Particulate matter air pollution components and risk for lung cancer

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Raaschou-Nielsen O[1,2], Beelen R[3], Wang M[3], Hoek G[3], Andersen ZJ[1,4], Hoffmann B[5,6], Stafoggia M[7], Samoli E[8], Weinmayr G[5,6,9], Dimakopoulou K[8], Nieuwenhuijsen M[10], Xun WW[11], Fischer P[12], Eriksen KT[1], Sørensen M[1], Tjønneland A[1], Ricceri F[13], de Hoogh K[11,14,15], Key T[16], Eeftens M[3,14,15], Peeters PH[17,18], Bueno-de-Mesquita HB[19–22], Meliefste K[3], Oftedal B[23], Schwarze PE[23], Nafstad P[23,24], Galassi C[13], Migliore E[13], Ranzi A[25], Cesaroni G[7], Badaloni C[7], Forastiere F[7], Penell J[26], De Faire U[26], Korek M[26], Pedersen N[27], Östenson C-G[28], Pershagen G[26], Fratiglioni L[29], Concin H[30], Nagel G[9,30], Jaensch A[9], Ineichen A[31], Naccarati A[31], Katsoulis M[32], Trichpoulou A[32], Keuken M[33], Jedynska A[33], Kooter IM[33], Kukkonen J[34], Brunekreef B[3,17], Sokhi RS[35], Katsouyanni K[8,36], Vineis P[11]

Affiliations

[1] Danish Cancer Society Research Center, Copenhagen, Denmark

[2] Department of Environmental Science, Aarhus University, Roskilde, Denmark

[3] Institute for Risk Assessment Sciences, Utrecht University, Utrecht, The Netherlands

[4] Center for Epidemiology and Screening, Department of Public Health, University of Copenhagen, Copenhagen, Denmark

[5] IUF–Leibniz Research Institute for Environmental Medicine, Düsseldorf, Germany

[6] University of Düsseldorf, Düsseldorf, Germany

[7] Department of Epidemiology, Lazio Regional Health Service, Local Health Unit ASL RME, Rome, Italy

[8] Department of Hygiene, Epidemiology and Medical Statistics, Medical School, National and Kapodistrian University of Athens, Athens, Greece

[9] Institute of Epidemiology and Medical Biometry, Ulm University, Ulm, Germany

[10] Center for Research in Environmental Epidemiology, Parc de Recerca Biomèdica de Barcelona, Barcelona, Spain

[11] MRC-HPA Centre for Environment and Health, Department of Epidemiology and Biostatistics, Imperial College London, London, United Kingdom

[12] National Institute for Public Health and the Environment, Center for Sustainability and Environmental Health, Bilthoven, The Netherlands

33 [13] Unit of Cancer Epidemiology, AO Citta' della Salute e della Scienza, University of Turin
34 and Center for Cancer Prevention, Turin, Italy
35 [14] Swiss Tropical and Public Health Institute, Basel, Switzerland
36 [15] University of Basel, Basel, Switzerland
37 [16] Cancer Epidemiology Unit, Nuffield Department of Population Health, University of
38 Oxford, Oxford, United Kingdom
39 [17] Julius Center for Health Sciences and Primary Care, University Medical Centre Utrecht,
40 Utrecht, The Netherlands
41 [18] School of Public Health, Imperial College, London, United Kingdom
42 [19] Department for Determinants of Chronic Diseases, National Institute for Public Health and
43 the Environment, Bilthoven, The Netherlands
44 [20] Department of Gastroenterology and Hepatology, University Medical Centre, Utrecht, The
45 Netherlands
46 [21] Department of Epidemiology and Biostatistics, School of Public Health, Imperial College
47 London, London, United Kingdom
48 [22] Department of Social and Preventive Medicine, Faculty of Medicine, University of
49 Malaya, Kuala Lumpur, Malaysia
50 [23] Norwegian Institute of Public Health, Oslo, Norway
51 [24] Institute of Health and Society, University of Oslo, Oslo, Norway
52 [25] Environmental Health Reference Centre, Regional Agency for Environmental Prevention
53 of Emilia-Romagna, Modena, Italy
54 [26] Institute of Environmental Medicine, Karolinska Institute, Stockholm, Sweden
55 [27] Department of Medical Epidemiology and Biostatistics, Karolinska Institute, Stockholm,
56 Sweden
57 [28] Department of Molecular Medicine and Surgery, Karolinska Institute, Karolinska
58 University Hospital, Stockholm, Sweden
59 [29] Aging Research Centre, Department of Neurobiology, Care Sciences and Society,
60 Karolinska Institute and Stockholm University, Stockholm, Sweden
61 [30] Agency for Preventive and Social Medicine, Bregenz, Austria
62 [31] Human Genetics Foundation, Molecular and Genetic Epidemiology Unit, Turin, Italy
63 [32] Hellenic Health Foundation, Athens, Greece
64 [33] Netherlands Organisation for Applied Scientific Research, Utrecht, The Netherlands
65 [34] Finnish Meteorological Institute, Helsinki, Finland

66 [35] Centre for Atmospheric and Instrumentation Research, University of Hertfordshire College
67 Lane, Hatfield, United Kingdom
68 [36] Department of Primary Care and Public Health Sciences and Environmental Research
69 Group, King's College London, United Kingdom
70
71 [*] Corresponding author at Danish Cancer Society Research Center, Strandboulevarden 49,
72 2100 Copenhagen Ø; email: ole@cancer.dk; telephone: +45 35257617
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Abstract

Background: Particulate matter (PM) air pollution is a human lung carcinogen; however, the components responsible have not been identified. We assessed the associations between PM components and lung cancer incidence.

Methods: We used data from 14 cohort studies in eight European countries. We geocoded baseline addresses and assessed air pollution with land-use regression models for eight elements (Cu, Fe, K, Ni, S, Si, V and Zn) in size fractions of $PM_{2.5}$ and PM_{10}. We used Cox regression models with adjustment for potential confounders for cohort-specific analyses and random effect models for meta-analysis.

Results: The 245 782 cohort members contributed 3 229 220 person–years at risk. During follow-up (mean, 13.1 years), 1878 incident cases of lung cancer were diagnosed. In the meta-analyses, elevated hazard ratios (HRs) for lung cancer were associated with all elements except V; none was statistically significant. In analyses restricted to participants who did not change residence during follow-up, statistically significant associations were found for $PM_{2.5}$ Cu (HR, 1.25; 95% CI, 1.01–1.53 per 5 ng/m^3), PM_{10} Zn (1.28; 1.02–1.59 per 20 ng/m^3), PM_{10} S (1.58; 1.03–2.44 per 200 ng/m^3), PM_{10} Ni (1.59; 1.12–2.26 per 2 ng/m^3) and PM_{10} K (1.17; 1.02–1.33 per 100 ng/m^3). In two-pollutant models, associations between PM_{10} and $PM_{2.5}$ and lung cancer were largely explained by $PM_{2.5}$ S.

Conclusions: This study indicates that the association between PM in air pollution and lung cancer can be attributed to various PM components and sources. PM containing S and Ni might be particularly important.

Key words: air pollution; particulate matter; sulphur; nickel; cohort study; lung cancer

108 **1. Introduction**

109 We recently reported from the European Study of Cohorts for Air Pollution Effects
110 (ESCAPE) that particulate matter (PM) in air pollution with a diameter < 10 μm (PM_{10}) and
111 2.5 μm ($PM_{2.5}$) is associated with a risk for the development of lung cancer (Raaschou-
112 Nielsen and others 2013). This result, among others, formed the basis for classification of
113 outdoor air pollution and PM in outdoor air as carcinogenic to humans in a recent Monograph
114 of the International Agency for Research on Cancer (Loomis and others 2013). Most
115 knowledge about associations between air pollution and risk for lung cancer is based on
116 measures of exposure to PM as a whole (Hamra and others 2014), sulphur oxide-related
117 pollution (Dockery and others 1993; Pope III and others 2002), oxides of nitrogen (Nafstad
118 and others 2003; Raaschou-Nielsen and others 2011) or cruder indicators such as proximity to
119 traffic (Beelen and others 2008; Hystad and others 2013). PM is a complex mixture of
120 particles from different sources with different composition. Little is known about the
121 associations between specific components of PM and risk for cancer, although this could be of
122 major importance in choosing the most efficient strategies for reducing the exposure of
123 populations to carcinogenic air pollution.

124 As the concentrations of specific components of PM in air are often correlated, it is
125 difficult to single out the specific components responsible for observed associations with
126 health effects. A specific issue in air pollution epidemiology is to assess whether associations
127 for specific components are stronger than associations for particle mass (Mostofsky and
128 others 2012). Particle mass is used in air quality regulations. Associations with lung cancer
129 have been indicated in studies of exposure to the PM components elemental Carbon (Garshick
130 and others 2012; Steenland and others 1998) and polycyclic aromatic hydrocarbons (Yuan
131 and others 2014), but, to our knowledge, no work on associations between exposure to other
132 elements of PM and risk for lung cancer in general populations has been published. PM
133 elements in air can serve as indicators of air pollution from different sources, but their
134 compounds may also be carcinogenic for the lung *per se*, as seen for nickel (International
135 Agency for Research on Cancer Monograph Working Group 2012).

136 Within the European study of Transport-related Air Pollution and Health Impacts—
137 Integrated Methodologies for Assessing Particulate Matter (TRANSPHORM;
138 www.transphorm.eu/), we analysed data from the 14 cohort of the ESCAPE
139 (www.escapeproject.eu/) study on lung cancer where PM air pollution was measured to
140 determine associations between elementary components of PM air pollution at the residence
141 and risk for lung cancer. A secondary aim was to investigate whether any particular

142 elementary component could explain the previously observed association between PM air
143 pollution and lung cancer.
144
145 **2. Methods**
146 *2.1 Study design and participants*
147 We conducted a prospective study of data collected within the ESCAPE and
148 TRANSPHORM projects. The 14 cohorts were in Sweden (European Prospective
149 Investigation into Cancer and Nutrition[EPIC]-Umeå, Swedish National Study on Aging and
150 Care in Kungsholmen [SNAC-K], Stockholm Screening Across the Lifespan Twin Study and
151 TwinGene [SALT], Stockholm 60 years old and IMPROVE study [60-y/IMPROVE],
152 Stockholm Diabetes Prevention Program [SDPP]), Norway (Oslo Health Study [HUBRO]),
153 Denmark (Diet, Cancer and Health Study [DCH]), the Netherlands (EPIC-Monitoring Project
154 on Risk Factors and Chronic Diseases in the Netherlands [MORGEN], EPIC-PROSPECT),
155 the UK (EPIC-Oxford), Austria (Vorarlberg Health Monitoring and Prevention Programme
156 [VHM&PP]), Italy (EPIC-Turin, Italian Studies of Respiratory Disorders in Childhood and
157 Environment [SIDRIA]-Turin and Rome, and Greece (EPIC-Athens); Figure 1). Most of the
158 study areas were large cities and the surrounding suburban or rural communities, as specified
159 in Table 1 and in the online appendix (pp. 2–15). Information on lifestyle etc. among cohort
160 participants was obtained by questionnaires or interviews at enrolment (see online appendix,
161 Table S1). The use of cohort data was approved by the local ethical and data protection
162 authorities. All participants signed informed consent forms at inception of the studies.
163
164 *2.2 Procedures and lung cancer definition*
165 Exposure was assessed in each area separately by standardised procedures. The association
166 between long-term exposure to air pollution and incidence of lung cancer was analysed in
167 each cohort separately at the local centre by common standardised protocols for outcome
168 definition, confounder models and statistical analysis. Cohort-specific effect estimates were
169 subsequently combined in a meta-analysis centrally. A pooled analysis of all cohort data was
170 not possible because of data-transfer and privacy issues. We included cancers located in the
171 bronchus and the lung (ICD10/ICDO3: C34.0–C34.9) and only primary cancers (i.e. not
172 metastases); lymphomas in the lung (ICDO3 morphology codes 9590/3–9729/3) were not
173 included. The cohort members were followed up for cancer incidence in national or local
174 cancer registries, except in the SIDRIA cohorts in Italy and Athens. In the SIDRIA cohorts,
175 hospital discharge and mortality register data were used. In Athens, cases were identified by

active follow-up using questionnaires and telephone interviews with participants or next-of-kin, followed by verification of the cancer case through pathology records, medical records, discharge diagnosis or death certificates (online appendix, Table S1).

2.3 Exposure assessment

Air pollution concentrations at the baseline residential addresses of study participants were estimated by Land Use Regression (LUR) models following a standardized procedure that has been described elsewhere (de Hoogh and others 2013; Eeftens and others 2012a). In brief, air pollution monitoring campaigns were performed between October 2008 and May 2011 in all study areas. Three two-week measurements of particles with aerodynamic diameter <2.5μm ($PM_{2.5}$) and <10μm (PM_{10}) were performed at 20 sites in each cohort area. The three measurements were then averaged, adjusting for temporal trends using data from a background monitoring site with continuous data (Eeftens and others 2012a; Eeftens and others 2012b). PM filters were weighed before and after each measurement centrally at IRAS, Utrecht University and were then sent to Cooper Environmental Services (Portland, OR, USA) to analyse elemental composition using X-Ray Fluorescence (XRF)(de Hoogh and others 2013). We collected information about potential predictor variables relating to nearby traffic intensity, population/household density and land use from Geographic Information Systems (GIS), and evaluated these to explain spatial variation of annual average concentrations using regression modelling. LUR model results for all study areas are shown in the online appendix (Tables S2-S9). The LUR models were evaluated using Leave-One-Out-Cross-Validation, which successively leaves one site out of the data and refits the model with the remaining N-1 sites. The LUR models were used to estimate ambient air pollution concentration at the participants' baseline addresses. If values of predictor variables for the cohort addresses were outside the range of values for the monitoring sites, values were truncated to the minimum and maximum values at the monitoring sites. Truncation was performed to prevent unrealistic predictions (e.g. related to too small distance to roads in GIS) and because we did not want to extrapolate the derived model beyond the range for which it was developed. Truncation has been shown to improve predictions at independent sites (Wang and others 2012)

We selected eight of the 48 measured elements for epidemiological evaluation (de Hoogh and others 2013; Tsai) on the basis of evidence for their health effects (toxicity), their representivity of major anthropogenic sources, a high percentage of detected samples (> 75%) and precise measurements. We selected Cu, Fe and Zn as indicators mainly of non-tailpipe

210 traffic emissions such as brake and tyre wear; S mainly for long-range transport; Ni and V for
211 mixed oil-burning and industry; Si for crustal material and K for biomass burning (de Hoogh
212 and others 2013; Eeftens and others 2014; Viana and others 2008; Wang and others 2014).
213 Each element can have multiple sources. Land use regression models for Cu, Fe, and Zn in
214 both fractions (PM_{10} and $PM_{2.5}$) had average cross-validation explained variance (R2)
215 between 52% and 84% with a large variability between areas (online appendix, Tables S2-
216 S9). Traffic variables contributed to most of these models, reflecting nontailpipe emissions.
217 Models for the other elements performed moderately with average cross-validation R2
218 generally between ~50% and ~60%. For $PM_{2.5}$ S the average cross-validation R2 was 32%
219 with a range from 2 to 67%, consistent with the relatively low spatial variation of sulphur
220 concentrations within the cohort areas.
221
222 *2.4 Statistical analyses*
223 Proportional hazards Cox regression models were fitted for each cohort, with age as the
224 underlying time scale. Participants were followed up for lung cancer from enrolment until
225 censoring. Participants with a cancer (except non-melanoma skin cancer) before enrolment
226 were excluded. Others were censored at the time of death, a diagnosis of any other cancer
227 (except non-melanoma skin cancer), emigration, disappearance, loss to follow-up for other
228 reasons or end of follow-up, whichever came first. We censored participants with another
229 cancer because cancer treatment and change of life style might change the subsequent risk for
230 development of another cancer. The proportional hazards assumption was tested in our
231 previous study with the identical set of potential confounders and no violation was observed
232 (Raaschou-Nielsen and others 2013). Exposure to air pollution was analysed as a linear
233 variable in three a-priori specified-confounder models identical to those applied previously
234 (Raaschou-Nielsen and others 2013). Model 1 included gender, calendar time (year of
235 enrolment, linear) and age (time axis). Model 2 included additional adjustment for smoking
236 status (never, former, current), smoking intensity, (smoking intensity)^2, smoking duration,
237 time since quitting smoking, environmental tobacco smoke, occupation, fruit intake, marital
238 status, educational level and employment status (all in reference to baseline). We entered a
239 squared term of smoking intensity because we expected a non-linear association with lung
240 cancer. Model 3 (the main model) included further adjustment for area-level socio-economic
241 status, which might be correlated with both air pollution levels and lung cancer incidence
242 rates and, thus, having the potential of being a confounder (Pope III and others 2002). The
243 definition of area-level socio-economic status differed by cohort (online appendix, p. 2-15). In

eight of the cohorts, income was used. In four cohorts, national or regional indices were used that incorporated multiple dimensions of SES. In one cohort education and another unemployment rate was used. In seven cohorts data was included at the municipality level, in the remaining five cohorts a smaller spatial scale was used (neighbourhood or census tract).

Information on at least age, gender, calendar time, smoking status, smoking intensity and smoking duration was available for all cohorts. Further information on the available variables for each cohort is given in the online appendix (pp. 2–15 and Table S10). We repeated the overall analyses after restriction to participants who had lived at the baseline address throughout the follow-up period, thus minimizing misclassification of long-term exposure relevant to the development of lung cancer in this sub-population.

First we fit models with one pollutant at a time and then we fit two-pollutant models for each element, including concentrations of particle mass ($PM_{2.5}$, PM_{10}, PM_{coarse}), $PM_{2.5}$ absorbance, NO_2 and NO_x, which were previously estimated at the cohort members' addresses (Raaschou-Nielsen and others 2013). The main purpose of the two pollutant analyses was to investigate whether the effect of the complex mixture can be represented better by individual components reflecting specific sources than with generic particle mass. We included cohort-specific results from two-pollutant models only if the Pearson correlation between the two pollutants was $\leq$ 0.7.

In the meta-analysis, we used random-effects models to pool the results for cohorts (DerSimonian and Laird 1986). I^2 statistics (Higgins and Thompson 2002) and p values for the χ^2 test from Cochran's Q were calculated to determine heterogeneity among cohort-specific effect estimates. Effect modification in relation to performance of the land-use regression models was tested with the χ^2 test of heterogeneity between meta-analysis estimates in two strata of cohorts, one stratum including cohorts with leave-one-out cross-validation R^2 below 0.50 and another stratum above.

We used a common STATA (www.stata.com) script for all analyses. All tests were two-sided, and p values < 0.05 were deemed statistically significant.

3. Results

The 14 cohorts in eight European countries consisted of 245 782 people, who contributed 3 229 220 person–years at risk; 1878 incident lung cancer cases were diagnosed during follow-up (average follow-up, 13.1 years) (Table 1). The details of each cohort, including the

278 characteristics of participants, the available variables and their distribution, are given in the
279 online appendix (pp. 2–15). Participants were recruited into most of the cohort studies in the
280 1990s. The number of participants and the number of lung cancer cases varied substantially
281 among cohorts; the Austrian and Danish cohorts contributed more than half the lung cancer
282 cases (Table 1).

283 Substantial variations in estimated annual mean concentrations of PM elements at
284 participant addresses were found both within and between cohorts. Higher concentrations of
285 all elements except Si were observed in southern study areas. For S, the variation within
286 cohorts was smaller than that between cohorts. The patterns seen for $PM_{2.5}$ (Figure 2) and
287 PM_{10} (online appendix, Figure S1) elements were similar. The correlation between PM
288 constituents and their corresponding PM_{10} and $PM_{2.5}$ mass concentration differed widely
289 across cohorts and PM constituent with typical median correlation coefficients between 0.4
290 and 0.6 (online appendix, Table S11).

291 In the overall analyses, exposure to all elements except V was associated with higher risks
292 for lung cancer. None of these associations were statistically significant in model 3, the main
293 model. Hazard ratios (HRs) were generally lower in models 2 and 3 than in the cruder model
294 1, consistent with our findings for $PM_{2.5}$ and PM_{10}; this difference in HRs between the models
295 was due to adjustment for smoking (Raaschou-Nielsen and others 2013). The results for 14 of
296 the element-particle size combinations showed no or low heterogeneity among the cohorts,
297 whereas heterogeneity was observed in the risk estimates for $PM_{2.5}$ S (I^2=0.47; p=0.03) and
298 $PM_{2.5}$ Ni (I^2=0.30; p=0.17) (Table 2).

299 In general, the results of the two-pollutant models showed little effect of mutual
300 adjustment for elements, although the risk estimate for PM Cu was affected by adjustment for
301 PM Fe and *vice versa* (online appendix Figures S2–3). The previously observed increased HR
302 for lung cancer in association with PM_{10} and $PM_{2.5}$ was robust to adjustment for elements in
303 two-pollutant models, although the association with PM_{10} was attenuated by adjustment for
304 $PM_{2.5}$ S and the association with $PM_{2.5}$ was attenuated by adjustment for $PM_{2.5}$ S, $PM_{2.5}$ K and
305 PM_{10} K. The HR associated with $PM_{2.5}$ S was robust to adjustment for PM_{10} and $PM_{2.5}$ (Table
306 3; online appendix, Figures S2–4).

307 Analyses restricted to participants who did not change residence during follow-up,
308 implying less misclassification of long-term exposure, showed higher HRs than observed in
309 the full population (Table 4). The higher HRs associated with exposure to $PM_{2.5}$ Cu, PM_{10} Zn
310 and PM_{10} K among participants who did not change residence were not due to selection of
311 cohorts for whom this information was available, whereas selection might have played a

312 minor role in the higher risk estimates associated with PM_{10} S, $PM_{2.5}$ S and PM_{10} Ni (Table
313 4). We observed statistically significant associations in non-movers between risk for lung
314 cancer and exposure to $PM_{2.5}$ Cu (HR, 1.25; 95% CI, 1.01–1.53 per 5 ng/m^3), PM_{10} Zn (1.28;
315 1.02–1.59 per 20 ng/m^3), PM_{10} S (1.58; 1.03–2.44 per 200 ng/m^3), PM_{10} Ni (1.59; 1.12–2.26
316 per 2 ng/m^3) and PM_{10} K (1.17; 1.02–1.33 per 100 ng/m^3). None of these estimates from the
317 meta-analysis showed signs of heterogeneity between cohort-specific HRs (Table 4). $PM_{2.5}$ S
318 was associated with a high HR, which, was not, however, statistically significant; this result
319 was based on heterogeneous cohort-specific results (I^2=0.57; p=0.01). Forest plots for
320 exposure of participants who did not change residence to all 16 PM components are shown in
321 the online appendix (Figures S5–20); the different contributions of the cohorts to the meta-
322 analysis estimates reflect differences in number of lung cancer cases and the contrast of
323 exposure.
324 There was no statistically significant difference in meta-analysis HRs for any PM element
325 between cohorts with land-use regression models showing leave-one-out cross-validation R2
326 values below and above 0.50, respectively (all p were > 0.20) (results not shown).
327
328 **4. Discussion**
329 This study shows non-significantly elevated HRs for lung cancer associated with
330 concentrations of Cu, Fe, Zn, S, Ni, Si and K in airborne PM at the residence. Analyses
331 restricted to participants who did not change residence during follow-up showed elevated HRs
332 for all PM elements, which were larger than for the full population. Associations were
333 statistically significant for $PM_{2.5}$ Cu, PM_{10} Zn, PM_{10} S, PM_{10} Ni and PM_{10} K. Adjustment for
334 other pollutants in two-pollutant models had little effect on risk estimates, with the exception
335 of $PM_{2.5}$ S: adjustment for $PM_{2.5}$ S reduced the HR for $PM_{2.5}$ and PM_{10}, whereas the HR for
336 $PM_{2.5}$ S was robust to adjustment for PM mass.
337
338 *4.1 Previous studies*
339 Our previous study based on ESCAPE data showed associations between risk for lung
340 cancer and PM in air pollution (Raaschou-Nielsen and others 2013). PM concentrations were
341 estimated from land-use regression models that included variables for the densities of
342 population, household, traffic and streets in the cohort areas and variables for ports and
343 industry in some areas, indicating that PM from multiple sources may be related to the lung
344 cancer risk. In line with this, the present study showed associations between lung cancer and
345 multiple PM components from different sources, including fossil fuel combustion, e.g. in

346 shipping, residential heating, industry and road traffic and non-tailpipe traffic emissions
347 (Viana and others 2008).
348 In the two-pollutant models, $PM_{2.5}$ S was more robustly associated with risk for lung
349 cancer than $PM_{2.5}$ or PM_{10} (Table 3). In both the Harvard Six Cities Study (Dockery and
350 others 1993) and the American Cancer Society Study on Particulate Air Pollution and
351 Mortality (ACS study) (Pope III and others 1995), associations were found between sulphate
352 air pollution and lung cancer mortality, in addition to the associations reported for $PM_{2.5}$
353 (Krewski and others 2000). A strong correlation between $PM_{2.5}$ and sulphate air pollution,
354 however, made it difficult to disentangle their effects in previous studies. The correlation
355 between $PM_{2.5}$ and sulphate was 0.98 in the Harvard Six Cities Study (Krewski and others
356 2000) and 0.73 in the ACS study (Pope III and others 1995); in the present study, the
357 correlation was more moderate with a range between 0.26 and 0.67 (mean: 0.47) (online
358 appendix, Table S11).
359 Previous studies of occupational exposure to nickel compounds have convincingly
360 established associations with cancers of the lung, nasal cavity and paranasal sinuses
361 (International Agency for Research on Cancer Monograph Working Group 2012); we also
362 found an association with PM_{10} Ni. Although inhalation of Ni from ambient air is considered
363 to be a minor route of exposure for the general population, it is present in combusted fossil
364 fuel, which is the major contributor of atmospheric Ni (International Agency for Research on
365 Cancer Monograph Working Group 2012). The association observed in the present study
366 could be due to Ni compounds *per se* or their presence in pollution from fossil fuel
367 combustion.
368
369 *4.2 Sulphur in PM*
370 In this study, PM S was associated with risk for lung cancer, although the relation was
371 statistically significant only for PM_{10} S among people who did not change residence during
372 follow-up. The result for $PM_{2.5}$ S was based on heterogeneous cohort-specific results (with
373 seven HRs above 1 and three HRs below 1) and therefore less robust than the estimates for
374 other elements. Further, the established association between the overall, mass-based PM
375 measures and risk for lung cancer (Loomis and others 2013) could to a great extent be
376 explained by $PM_{2.5}$ S in the two-pollutant models, whereas the HR associated with $PM_{2.5}$ S
377 was virtually unaffected by adjustment for PM mass. Acknowledging the caveats of two-
378 pollutant models to investigate effects of complex mixtures (Mostofsky and others 2012),
379 these findings indicate a more robust association with $PM_{2.5}$ S than with the two PM mass

380 measures (PM_{10} and $PM_{2.5}$). The correlation between S and PM mass was generally moderate
381 (median correlation coefficient = 0.48 for $PM_{2.5}$ and 0.32 for PM_{10}) and PM is affected by
382 many more sources than long-range transport of sulphur containing particles.
383 Arguments for a particular role of $PM_{2.5}$ S in PM-associated lung carcinogenicity include
384 the relatively high HR associated with $PM_{2.5}$ S (Tables 2 and 4) and the finding that $PM_{2.5}$ S
385 explained some of the associations between $PM_{2.5}$ and PM_{10} and risk for lung cancer in two-
386 pollutant models. The association between $PM_{2.5}$ S and risk for lung cancer was, however,
387 sensitive to adjustment, never reached statistical significance and showed statistically
388 significant heterogeneity between cohort-specific HRs in the meta-analysis. Further, sulphate
389 particles, which make up a large proportion of PM S in ambient air, are not known to be
390 carcinogenic. S in PM probably represents a mixture of pollutants that is also rich in other
391 (secondary) combustion-related components, such as secondary organics or polycyclic
392 aromatic hydrocarbons. More studies are needed to determine the role of S and associated
393 components in the carcinogenicity of PM in air pollution.
394
395 *4.3 Strengths and limitations*
396 The study benefited from a large number of participants in the 14 cohort studies, widely
397 different levels of air pollution and virtually complete follow-up. The strengths of our study
398 also include the use of standardised protocols for exposure assessment and data analysis. We
399 assessed multiple PM elements, with a high percentage of detectable samples and highly
400 precise measurements in all 14 cohorts. Further, we took advantage of exposure assessment at
401 address level, such that within-city contrasts in PM element concentrations were used in the
402 risk analyses. We adjusted the analyses for a number of potential confounders. In particular,
403 all cohort-specific analyses were adjusted for the important smoking variables smoking status,
404 smoking intensity and smoking duration. Other potential confounding factors affected the risk
405 estimates associated with PM only marginally (Raaschou-Nielsen and others 2013), although
406 the possibility of residual confounding or confounding from risk factors not accounted for,
407 such as radon, cannot be excluded.
408 The study also benefited from knowledge about residential mobility during follow-up.
409 Exposure was assessed at the address at the time of enrolment, and some participants changed
410 residence after enrolment. We conducted an additional analysis including only participants
411 who did not change residence during follow-up in order to obtain a more precise assessment
412 of long-term exposure. The stronger associations between PM elements and risk for lung
413 cancer in this sub-population add credibility to our findings. Information about addresses and

414 exposure from several decades before enrolment would have been ideal due to the long
415 incubation period for lung cancer. Such information would also have facilitated analyses of
416 latency periods, which our data did not permit.

417 Our study has some limitations. We used measurements made in 2008–2011 to develop
418 land use regression models but applied them to addresses of participants at baseline, which
419 was mainly 10–15 years earlier. Recent research in Canada, Italy and the Netherlands shows,
420 however, that spatial contrasts of NO_2 are stable over 10-year periods (Cesaroni and others
421 2012; Eeftens and others 2011; Wang and others 2013), and spatial models for black smoke in
422 the United Kingdom provided reasonable predictions, even going back to the 1960s (Gulliver
423 and others 2011). We cannot rule out the possibility that the spatial contrast was less stable
424 for specific elements. The information about potential confounders was collected at baseline
425 and would therefore not reflect changes in life style after baseline. The mean age of the
426 participating cohort members ranged from 43 to 73 years and we believe that life style in
427 these age groups is more stable than earlier in life.

428 We used land-use regression models to estimate exposure to PM elements, which involves
429 some degree of misclassification. Any misclassification would, however, be non-differential
430 and would consequently not be expected to create artificial associations. In the two-pollutant
431 models, different degrees of misclassification of PM elements would affect the results. Thus,
432 when two PM elements are correlated, some of the association between lung cancer and the
433 element with greater misclassification could be shifted to the risk estimate for the element
434 with less misclassification. Measurement precision was best for S, Cu and Fe but poorer for
435 Ni and V (de Hoogh and others 2013), but the performance of the land use regression model
436 for S was among the lowest when evaluated by the model R^2. Therefore, a lower degree of
437 misclassification hardly explains why $PM_{2.5}$ S rather than other elements accounted for the
438 associations between PM_{10} and $PM_{2.5}$ and risk for lung cancer. Two pollutant models can be
439 difficult to interpret especially if the same sources contribute to several PM components and
440 create high correlations. Further, only two of the many PM constituents were included in each
441 model. The results of these models, thus, should not be interpreted as the independent effect
442 of the specific element but rather as a representation of the effect of a complex mixture. Still,
443 they can contribute to a better understanding of the PM mixture and its association with risk
444 for lung cancer.

445 Analysis of eight elements in two different PM fractions involved 16 main analyses and 16
446 analyses of participants who did not change residence during follow-up; we therefore cannot
447 exclude the possibility that some of the significant associations were due to multiple testing.

448 *4.4 Conclusion*

449 In conclusion, associations with risk for lung cancer were found with several PM elements
450 from different sources; the strongest associations were seen for participants who did not
451 change their address during follow-up. Considering strengths and limitations, this study
452 indicates that the association between PM in air pollution and lung cancer can be attributed to
453 various PM components and sources; S- and Ni-containing PM might be particularly
454 important, but this must be confirmed in future studies.

455

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461

462 **Supplementary data**

463 Supplementary data are available online.

464

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Table 1. Characteristics of 14 cohorts, lung cancer cases, mean particulate matter concentrations and smoking prevalence among participants at baseline

Cohort[a]	Study area	N participants	N lung cancer cases[b]	Mean age at baseline; years (SD)	Baseline period	Mean follow-up time (years)	Person-years at risk	$PM_{2.5}$ ($\mu g/m^3$); mean (SD))	PM_{10} ($\mu g/m^3$); mean (SD))	Present/ex-/never smokers (%)
HUBRO	City of Oslo, Norway	17,640	75	47.8 (15.0)	2000-2001	8.5	150,424	8.9 (1.3)	13.5 (3.1)	26/27/47
SNAC-K	City of Stockholm, Sweden	2384	18	73.1 (10.7)	2001-2004	5.8	13,840	8.0 (1.3)	16.4 (6.0)	14/37/49
SALT/Twin gene	Stockholm County, Sweden	4731	29	57.9 (10.2)	1998-2002	8.3	39,263	7.3 (1.3)	14.9 (3.9)	24/36/40
60-y/IMPROVE	Stockholm County, Sweden	3813	38	60.4 (0.1)	1997-1999	11.2	42,553	7.3 (1.3)	15.0 (3.8)	21/38/41
SDPP	Stockholm County, Sweden	7116	35	47.1 (5.0)	1992-1998	13.5	96,257	6.6 (1.2)	13.6 (3.2)	26/36/38
DCH	City of Copenhagen and surrounding areas, Denmark	37,447	638	56.8 (4.4)	1993-1997	12.4	463,525	11.3 (0.9)	17.1 (1.9)	37/28/35
EPIC-MORGEN	Cities of Amsterdam, Maastricht and Doetinchem and surrounding rural areas,	15,993	92	43.7 (10.7)	1993-1997	12.1	193,042	16.9 (0.6)	25.6 (1.7)	36/29/35

	Netherlands									
EPIC-PROSPECT	City of Utrecht and surrounding rural areas, Netherlands	14,630	112	57.6 (6.0)	1993-1997	11.5	168,599	16.8 (0.5)	25.3 (1.2)	22/33/45
EPIC-Oxford	Urban and rural areas in a zone of 10 km around London-Oxford area, United Kingdom	8132	24	45.5 (13.0)	1993-2001	11.1	97,556	10.2 (1.0)	16.9 (1.9)	12/27/61
VHM&PP	State of Vorarlberg, excluding high mountain areas (> 600 m) and areas within 300 m of State border, Austria	108,018	678	42.8 (14.9)	1985-2005	15.6	1,679,225	13.6 (1.2)	20.7 (2.4)	13/7/80
EPIC-Turin	City of Turin, Italy	7216	48	50.4 (7.6)	1993-1998	12.1	87,147	30.1 (2.0)	46.6 (4.6)	25/32/43
SIDRIA-Turin	City of Turin, Italy	4816	19	44.0 (6.2)	1999	10.5	50,590	31.0 (1.7)	48.1 (4.1)	42/21/38
SIDRIA-Rome	City of Rome, Italy	9105	53	44.3 (6.0)	1999	11.2	102,027	19.4 (1.8)	36.5 (5.0)	42/23/35
EPIC-Athens	Greater Athens Area, Greece	4096	18	49.0 (11.7)	1994-1999	11.0	45,173	20.4 (2.7)	45.2 (13.7)	41/20/39

Table 2. Pooled hazard ratios for lung cancer in association with exposure to elemental components of PM* for all participants and measures of heterogeneity between underlying cohort-specific results. Pooled hazard ratios and heterogeneity derive from random-effects meta-analyses with confounder models 1, 2 and 3[†].

Exposure	No. of cohorts	No. of lung cancer cases	Model 1[†]	Model 2[†]	Model 3[†]	Measures of heterogeneity[‡]	
			HR (95% CI)			I^2 (%)	P[§]
$PM_{2.5}$ Cu	14	1,878	1.21 (1.04-1.41)	1.11 (0.95-1.30)	1.13 (0.96-1.32)	0	0.61
PM_{10} Cu	14	1,878	1.14 (1.03-1.26)	1.07 (0.96-1.18)	1.07 (0.97-1.19)	0	0.62
$PM_{2.5}$ Fe	14	1,878	1.19 (1.06-1.33)	1.06 (0.92-1.22)	1.08 (0.92-1.27)	16	0.28
PM_{10} Fe	14	1,878	1.14 (1.01-1.28)	1.05 (0.93-1.18)	1.05 (0.93-1.19)	0	0.78
$PM_{2.5}$ Zn	14	1,878	1.00 (0.91-1.11)	0.99 (0.90-1.10)	1.02 (0.92-1.12)	0	0.74
PM_{10} Zn	14	1,878	1.11 (0.98-1.24)	1.05 (0.93-1.18)	1.08 (0.96-1.22)	0	0.59
$PM_{2.5}$ S	14	1,878	1.76 (1.29-2.39)	1.31 (0.76-2.25)	1.34 (0.74-2.42)	47	0.03
PM_{10} S	14	1,878	1.18 (0.94-1.49)	1.03 (0.81-1.30)	1.03 (0.81-1.31)	0	0.70
$PM_{2.5}$ Ni	10[¶]	1,758	1.15 (0.81-1.62)	1.04 (0.74-1.47)	1.02 (0.74-1.41)	30	0.17
PM_{10} Ni	13[**]	1,803	1.39 (1.04-1.88)	1.17 (0.94-1.45)	1.15 (0.93-1.42)	0	0.70
$PM_{2.5}$ V	12[††]	1,125	1.24 (0.80-1.91)	0.97 (0.75-1.26)	0.92 (0.71-1.21)	0	0.74
PM_{10} V	14	1,878	1.07 (0.69-1.65)	0.94 (0.67-1.33)	0.93 (0.68-1.26)	10	0.34
$PM_{2.5}$ Si	12[‡‡]	1,785	1.11 (0.90-1.38)	1.10 (0.89-1.37)	1.12 (0.90-1.40)	0	0.72
PM_{10} Si	14	1,878	1.12 (0.87-1.46)	1.03 (0.90-1.18)	1.04 (0.90-1.21)	3	0.42
$PM_{2.5}$ K	14	1,878	1.06 (0.91-1.23)	1.02 (0.92-1.13)	1.03 (0.93-1.14)	0	0.64
PM_{10} K	13[**]	1,803	1.05 (0.94-1.17)	1.05 (0.95-1.16)	1.06 (0.96-1.17)	0	0.67

* HRs presented for the following increments: 5 ng/m³ $PM_{2.5}$ Cu, 20 ng/m³ PM_{10} Cu, 100 ng/m³ $PM_{2.5}$ Fe, 500 ng/m³ PM_{10} Fe, 10 ng/m³ $PM_{2.5}$ Zn, 20 ng/m³ PM_{10} Zn, 200 ng/m³ $PM_{2.5}$ S, 200 ng/m³ PM_{10} S, 1 ng/m³ $PM_{2.5}$ Ni, 2 ng/m³ PM_{10} Ni, 2 ng/m³ $PM_{2.5}$ V, 3 ng/m³ PM_{10} V, 100 ng/m³ $PM_{2.5}$ Si, 500 ng/m³ PM_{10} Si, 50 ng/m³ $PM_{2.5}$ K, and 100 ng/m³ PM_{10} K.

† Model 1: age (time scale in Cox model), sex, calendar time; model 2: Model 1 + smoking status, smoking intensity, (smoking intensity)^2, smoking duration, time since quitting smoking, environmental tobacco smoke, occupation, fruit intake, marital status, educational level, employment status; model 3: Model 2 + area-level socio-economic status. We included only participants for whom data were not missing for any of the variables included in model 3, thus using an identical data set for analyses with all three models

‡ Relating to model 3

§ Cochran test for heterogeneity

q No modelled air pollution estimates available for SNAC-K, SALT/Twin gene, 60-yr/IMPROVE, SDPP

**No modelled air pollution estimates available for HUBRO

†† No modelled air pollution estimates available for HUBRO, VHM&PP

‡‡ No modelled air pollution estimates available for HUBRO, EPIC-Athens

Table 3. Hazard ratios for lung cancer associated with exposure to $PM_{2.5}$ (per 5 μg/m^3), PM_{10} (per 10 μg/m^3) and $PM_{2.5}$ S (per 200 ng/m^3) both in one pollutant and in mutually adjusted two-pollutant models. The results derive from random-effects meta-analyses of cohort-specific results using confounder model 3*.

Pollutant	Second pollutant adjusted for	No. of cohorts	HR (95% CI)
$PM_{2.5}$	None	14	1.20 (0.97-1.49)
$PM_{2.5}$	$PM_{2.5}$ S	14	1.02 (0.80-1.31)
PM_{10}	None	14	1.23 (1.04-1.46)
PM_{10}	$PM_{2.5}$ S	14	1.11 (0.91-1.35)
$PM_{2.5}$ S	None	14	1.34 (0.74-2.42)
$PM_{2.5}$ S	$PM_{2.5}$	14	1.30 (0.71-2.38)
$PM_{2.5}$ S	PM_{10}	14	1.28 (0.67-2.43)

*Model 3: age (time scale in Cox model), sex, calendar time, smoking status, smoking intensity, (smoking intensity)^2, smoking duration, time since quitting smoking, environmental tobacco smoke, occupation, fruit intake, marital status, educational level, employment status, area-level socio-economic status

Table 4. Hazard ratios for lung cancer in association with exposure to elemental components of PM* for participants who did not change residence during follow-up and measures of heterogeneity between the underlying cohort-specific results. The results derive from random-effects meta-analyses with confounder model 3†

	Participants who did not change residence					All participants (same cohorts)
				Measure of heterogeneity		
Exposure	No. of cohorts	No. of lung cancer cases	HR (95% CI)	I^2 (%)	P‡	HR (95% CI)
$PM_{2.5}$ Cu	10§	893	1.25 (1.01-1.53)	0	0.67	1.14 (0.97-1.35)
PM_{10} Cu	10§	893	1.14 (0.96-1.35)	16	0.30	1.08 (0.96-1.20)
$PM_{2.5}$ Fe	10§	893	1.08 (0.93-1.25)	0	0.63	1.08 (0.90-1.29)
PM_{10} Fe	10§	893	1.10 (0.94-1.28)	0	0.81	1.05 (0.92-1.20)
$PM_{2.5}$ Zn	10§	893	1.11 (0.88-1.39)	0	0.57	0.99 (0.83-1.17)
PM_{10} Zn	10§	893	1.28 (1.02-1.59)	0	0.74	1.09 (0.92-1.30)
$PM_{2.5}$ S	10§	893	2.05 (0.73-5.75)	57	0.01	1.47 (0.65-3.30)
PM_{10} S	10§	893	1.58 (1.03-2.44)	6	0.39	1.10 (0.85-1.44)
$PM_{2.5}$ Ni	6¶	804	1.13 (0.77-1.65)	0	0.68	1.01 (0.73-1.41)
PM_{10} Ni	9**	839	1.59 (1.12-2.26)	0	0.44	1.29 (0.96-1.72)
$PM_{2.5}$ V	8††	621	1.07 (0.71-1.61)	0	0.96	1.02 (0.70-1.49)
PM_{10} V	10§	893	1.12 (0.77-1.64)	0	0.47	1.01 (0.70-1.45)
$PM_{2.5}$ Si	8‡‡	821	1.26 (0.85-1.86)	33	0.17	1.11 (0.88-1.41)
PM_{10} Si	10§	893	1.13 (0.95-1.36)	0	0.54	1.02 (0.88-1.18)
$PM_{2.5}$ K	10§	893	1.18 (0.99-1.40)	0	0.46	1.02 (0.92-1.14)
PM_{10} K	9**	839	1.17 (1.02-1.33)	0	0.68	1.07 (0.96-1.18)

* HRs presented for the following increments: 5 ng/m³ $PM_{2.5}$ Cu, 20 ng/m³ PM_{10} Cu, 100 ng/m³ $PM_{2.5}$ Fe, 500 ng/m³ PM_{10} Fe, 10 ng/m³ $PM_{2.5}$ Zn, 20 ng/m³ PM_{10} Zn, 200 ng/m³ $PM_{2.5}$ S, 200 ng/m³ PM_{10} S, 1 ng/m³ $PM_{2.5}$ Ni, 2 ng/m³ PM_{10} Ni, 2 ng/m³ $PM_{2.5}$ V, 3 ng/m³ PM_{10} V, 100 ng/m³ $PM_{2.5}$ Si, 500 ng/m³ PM_{10} Si, 50 ng/m³ $PM_{2.5}$ K, and 100 ng/m³ PM_{10} K.

† Model 3: age (time scale in Cox model), sex, calendar time, smoking status, smoking intensity, $(\text{smoking intensity})^2$, smoking duration, time since quitting smoking, environmental tobacco smoke, occupation, fruit intake, marital status, educational level, employment status, area-level socio-economic status.

‡ Cochrans test for heterogeneity

§ HUBRO, SNAC-K, SALT/Twin gene, 60-yr/IMPROVE, SDPP, DCH, VHM&PP, SIDRIA-Turin, SIDRIA-Rome, EPIC-Athens

q HUBRO, DCH, VHM&PP, SIDRIA-Turin, SIDRIA-Rome, EPIC-Athens

** SNAC-K, SALT/Twin gene, 60-yr/IMPROVE, SDPP, DCH, VHM&PP, SIDRIA-Turin, SIDRIA-Rome, EPIC-Athens

†† SNAC-K, SALT/Twin gene, 60-yr/IMPROVE, SDPP, DCH, SIDRIA-Turin, SIDRIA-Rome, EPIC-Athens

‡‡ SNAC-K, SALT/Twin gene, 60-yr/IMPROVE, SDPP, DCH, VHM&PP, SIDRIA-Turin, SIDRIA-Rome

Figure 1

Figure 1. Cohort locations. Four cohorts were located in Stockholm, two in the Netherlands and two in Turin.

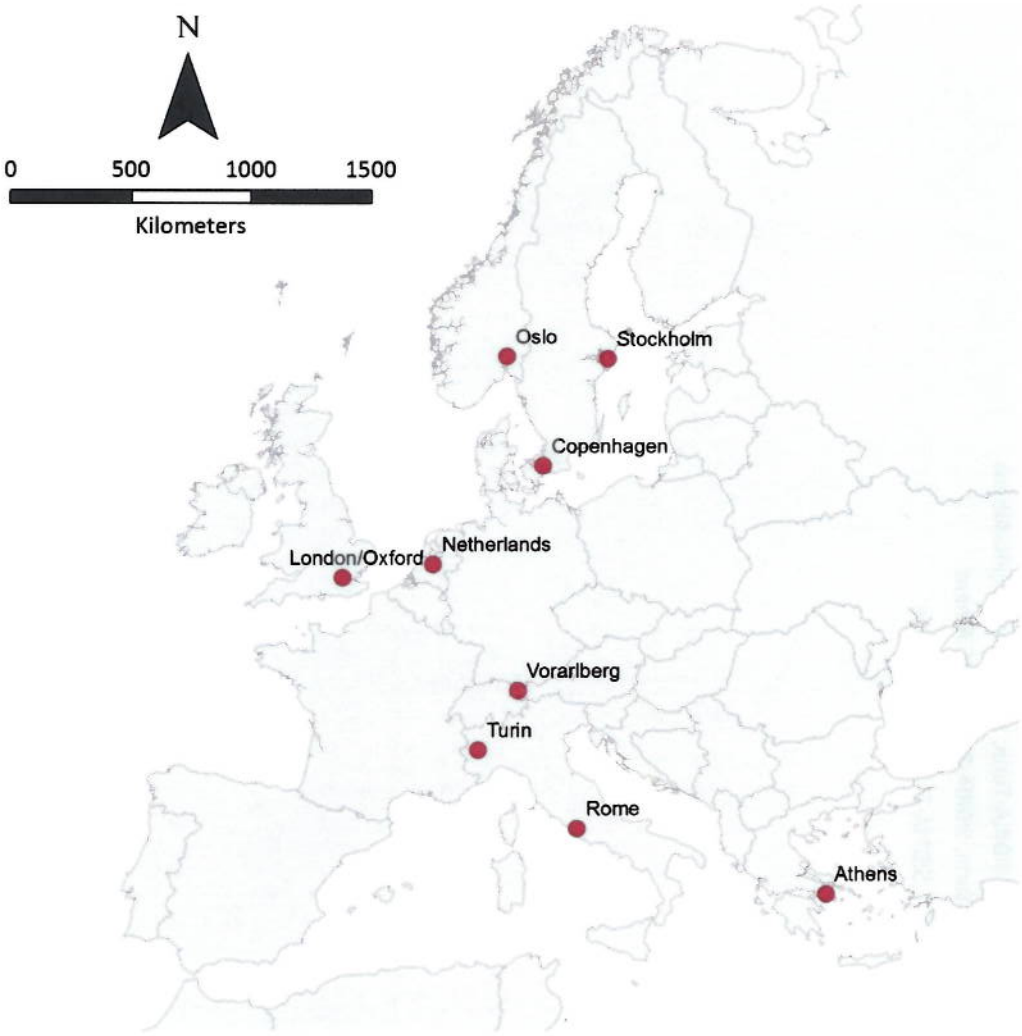
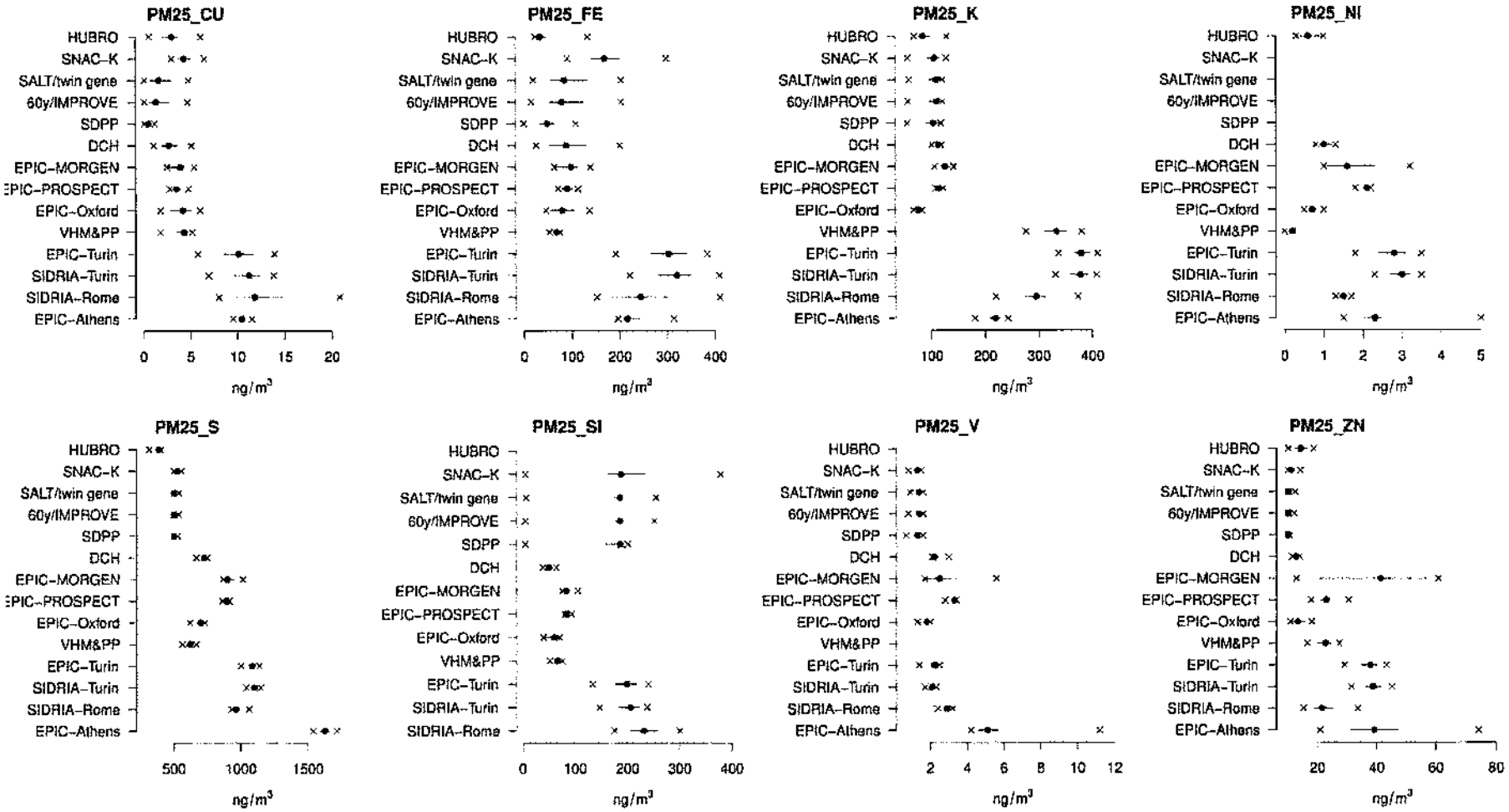


Figure 2

Figure 2: Estimated annual mean concentrations (ng/m^3) of $PM_{2.5}$ elemental components at participants' addresses in each cohort. The solid circles and bars show the median and 25% and 75% percentile concentrations; the x shows the 5% and 95% percentile values.



Supplementary Information

Click here to download Supplementary Information: Supplementary appendix 15.pdf