mouse responses being primarily attributable to the coal combustion source category (Lippmann et al, 2013; Lippmann, 2014). Moreover, fossil fuel

sources, and notably coal combustion, are usually higher in sulfur content than biomass particles, resulting in sulfates, a secondary aerosol component that has been associated with increased mortality. The potential interaction of trace metals and sulfur in increasing the toxicity of $PM_{2.5}$ mass has been posited in the recent British Committee on the Medical Effects of Air Pollutants (COMEAP) Report (2009), which states that: “Sulphates could play a role in the capacity of $PM_{2.5}$ to drive pulmonary inflammation via either increasing metal mobilisation from PM, and hence increasing the ability to drive oxidative stress leading to inflammation.... Inflammation in the lung could then initiate changes in blood clotting, and/or activation of macrophages in atherosclerotic plaques increasing their instability.”

While evidence on acute respiratory effects of biomass PM has been well documented (Henderson and Johnson 2012; Martin et al. 2013), evidence of cardiovascular disease impacts by PM from biomass is less certain. Indeed, a recent cohort study of chronic biomass cooking pollution exposures in Bangladesh found a significant increase in respiratory mortality, but not in cardiac deaths (Alam et al. 2013). While the biological mechanism(s) responsible for the apparently greater long-term cardiovascular toxicity of fossil fuel combustion particles versus others not enriched in transition metals and sulfur (e.g., soil and biomass) are not yet known, there are plausible toxicological pathways consistent with these constituents in fossil fuel $PM_{2.5}$, and especially coal $PM_{2.5}$, being more strongly associated with IHD mortality (Brook et al. 2010). Although this is a US-based study of older adults, these findings have potentially broad policy implications: as the developing world deals with an increasing disease burden from air pollution, reductions in fossil fuel combustion, and especially coal-combustion, may well be the most efficacious policy approach to reduce air pollution’s global human health burden.

Recent risk assessments have been conducted based on exposure to concentrations of $PM_{2.5}$

mass decomposed into its pollution sources (e.g., Lelieveld et al, 2015). As discussed by Jerrett (2015), these past assessments have generally assumed that the change in risk associated with $PM_{2.5}$ mass concentration is independent of source. This new study provides evidence that there may, in fact, exist sources where the risk per $\mu g/m^3$ appears to be either greater than (e.g., coal) or less than (e.g., biomass) the effect estimate derived in past epidemiological studies from the overall mass concentration. While these new findings are supported by biological plausibility (as discussed above), further research is needed to further test the generalizability of the associations found (e.g., in younger populations).

In summary, we estimated associations between IHD mortality and long-term exposures to elemental constituents and source components of $PM_{2.5}$ in a U.S. cohort of older adults with follow-up from 1982 through 2004. Exposure to fossil fuel combustion-related $PM_{2.5}$ air pollution, especially from coal combustion, but also from diesel traffic-related emissions, was significantly associated with IHD mortality in our study population.” This finding, combined with past results and other knowledge of $PM_{2.5}$ constituent toxicity, suggests that the greatest cardiovascular mortality benefits from $PM_{2.5}$ control may be achieved via reductions in fossil fuel $PM_{2.5}$ exposures, especially in $PM_{2.5}$ from coal combustion. This research potentially has both clean air policy and climate change mitigation policy implications, as it provides an indication as to which of the various sources of elemental carbon, carbon dioxide (CO_2), and particulate matter, if reduced, might return the greatest public health benefits.

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Table 1. Descriptive Statistics of CPS-II Cohort Characteristics As a Function of PM_{2.5} Concentration Quartile^{a,b}

Variable	Entire Cohort (N= 445,860)	PM _{2.5} Quartiles			
		8.60-13.35 (N=109,313)	13.36-15.16 (N=109,684)	15.17-16.49 (N=101,775)	16.50-26.93 (N=125,088)
No. of MSAs	100	26	31	23	20
Age (years)	56.6+/-10.5	57.4+/-10.6	56.5+/-10.4	56.3+/-10.6	56.5+/-10.4
Male Sex (%)	43.6	43.9	43.7	43.5	43.3
Non-Hispanic White Race (%)	94.1	96.3	94.5	92.2	93.3
Education					
Less than HS	12.5	11.8	13.5	11.7	13.0
HS	31.3	31.3	32.8	29.3	31.6
More than HS	56.2	56.9	53.7	59.0	55.4
Smoking Status					
Current smokers					
% of participants	21.6	20.0	22.1	22.0	22.3
No. of cigs/day	22.1+/-12.5	22.1+/-12.6	22.2+/-12.5	21.9+/-12.5	22.2+/-12.6
Duration (year)	33.3+/-11.1	33.6+/-11.0	33.2+/-10.9	33.3+/-11.2	33.2+/-11.1
Started smoking<18yr	41.0	40.2	41.6	40.9	41.2
Former smokers					
% of participants	25.3	25.4	25.2	25.8	24.8
No. of cigs/day	21.3+/-14.9	21.3+/-14.7	21.6+/-15.0	21.1+/-14.9	21.3+/-14.9
Duration (year)	22.1+/-12.6	21.9+/-12.6	22.2+/-12.5	22.0+/-12.6	22.2+/-12.7
Started smoking<18yr	38.3	37.1	39.2	39.2	37.9
Exposure to Smoking (hr/day)	3.2+/-4.4	2.9+/-4.3	3.3+/-4.5	3.3+/-4.4	3.3+/-4.5
Ever pipe or cigar smoker only (%)	9.7	9.4	9.8	10.0	9.6
Marital Status					
Married	83.7	84.9	83.6	83.8	83.7
Single	3.5	3.0	3.5	4.2	3.4
Other	12.8	12.1	12.9	13.0	13.3
Body-mass index	25.1+/-4.1	25.1+/-4.0	25.3+/-4.1	25.0+/-4.1	25.2+/-4.1
Occupational Dirtiness Index					
Level 0	50.4	50.6	49.5	50.4	51.1
Level 1	13.0	12.6	13.5	13.5	12.6
Level 2	11.2	11.9	10.5	11.6	10.8
Level 3	4.7	4.8	4.9	4.5	4.7
Level 4	6.4	6.7	7.3	6.0	5.7
Level 5	4.3	4.4	4.6	3.8	4.2
Level 6	1.2	1.0	1.2	1.0	1.4
Not able to ascertain	8.8	8.0	8.5	9.2	9.5
Industrial Exposures (%)	19.7	19.5	20.2	19.0	19.9
Fat Consumption					
1 st quintile	14.5	13.4	14.7	14.9	14.8
2 nd quintile	15.9	15.4	15.9	15.9	16.2
3 rd quintile	17.3	17.4	17.1	17.3	17.5
4 th quintile	21.1	21.6	21.1	20.7	21.1
5 th quintile	31.2	32.2	31.2	31.2	30.4
Vegetable, Fruit, Fiber Consumption					
1 st quintile	17.1	16.2	18.1	16.5	17.2
2 nd quintile	20.1	19.5	20.8	19.8	20.2

3 rd quintile	18.9	18.8	18.9	19.2	18.7
4 th quintile	22.6	23.0	22.0	22.9	22.5
5 th quintile	21.3	22.5	20.2	21.6	21.1
Beer Consumption					
Yes	22.4	22.4	22.8	22.4	22.0
No	9.5	9.5	9.2	9.4	9.7
Missing	68.1	68.1	68.0	68.2	68.3
Liquor Consumption					
Yes	26.7	28.2	26.1	27.3	25.5
No	8.8	8.6	8.6	8.6	9.1
Missing	64.5	63.2	65.3	64.1	65.4
Wine Consumption					
Yes	22.0	21.8	21.7	22.5	21.9
No	8.9	9.1	8.8	8.8	9.1
Missing	69.1	69.1	69.5	68.7	69.0
Ecologic risk factors (MSA Level)					
Black (%)	10.5+/-18.0	5.9+/-12.3	11.9+/-19.3	14.3+/-20.2	10.4+/-18.1
Hispanic (%)	5.2+/-10.2	6.2+/-11.2	4.4+/-8.4	3.4+/-5.6	6.6+/-12.9
High-school education or greater (%)	33.8+/-12.6	35.7+/-11.6	31.4+/-11.5	35.4+/-13.3	33.0+/-13.4
Unemployment rate (%)	5.4+/-3.0	5.3+/-2.4	5.6+/-3.1	4.9+/-3.0	5.6+/-3.4
Gini coefficient of income inequality	0.39+/-0.05	0.39+/-0.05	0.39+/-0.05	0.39+/-0.05	0.39+/-0.04
Annual household income (\$1000s)	36.5+/-13.9	34.7+/-12.2	35.9+/-14.0	39.2+/-15.4	36.5+/-13.5

MSA = Metropolitan Statistical Area; HS = High School.

^aPM_{2.5} mass concentration quintiles computed for 2000-2005 using data matched to MSA's from the Health Effects Institute (HEI) Atmospheric and Environmental Research (AER) database.

^b Characteristics are as collected at baseline using the ACS questionnaire (Krewski et al, 2002). These include active smoking and former smoking (yes/no for each; and cigarettes/day, duration, and initiation < 18 years among active and former smokers, respectively); ever cigar/pipe smoker (yes/no); passive smoke exposure (hrs./day); possible workplace exposure to PM (yes/no); occupational dirtiness index (7 categories with an indicator of exposure or not, plus a missing data category); marital status (married, single, or other); education (< high school, high school, or > high school); body mass index (BMI) and BMI²; consumption of beer, wine, and other alcohol (yes, no, or missing, with separate variables for each type of alcohol); quintile of dietary fat consumption; and quintile of combined dietary vegetable, fruit, and fiber consumption. Six enrollment question variables were used to record past occupational exposures to asbestos, chemicals/ acids/solvents, coal/stone dust, coal tar/pitch/asphalt, diesel engine exhaust, or formaldehyde, and these were then collapsed into one variable for the statistical analyses by identifying a participant as occupationally exposed if a "1" for "yes" appeared for any one of the six variables (Krewski et al, 2009).

Table 2. Descriptive Statistics of PM_{2.5} pollution indices, their units, Mean levels (Standard Deviations), Interquartile Ranges (IQR), and 10th-90th%ile Range for Participants in 100 MSA's during 2000-2005 (derived as per Thurston et al, 2011).

PM Metric	Units	Mean (±SD)	IQR	10th %ile - 90th %ile
As	ng/m ³	1.4 ± 0.5	0.55	0.9 – 2.0
Ca	ng/m ³	61.1 ± 35.1	43.8	29.6 – 100.4
Cl	ng/m ³	34.6 ± 38.3	33.5	7.8 – 69.9
Fe	ng/m ³	106.6 ± 56.2	47.8	59.1 – 220.9
Pb	ng/m ³	5.1 ± 3.3	2.6	2.7 – 9.3
Mn	ng/m ³	3.7 ± 5.1	2.1	1.5 – 6.3
Ni	ng/m ³	2.0 ± 2.5	1.5	0.7 – 4.0
Se	ng/m ³	1.4 ± 0.9	0.8	0.7 – 2.1
V	ng/m ³	2.5 ± 2.0	2.6	0.8 – 6.4
Si	ng/m ³	104.4 ± 55.1	42.9	61.5 – 157.6
Zn	ng/m ³	18.0 ± 14.8	10.1	7.6 – 31.8
K	ng/m ³	68.4 ± 18.6	21.9	48.0 – 93.4
Na	ng/m ³	71.7 ± 48.2	33.4	35.7 – 141.2
EC	µg/m ³	0.8 ± 0.3	0.26	0.5 – 1.1
OC	µg/m ³	4.4 ± 0.9	0.98	3.5 – 5.3
S	µg/m ³	1.3 ± 0.4	0.53	0.7 - 1.7
PM _{2.5}	µg/m ³	15.0 ± 2.7	3.01	11.3 -17.6
Crustal/Soil	µg/m ³	0.8 ± 0.5	0.56	0.4 – 1.3
Metals-related	µg/m ³	0.2 ± 0.2	0.18	0.0 – 0.3
Traffic-related	µg/m ³	5.5 ± 2.2	2.40	2.9 – 7.6
Salt Aerosols	µg/m ³	0.1 ± 0.2	0.10	0.0 – 0.4
Oil Combustion	µg/m ³	1.1 ± 1.1	1.09	0.3 – 2.2
Steel Industry	µg/m ³	0.0 ± 0.1	0.00	0.0 – 0.1
Coal Combustion	µg/m ³	1.1 ± 0.9	0.64	0.3 – 1.9
Biomass Burning	µg/m ³	1.4 ± 0.7	0.54	0.9 – 2.0

Table 3. Trace Element and Source Impact IHD Mortality Hazard Ratios per Interquartile Range for Alternative Cox Proportional Hazard Model Specifications

Exposure Variable (IQR)	IQR CPH Hazard Ratio (95 th tile CI) [nNo Random Effects, No Contextual Vars.] ^a	IQR CPH Hazard Ratio (95 th tile CI) [No Random Effects, With Contextual Vars.] ^a	IQR CPH-RE Hazard Ratio (95 th tile CI) [With Random Effects, No Contextual Vars.] ^a	IQR CPH-RE Hazard Ratio (95 th tile CI) [With Random Effects and Contextual Vars.] ^a
PM _{2.5} (3.1347 µg/m ³)	1.04 (1.03, 1.054)	1.02 (1.01, 1.03)	1.05 (1.02, 1.08)	1.03 (1.00, 1.06)
As (0.00055 µg/m ³)	1.03 (1.02, 1.04)	1.04 (1.02, 1.05)	1.04 (1.01, 1.06)	1.04 (1.02, 1.06)
Ca (0.04382 µg/m ³)	1.02 (1.01, 1.03)	1.01 (1.00, 1.03)	1.02 (0.99, 1.05)	1.01 (0.98, 1.03)
Cl (0.03350 µg/m ³)	1.03 (1.02, 1.04)	1.02 (1.01, 1.03)	1.03 (1.00, 1.05)	1.02 (1.00, 1.05)
Fe (0.04775 µg/m ³)	1.03 (1.02, 1.04)	1.02 (1.01, 1.03)	1.03 (1.00, 1.05)	1.02 (1.00, 1.05)
Pb (0.00259 µg/m ³)	1.03 (1.02, 1.04)	1.03 (1.02, 1.04)	1.03 (1.01, 1.04)	1.03 (1.01, 1.04)
Mn (0.00207 µg/m ³)	1.00 (1.00, 1.01)	1.00 (1.00, 1.01)	1.00 (0.99, 1.01)	1.00 (0.99, 1.01)
Ni (0.00145 µg/m ³)	1.01 (1.01, 1.02)	1.01 (1.00, 1.02)	1.01 (0.99, 1.03)	1.01 (0.99, 1.03)
Se (0.00081 µg/m ³)	1.03 (1.02, 1.04)	1.03 (1.01, 1.03)	1.03 (1.01, 1.06)	1.03 (1.01, 1.06)
V (0.00263 µg/m ³)	1.01 (1.00, 1.03)	1.00 (0.97, 1.01)	1.01 (0.97, 1.05)	1.01 (0.97, 1.05)
Si (0.04288 µg/m ³)	1.01 (1.00, 1.013)	0.99 (0.98, 1.005)	1.00 (0.98, 1.027)	0.99 (0.97, 1.018)
Zn (0.01013 µg/m ³)	1.02 (1.01, 1.02)	1.01 (1.01, 1.02)	1.01 (0.99, 1.02)	1.01 (0.99, 1.02)
K (0.02186 µg/m ³)	1.00 (0.99, 1.02)	1.00 (0.98, 1.01)	1.00 (0.97, 1.03)	0.99 (0.96, 1.02)
Na (0.03337 µg/m ³)	1.01 (1.01, 1.02)	1.01 (0.99, 1.02)	1.01 (0.99, 1.03)	1.01 (0.99, 1.04)
EC (0.25755 µg/m ³)	1.04 (1.03, 1.05)	1.03 (1.01, 1.04)	1.03 (1.00, 1.06)	1.03 (1.00, 1.06)
OC (0.97547 µg/m ³)	1.01 (0.99, 1.02)	0.99 (0.97, 1.00)	1.00 (0.97, 1.03)	0.99 (0.96, 1.01)
S (0.52882 µg/m ³)	1.02 (1.00, 1.03)	1.05 (1.02, 1.07)	1.03 (0.99, 1.066)	1.06 (1.02, 1.11)
Biomass Burning (0.54040 µg/m ³)	1.00 (0.99, 1.01)	1.00 (0.99, 1.01)	1.00 (0.98, 1.02)	0.99 (0.98, 1.01)
Coal Combustion (0.64208 µg/m ³)	1.02 (1.02, 1.03)	1.02 (1.01, 1.03)	1.03 (1.01, 1.06)	1.03 (1.01, 1.05)
Steel Industry ^b (0.1 µg/m ³)	1.01 (0.99, 1.03)	1.01 (0.99, 1.02)	0.99 (0.95, 1.03)	1.0 (0.97, 1.03)
Oil Combustion (1.08574 µg/m ³)	1.01 (1.00, 1.02)	1.00 (0.99, 1.02)	1.01 (0.98, 1.04)	1.01 (0.98, 1.04)
Salt Aerosols (0.10488 µg/m ³)	1.02 (1.01, 1.02)	1.01 (1.00, 1.02)	1.01 (0.99, 1.03)	1.02 (0.99, 1.039)
Traffic-related (2.39980 µg/m ³)	1.03 (1.02, 1.04)	1.03 (1.01, 1.05)	1.02 (0.98, 1.05)	1.03 (0.99, 1.07)

Metals-related (0.17518 $\mu\text{g}/\text{m}^3$)	1.01 (1.00, 1.02)	1.01 (1.01, 1.02)	1.01 (1.00, 1.03)	1.02 (1.00, 1.03)
Crustal/Soil (0.56015 $\mu\text{g}/\text{m}^3$)	1.01 (1.00, 1.02)	0.99 (0.98, 1.01)	1.01 (0.98, 1.05)	1.00 (0.97, 1.03)

^aAll models include 42 individual-level variables. Random Effects adjustments are at MSA-level. The 6 ecological contextual variables were obtained from the 1990 U.S. Census (median household income, percentage of persons over the age of 16 years who were unemployed, percentage of adults with a post-secondary education, Gini coefficient of income inequality, and percent Black and percent Hispanic population)(see text).

^bSteel Increment = 0.1, as Steel IQR = 0.0.

Figure 1. Mean PM_{2.5} mass concentration in each of the 100 Study Metropolitan Areas (developed for 2000-2005 from the Health Effects Institute (HEI) Atmospheric and Environmental Research (AER) database (HEI, 2007).

Figure 2. Cox Random Effects Model Ischemic Disease Mortality Associations with PM_{2.5} Elements and Source Contributions per Interquartile Range (IQR)

[Steel Increment = 0.1 µg/m³, as Steel IQR = 0.0].

42 variables collected at enrollment were included to control for individual characteristics, including: active smoking and former smoking; ever cigar/pipe smoker; passive smoke exposure; workplace exposure to PM; occupational dirtiness index; marital status; education; body mass index (BMI) and BMI²; consumption of alcohol; dietary fat consumption; and dietary vegetable, fruit, and fiber consumption. Six enrollment question variables were used to record past occupational exposures collapsed into one variable (Krewski et al, 2002; 2009). Six ecologic covariates obtained from the 1990 U.S. Census (median household income, percentage of persons over the age of 16 years who were unemployed, percentage of adults with a post-secondary education, Gini coefficient of income inequality, and percent Black and percent Hispanic population). These models also incorporated an MSA-level random effects adjustment.

Figure 3. IHD Mortality Hazard Ratios for Source-Specific PM_{2.5} (HR per µg/m³) with Other PM_{2.5} Mass (i.e., PM_{2.5} mass – source specific mass) (HR per 10 µg/m³) Simultaneously Included in RE- CPH Model.

42 variables collected at enrollment were included to control for individual characteristics, including: active smoking and former smoking; ever cigar/pipe smoker; passive smoke exposure; workplace exposure to PM; occupational dirtiness index; marital status; education; body mass index (BMI) and BMI²; consumption of alcohol; dietary fat consumption; and dietary vegetable, fruit, and fiber consumption. Six enrollment question variables were used to record past occupational exposures collapsed into one variable (Krewski et al, 2002; 2009). Six ecologic covariates obtained from the 1990 U.S. Census (median household income, percentage of persons over the age of 16 years who were unemployed, percentage of adults with a post-secondary education, Gini coefficient of income inequality, and percent Black and percent Hispanic population). These models also incorporated an MSA-level random effects adjustment. IQRs listed in Table 1, numeric HR's and CI's listed in Table 3.

Figure 4. Concentration–Response curves (solid lines) and 95% CIs (dashed lines) for Source-Related PM_{2.5} (µg/m³) for Coal, Traffic, Soil, and Biomass Source Contributions to PM_{2.5} mass, in a model specified consistent with the RE-CPH model. [Green lines along abscissa indicate data density]

42 variables collected at enrollment were included to control for individual characteristics, including: active smoking and former smoking; ever cigar/pipe smoker; passive smoke exposure; workplace exposure to PM; occupational dirtiness index; marital status; education; body mass index (BMI) and BMI²; consumption of alcohol; dietary fat consumption; and dietary vegetable,

fruit, and fiber consumption. Six enrollment question variables were used to record past occupational exposures collapsed into one variable (Krewski et al, 2002; 2009). Six ecologic covariates obtained from the 1990 U.S. Census (median household income, percentage of persons over the age of 16 years who were unemployed, percentage of adults with a post-secondary education, Gini coefficient of income inequality, and percent Black and percent Hispanic population). All models also incorporated MSA-level random effects.

Figure 1.

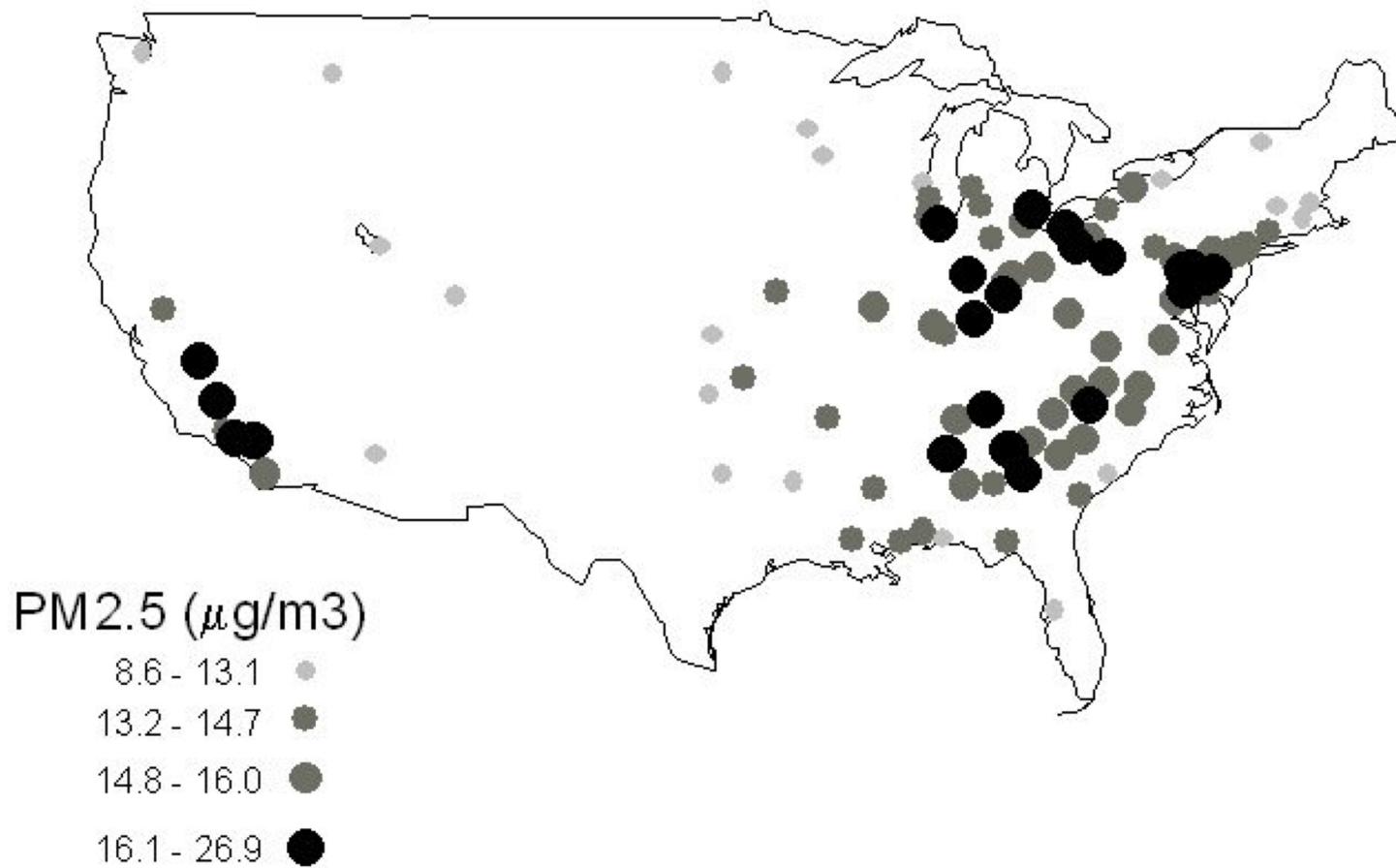


Figure 2.

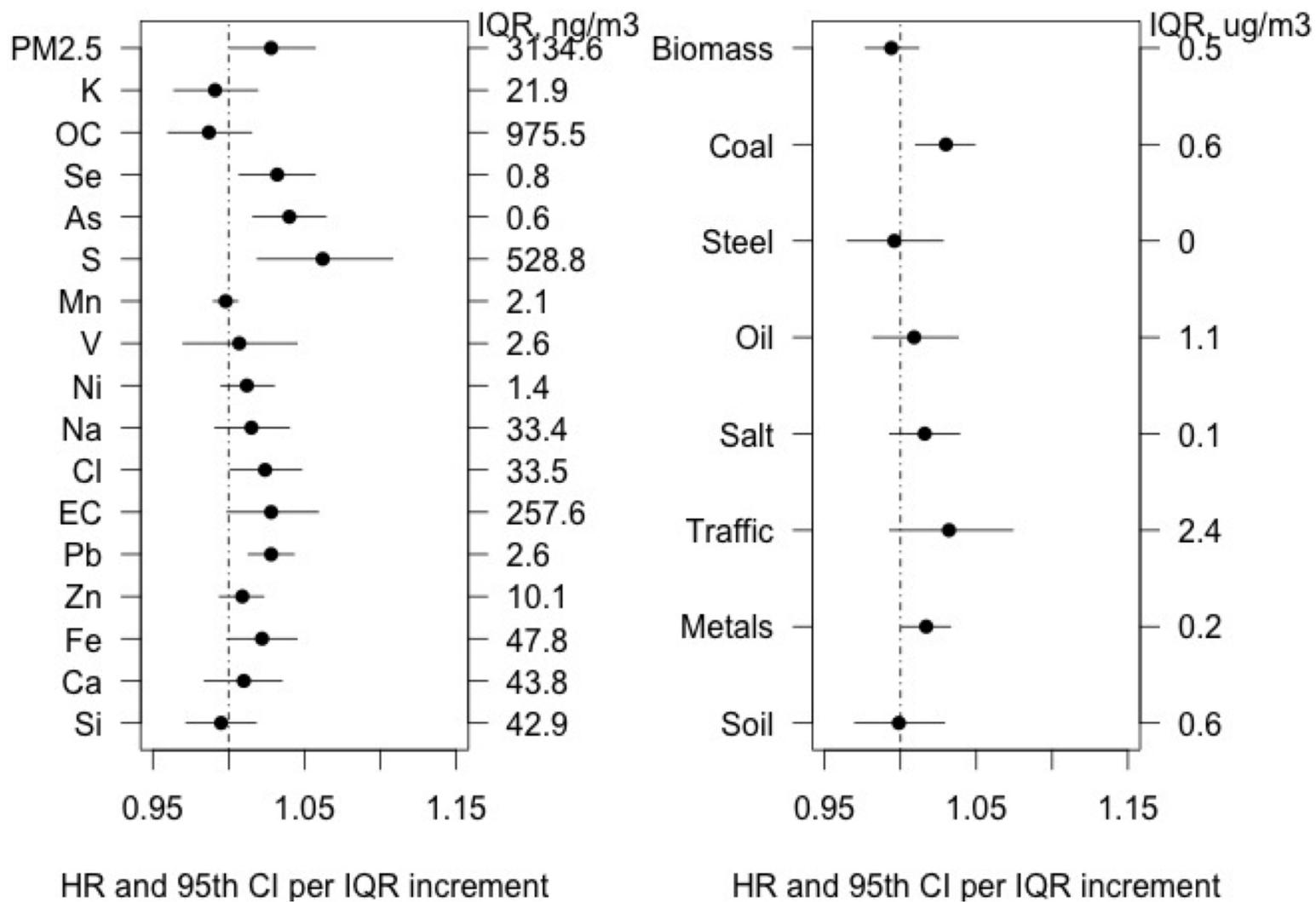


Figure 3.

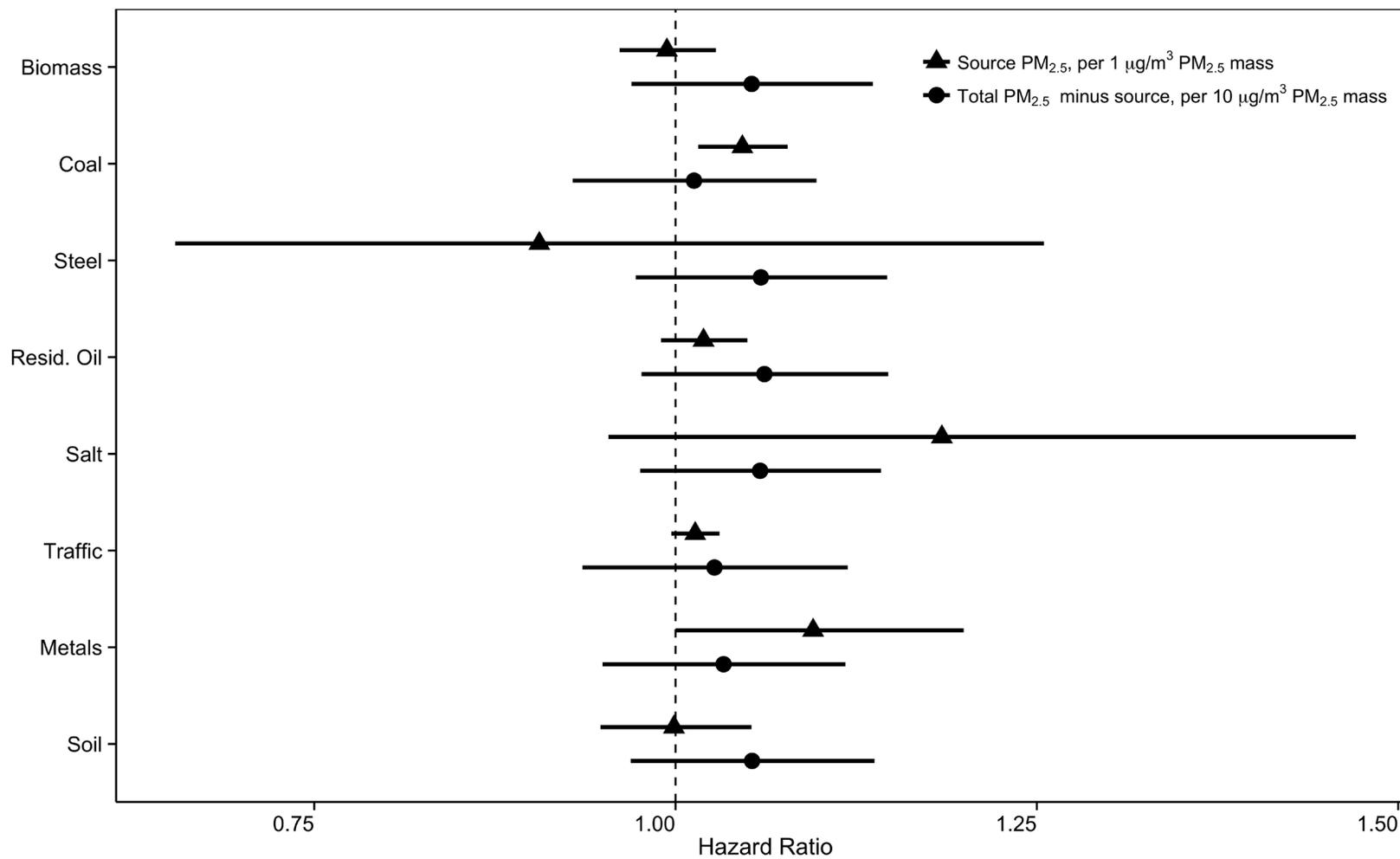


Figure 4.

