Science of the Total Environment 804 (2022) 150091

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Variability in the association between long-term exposure to ambient air pollution and mortality by exposure assessment method and covariate adjustment: A census-based country-wide cohort study

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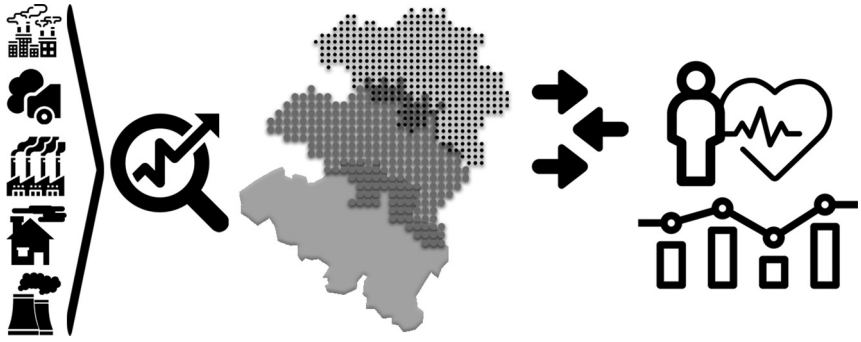
https://doi.org/10.1016/j.scitotenv.2021.150091

HIGHLIGHTS

- Large prospective country-wide cohort study including nearly 5.5 million adults
- Non-accidental and cause-specific mortality over long-term ten years follow-up
- Several ambient air pollutants evaluated using two exposure assessment models.
- Most robust associations observed between both NO_2 or BC and lung cancer mortality.
- Associations varied mildly between hybrid LUR and interpolation-dispersion model.
- Magnitude associations differed by differential adjustment for area-level indicators.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 25 April 2021
Received in revised form 2 August 2021
Accepted 29 August 2021
Available online 4 September 2021

Editor: Wei Huang

Keywords:
Population-based
Environmental hazard
Exposure assessment
Survival analysis
Cause-specific mortality
Health effects

ABSTRACT

Background: Ambient air pollution exposure has been associated with higher mortality risk in numerous studies. We assessed potential variability in the magnitude of this association for non-accidental, cardiovascular disease, respiratory disease, and lung cancer mortality in a country-wide administrative cohort by exposure assessment method and by adjustment for geographic subdivisions.

Methods: We used the Belgian 2001 census linked to population and mortality register including nearly 5.5 million adults aged ≥30 (mean follow-up: 9.97 years). Annual mean concentrations for fine particulate matter ($PM_{2.5}$), nitrogen dioxide (NO_2), black carbon (BC) and ozone (O_3) were assessed at baseline residential address using two exposure methods; Europe-wide hybrid land use regression (LUR) models [100x100m], and Belgium-wide interpolation-dispersion (RIO-IFDM) models [25x25m]. We used Cox proportional hazards models with age as the underlying time scale and adjusted for various individual and area-level covariates. We further adjusted main models for two different area-levels following the European Nomenclature of Territorial Units for Statistics (NUTS); NUTS-1 ($n = 3$), or NUTS-3 ($n = 43$).

Results: We found no consistent differences between both exposure methods. We observed most robust associations with lung cancer mortality. Hazard Ratios (HRs) per 10 μg/m^3 increase for NO_2 were 1.060 (95%CI 1.042-1.078) [hybrid LUR] and 1.040 (95%CI 1.022-1.058) [RIO-IFDM]. Associations with non-accidental, respiratory disease and cardiovascular disease mortality were generally null in main models but were enhanced after further adjustment for NUTS-1 or NUTS-3. HRs for non-accidental mortality per 5 μg/m^3 increase for $PM_{2.5}$ for the main model using hybrid LUR exposure were 1.023 (95%CI 1.011-1.035). After including random effects HRs were 1.044 (95%CI 1.033-1.057) [NUTS-1] and 1.076 (95%CI 1.060-1.092) [NUTS-3].

Conclusion: Long-term air pollution exposure was associated with higher lung cancer mortality risk but not consistently with the other studied causes. Magnitude of associations varied by adjustment for geographic subdivisions, area-level socio-economic covariates and less by exposure assessment method.

1. Introduction

Over the past few years, a relatively large number of studies on the association between long-term exposure to ambient air pollution and mortality has been published (Hoek et al., 2013; Atkinson et al., 2018; Huangfu and Atkinson, 2020; Chen and Hoek, 2020; Huang et al., 2021). The majority of studies reported increased mortality risks, although large variation has been observed in magnitude of the effect estimates both between and within countries (Hoek et al., 2013; Atkinson et al., 2018; Huangfu and Atkinson, 2020; Chen and Hoek, 2020; Huang et al., 2021). Part of this heterogeneity in air pollution epidemiological studies might be explained by methodological differences in exposure assessment method, study design or statistical data analysis approach, or by study-specific contextual differences. So far there is little evidence on how air pollution exposure assessment method affects mortality risk estimates (Yap et al., 2012; Jerrett et al., 2016; Klompmaker et al., 2020; Samoli et al., 2020; Butland et al., 2020; Gariazzo et al., 2021). Multicenter studies provide a great opportunity to investigate some of this heterogeneity. This study forms part of the Effects of Low-level Air Pollution: A Study in Europe (ELAPSE) project (www.elapseproject.eu) (Klompmaker et al., 2020; Hvidtfeldt et al., 2020), where Belgium is one of the seven participating European countries contributing to the project with large administrative cohort data. The project's central approach was to harmonize to the greatest extent possible exposure assessment, outcome and confounder definitions as well as statistical methods between different administrative cohorts. Study-specific contextual heterogeneity is likely to remain notwithstanding large harmonization efforts and may potentially affect health effect estimates in relation to long-term exposure to air pollution. Study-specific between-area variability in mortality patterns has been widely observed in several country-wide studies, including in Belgium (Deboosere and Gadeyne, 2002; Van Hemelrijck et al., 2016). Air pollution health effect estimates may be affected if broad scale air pollution patterns are correlated to regional mortality patterns. In recent North American cohort studies, investigators have adjusted for geographic subdivisions of the country to account for potential variability in spatial patterns (Crouse

et al., 2012, 2015; Di et al., 2017). The current study presents results for the Belgian administrative cohort on the association between long-term exposure to several ambient air pollutants (fine particulate matter ($PM_{2.5}$), nitrogen dioxide (NO_2), black carbon (BC) and ozone (O_3)) and non-accidental, cardiovascular disease, respiratory disease, and lung cancer mortality during a ten-year follow-up period for about 5.5 million Belgian adults. The aim of this study was to explore and assess potential variability in mortality effect estimates by different air pollution exposure assessment methods and by additional adjustment for geographic subdivisions of the country.

2. Methods

2.1. Data design and study population

Administrative cohort data was based on the Belgian 2001 census which was linked to population, emigration and mortality follow-up data for the study period October 1, 2001-December 31, 2011 (10.25 years). Data were made available by the Belgian statistical office (Statbel) and contained individual information for the entire population officially residing in Belgium at the time of the census. Individuals were geolocated based on the XY-coordinate of their residential address at baseline, near-complete with 98.7% of individuals included. All adults aged 30 and older with complete covariate information were included in the present study. We excluded about 15% of individuals with missing data on main covariates.

Individual sociodemographic covariates were collected through a census questionnaire at baseline, and included: age, sex, marital status (single, cohabiting/married, separated/divorced and widowed), country of origin (local vs foreign), education level (no/primary, secondary and tertiary), and occupational status (employed/self-employed, unemployed, homemaker and retired). Available area-level socio-economic position (SEP) covariates consisted of mean income (i.e. mean household net taxable income), unemployment (i.e. percentage of working age population unemployed), low education (i.e. percentage of population with no/primary education), and ethnicity (i.e. percentage of non-Western migrants). All area-level SEP indicators were retrieved from the Belgian 2011 census, except for ethnicity which was only obtainable for the year 2001. Area-level SEP variables were available at two different area-levels: 1) neighbourhood ($n = 6344$), i.e. geographical units having a size in between those of census tracts ($n = 19{,}781$) and local administrative units (LAU) ($n = 589$); and 2) NUTS-3 ($n = 43$), i.e. as defined by the European Nomenclature of Territorial Units for Statistics (NUTS) (Eurostat, 2018). Both aforementioned area-level SEP definitions and selected spatial levels were based on the statistical protocol of ELAPSE (Klompmaker et al., 2020).

2.2. Air pollution exposure assessment

Air pollution exposure assessment was done using two approaches: Europe-wide hybrid land use regression (LUR) and Belgian interpolation-dispersion (RIO-IFDM) exposure models. Annual mean concentrations for different ambient air pollutants ($PM_{2.5}$, NO_2, BC and O_3) for the year 2010 were assigned to the residential geocode at baseline (01/10/2001). The measurements for O_3 were obtained by averaging warm season months from April through September. A brief description of the methodologies of both models is given below and an overview of the differences can be found in supplementary material (S1).

2.2.1. European hybrid LUR model

In the framework of ELAPSE, Europe-wide air pollution exposure assessment was developed and validated following a harmonized protocol, described in detail by de Hoogh et al. (2018). In brief, hybrid LUR models were developed by combining air pollution monitoring data with predictor variables obtained from satellite derived air pollution data, chemical transport model data, and land cover and road traffic data. Monitoring data for $PM_{2.5}$, NO_2 and O_3 warm season were derived from Airbase version 8 routine data (EEA European environment agency, 2014; de Hoogh et al., 2016). As Airbase data were not available for BC, European Study of Cohorts for Air Pollution Effects (ESCAPE) monitoring data were used instead (Eeftens et al., 2012a, 2012b). Models were developed at a spatial resolution of 100 × 100 m for the year 2010 (annual mean). Estimates for $PM_{2.5}$, NO_2 and O_3 were expressed in micrograms per cubic meter ($\mu g/m^3$) and for BC in 10^{-5} m^{-1} (i.e. similar magnitude compared to BC in $\mu g/m^3$).

2.2.2. Belgian RIO-IFDM model

Air quality model exposure predictions for the same pollutants and year were provided by the Belgian Interregional Environment Agency (IRCEL-CELINE). The estimates were obtained through the coupling of a spatial interpolation model (RIO) and a dispersion model (IFDM). The interpolation model uses air quality measurements from fixed measuring stations and CORINE Land Cover data (EEA European environment agency, 2019; Hooyberghs et al., 2006). These background results were combined with a dispersion receptor model using emissions from industrial point and traffic line sources and meteorological data (Lefebvre and Vranckx, 2013). The results are modeled on high-resolution grids of 25 × 25 m. Further details regarding the applied model chain can be consulted in the following technical report by Lefebvre and Vranckx (2013). All annual mean concentrations were expressed in micrograms per cubic meter ($\mu g/m^3$).

2.3. Mortality outcomes

The studied mortality outcomes were identified through the WHO International Classification of Diseases, Tenth Revision codes (ICD-10) (W.H.O., 2004), based on the selection of the underlying cause of death on the death certificates. We considered non-accidental (ICD-10: A00-R99), cardiovascular disease (ICD-10: I10-I70), respiratory disease (ICD-10: J00-J99), and lung cancer mortality (ICD-10: C34.0-C34.9).

2.4. Statistical analyses

We assessed the association between the different air pollutants and mortality outcomes using Cox proportional hazard models with age as the underlying time scale. Individuals were right censored when information about their survival time was incomplete, i.e. death to another cause not under study for cause-specific outcomes, loss to follow-up due to emigration or end of follow-up (31/12/2011).

Three models with increasing degree of adjustment were defined a priori within the ELAPSE project (Klompmaker et al., 2020; Hvidtfeldt et al., 2020): model 1 (M1) stratified by sex and accounted for within-area correlations of the individuals by including a cluster term for neighbourhood (Therneau, 2015); model 2 (M2) adding to M1 with additional adjustment for individual sociodemographic covariates (marital status, country of origin, education level and occupational status), and model 3 (M3) adding to M2 with additional control for area-level SEP indicators (mean income, unemployment, low education, and ethnicity). In the analysis, area-level SEP was operationalized as the NUTS-3 area-level SEP variable and the deviation between NUTS-3 and neighbourhood area-level SEP variable. In ELAPSE we a priori decided to adjust for multiple dimensions of SEP at both a neighbourhood and regional scale to adjust for potential confounding by socio-economic indicators.

We evaluated the shape of the concentration-response curves for the relationship between the different air pollutants and mortality outcomes. We specified natural spline plots for three degrees of freedom (df) (Eisen et al., 2004) and compared the goodness of fit of these models with the models specified with a linear term (M3) using the Bayesian Information Criterion (BIC). No clear deviation from linearity was found based on the model fit nor the splines (i.e. large uncertainty observed about the shape at low and high end of the distribution as indicated by the 95% CIs), thus exposure hazard ratios (HR) were reported

as a continuous linear term (Supplementary Fig. S1). For linear models, results are presented as HRs with 95% CIs using pollutant-specific increments based on the ESCAPE project: 5 μg/m^3 for $PM_{2.5}$, 10 μg/m^3 for NO_2, 0.5 10^{-5} m^{-1} (hybrid LUR) or 0.5 μg/m^3 (RIO-IFDM) for BC, and 10 μg/m^3 for O_3.

Based on the single pollutant main model (M3), we specified two-pollutant models where pollutants within the same exposure model (i.e. hybrid LUR and RIO-IFDM) were simultaneously entered in the model to assess potential co-pollutant confounding.

In additional analyses, we specified two alternative mixed-effect Cox models with random intercept. Both included additional levels of spatial correlation to account for potential differences in mortality rate between geographical areas not accounted for in the main model. The first model adjusted for both neighbourhood and large geographical NUTS-1 area-level ($n = 3$), whereas the second model adjusted for both neighbourhood and NUTS-3 area-level ($n = 43$). To explore potential effect modification, we included multiplicative interaction terms into our main model between each of the pollutants and age (<65 years or ≥ 65 years), and education level (no/primary education, secondary education or tertiary education). We evaluated the goodness of fit of models with and without interaction term using the Wald test.

As sensitivity analyses, we repeated M1 with the full population sample (i.e. complete cases analysis using only M1 covariates) and compared these with the reduced sample of the main model (i.e. complete cases after including M3 covariates). We further evaluated the consistency of our effect estimates to area-level SEP adjustment in our main model (M3) by specifying models where each of the four available area-level SEP indicator was adjusted for separately instead of combined. Additionally, we indirectly adjusted main model HRs to account for important missing health-related behavioral indicators in the census in relation to mortality risk. We used the method proposed by Shin et al. (2014) to apply indirect adjustment for both smoking status (current, former or never) and body mass index (BMI) (underweight <18.5, normal 18.5-24.9, overweight 25-29.9 or obese ≥30). In brief, the indirect adjustment method extracts ancillary information on these health-related behavioral indicators from a dataset representative of the study population. We obtained the Belgian 2001 Health Interview Survey (HIS) (http://www.healthsurvey.be) matching with the baseline year of the administrative cohort. The HIS also included the same individual and area-level covariates as in our main model, with the exception of marital status which was not available. We assigned identical exposure models to the HIS participants, following the same procedure as previously described in Section 2.2. We then ran multivariate linear regression models with the harmonized HIS data to retrieve the estimates based on the association between the air pollutants and the available health-related behavioral indicators. The indirect adjustment method also uses estimates based on the association between the health-related behavioral indicators and the different mortality outcomes under study, which have been retrieved from ELAPSE pooled cohort analysis. More information on the applied indirect adjustment method (Shin et al., 2014) or the ELAPSE pooled dataset (Brunekreef et al., 2021) can be found elsewhere.

Statistical significance was set at p-value < 0.05. Statistical analyses and exposure data linkages were performed in R version 3.4.0 (R Core Team, 2019) and RStudio (RStudio Team, 2019) using the following packages: survival (Therneau, 2015), coxme (Therneau, 2018), ggplot2 (Wickham, 2009), data.table (Dowle and Srinivasan, 2017), gdalUtils (Greenberg and Mattiuzzi, 2015), raster (Hijmans, 2016), rgdal (Bivand et al., 2017), and base and dependency packages.

3. Results

3.1. Study population and air pollution exposure

The included study population consisted of 5,474,470 adults, with a total of 54,574,471 person-years and mean follow-up period of 9.97 years (Table 1). The number of men and women was nearly equal with a mean age at baseline of 52.6 years. The majority of subjects were born in Belgium (96.6%), were cohabiting/married (68.3%), had obtained secondary education level or higher (76.3%), and were employed (53.3%) at the time of the census. We observed 707,138 individuals who died from non-accidental causes of which 33.2% from cardiovascular disease, 11.6% from respiratory disease, and 7.4% from lung cancer mortality.

The exposure distribution and pairwise correlations for the different pollutants are summarised in Table 2, Supplementary Table S1 and Supplementary Figs. S2-S3. For all four pollutants, median values were higher in hybrid LUR compared to RIO-IFDM exposure models, whereas the interquartile range (IQR) was moderately lower in hybrid LUR models (Table 2). Lower variability of the hybrid LUR model is particularly reflected in the lowest and highest percentiles of the distributions, whereas the range of observed concentrations was wider for all different pollutants in the RIO-IFDM model (Supplementary Fig. S2). The broad spatial patterns of exposure distributions agreed quite well between both exposure models for all pollutants (Supplementary Fig. S3).

Pearson correlations between hybrid LUR and RIO-IFDM models were 0.64, 0.86, 0.82 and 0.76 for $PM_{2.5}$, NO_2, BC and O_3, respectively (Supplementary Table S1). Generally, correlations between pollutants

Table 1
Characteristics of the studied cohort at baseline (Belgian 2001 census).
Source: Belgian 2001 census linked to population, emigration and mortality register (2001-2011).

Study population characteristics		Description
N total (>30 years)		5,474,470
Person years at risk		54,574,471
Mean # years follow-up period (time period)		9.97 (2001−2011)
Individual level covariates		
Age: mean (± SD)		52.6 (15.2)
Women: n (%)		2,769,925 (50.6)
Country of origin local (Belgium): n (%)		5,302,040 (96.9)
Marital status: n (%)		
Single		675,491 (12.3)
Cohabiting/married		3,739,836 (68.3)
Separated/divorced		541,609 (9.9)
Widowed		517,534 (9.5)
Education level: n (%)		
No/primary		1,301,645 (23.8)
Secondary		2,839,904 (51.9)
Tertiary		1,332,921 (24.3)
Occupational status: n (%)		
Employed/self-employed		2,919,361 (53.3)
Unemployed		276,946 (5.1)
Homemaker		463,237 (8.6)
Retired		1,814,926 (33.2)
Area level covariates: mean (± SD)		
Mean income[a] (€):	Neighbourhood	29,514.0 (5529.9)
	NUTS-3[e]	30,134.1 (2878.5)
Unemployment[b] (%):	Neighbourhood	8.24 (6.10)
	NUTS-3[e]	8.25 (4.70)
Low education[c] (%):	Neighbourhood	15.73 (4.86)
	NUTS-3[e]	15.87 (2.28)
Ethnicity[d] (%):	Neighbourhood	5.44 (9.17)
	NUTS-3[e]	5.88 (6.44)
Mortality outcomes: n (%)		
Non-accidental (ICD-10[f]: A00-R99)		707,138 (12.9)
Cardiovascular (ICD-10[f]: I10-I70)		234,549 (4.3)
Respiratory (ICD-10[f]: J00-J99)		82,341 (1.5)
Lung cancer (ICD-10[f]: C34.0-C34.9)		52,211 (0.9)

[a] Mean income: mean household net taxable income in euros.
[b] Unemployment: percentage of working age population unemployed.
[c] Low education: percentage of population with no/primary education.
[d] Ethnicity: percentage of non-Western migrants.
[e] NUTS-3: European Nomenclature of Territorial Units for Statistics.
[f] ICD-10: WHO International Classification of Diseases, Tenth Revision codes.

Table 2
Distribution of air pollution exposure (2010) at residential baseline address.

		Min	5th percentile	25th percentile	Median	75th percentile	95th percentile	Max	IQR
$PM_{2.5}$	Hybrid LUR ($\mu g/m^3$)	8.30	15.60	17.86	18.73	19.56	20.74	24.04	1.70
	RIO-IFDM ($\mu g/m^3$)	0.75	12.73	15.03	16.03	17.45	19.80	40.55	2.42
NO_2	Hybrid LUR ($\mu g/m^3$)	7.43	20.31	25.59	29.20	34.14	44.55	93.76	8.54
	RIO-IFDM ($\mu g/m^3$	1.03	14.57	18.85	22.66	28.58	39.01	154.79	9.73
BC	Hybrid LUR (10^{-5} m^{-1})	0.94	1.37	1.57	1.74	1.97	2.40	5.01	0.40
	RIO-IFDM ($\mu g/m^3$)	0.07	1.06	1.29	1.47	1.83	2.67	23.08	0.54
O_3	Hybrid LUR ($\mu g/m^3$)	38.75	68.42	75.15	77.50	79.47	83.50	91.01	4.33
	RIO-IFDM ($\mu g/m^3$)	3.18	41.06	47.16	50.62	53.28	57.53	65.23	6.13

were stronger in the RIO-IFDM compared to hybrid LUR exposure model (e.g. 0.83 vs 0.62 between $PM_{2.5}$ and NO_2, respectively). Correlations between different pollutants were moderate to high, especially between NO_2 and BC. Also, expectedly, O_3 was negatively correlated with all other pollutants.

3.2. Association between air pollution and mortality

3.2.1. Main analyses

Hazard ratios (HRs) from single-pollutant models with increasing confounder adjustment for different mortality outcomes under study are presented in Fig. 1 and Supplementary Table S2. HRs were sensitive to incremental adjustment for potential confounders. Overall, hazard ratios increased after individual level covariate adjustment (M2) for $PM_{2.5}$, NO_2 and BC. After area-level SEP covariate adjustment (M3), HRs mostly attenuated, except for associations with $PM_{2.5}$ where HRs generally increased. In single pollutant main models (M3), we found small HRs both above and below unity with differing patterns depending on the studied outcome. Main model HRs ranged between 0.975 and 1.060 (Fig. 1 and Supplementary Table S2). For non-accidental mortality we only found a significant association for $PM_{2.5}$ with the hybrid LUR model (HR: 1.023, 95%CI 1.011-1.035). Observed HRs for cardiovascular mortality were mostly below unity, except for O_3 where HRs were above unity. For both respiratory and lung cancer mortality, HRs were mainly larger than unity, with strongest HRs observed with NO_2 and BC. HRs between hybrid LUR versus RIO-IFDM exposure models generally agreed for the different outcomes, although stronger estimates were mainly found in hybrid LUR models (Supplementary Table S3 with M3 HRs per IQR increase). The difference in HRs between the hybrid LUR and RIO-IFDM model exposures was larger in the fully adjusted model (M3) than in the age and sex only model (M1).

Our main results were relatively robust after further adjustment in two-pollutant models (Table 3). However, interpretation of these estimates must be with caution due to potential multicollinearity, especially between NO_2 and BC. The association between non-accidental mortality and $PM_{2.5}$ remained and became slightly stronger after adjustment for NO_2, BC or O_3. Associations with NO_2 became stronger after adjustment for O_3. Associations with O_3 became larger than unity and significant after adjustment for the other pollutants with the hybrid LUR exposure model. For cardiovascular mortality, negative associations with O_3 remained significant only after adjustment for $PM_{2.5}$ in hybrid LUR and BC in RIO-IFDM exposure models. The significant inverse associations in single pollutant models approached unity after adjustment for O_3. Associations with lung cancer mortality remained in both hybrid LUR and RIO-IFDM exposure models for NO_2 and BC after adjustment for other pollutants, except for BC after NO_2 adjustment. Associations in two-pollutant models were most notable in both respiratory and lung cancer mortality where HRs generally were stronger after adjustment for O_3, in addition to higher estimates for O_3.

3.2.2. Additional analyses

In additional analysis, we further accounted for between-area variability by including a random intercept in our main models for neighbourhood and NUTS-1 ($n = 3$) or neighbourhood and NUTS-3 area-level ($n = 43$) (Fig. 1 and Supplementary Table S4). Specification of random effects with NUTS-1 area-level only mildly affected HRs, with the exception of non-accidental mortality where associations between $PM_{2.5}$, NO_2 and BC became larger than unity and statistically significant, albeit with small HRs. Estimates were influenced more when allowing for random effects with the spatially more detailed level of NUTS-3, and generally resulted in substantially larger HRs, mainly for associations with $PM_{2.5}$. Overall, most HRs that were above unity in our main model (M3) became stronger for $PM_{2.5}$, NO_2 and BC. HRs in models with aforementioned pollutants that were lower than unity lost statistical significance or became larger than unity with increasing degree of area-level adjustment. HRs for associations with O_3 became inversely statistically significant with increasing area-control for non-accidental, respiratory and lung cancer mortality. Associations with O_3 and cardiovascular mortality did not retain statistical significance. Also, differences in effect estimates between the two exposure assessment methods became smaller and more stable when introducing random effects with NUTS-1 or more pronouncedly including the spatially more refined NUTS-3 area-level.

Effect modification analyses by age indicated stronger associations for all mortality outcomes under study with $PM_{2.5}$, NO_2 and BC in younger age (<65 years), and with O_3 in older age (≥65 years) (Supplementary Table S5). Observed effect modification patterns by education level were overall suggestive of stronger associations for $PM_{2.5}$, NO_2 and BC among individuals with tertiary education (Supplementary Table S5).

3.2.3. Sensitivity analyses

Effect estimates for M1 including the full population sample (i.e. individuals without any missing value for air pollution exposure, age and sex) were almost identical for non-accidental and cardiovascular mortality and slightly stronger for respiratory and lung cancer mortality, although very similar compared to the reduced sample (i.e. with no missing additional covariates) used in the main models (Supplementary Table S6).

HRs were sensitive to the inclusion of different area-level SEP covariates (Supplementary Table S7). When adjusting separately for each area-level SEP variable, HRs differed in both directions from M2 and the main model (M3; i.e. all available area-level SEP indicators combined). For example, for non-accidental and respiratory mortality in model SEP3, effects were downward for $PM_{2.5}$ and upward for NO_2 compared to the main model. The observed sensitivity was less for lung cancer mortality where HRs were larger. No substantial differences were observed between the different exposure models.

Study population characteristics between cohort and survey data were fairly similar (Supplementary Table S8), suggesting the use of the survey for the retrieval of ancillary information to be adequate. Indirect adjusted HRs for smoking status and BMI were generally higher in all mortality outcomes and for both exposure models. Strongest effect estimates were consistently observed in mortality associations with $PM_{2.5}$ (Supplementary Table S9).

4. Discussion

We observed associations between long-term exposure to ambient air pollution and mortality risk for natural and cause-specific mortality

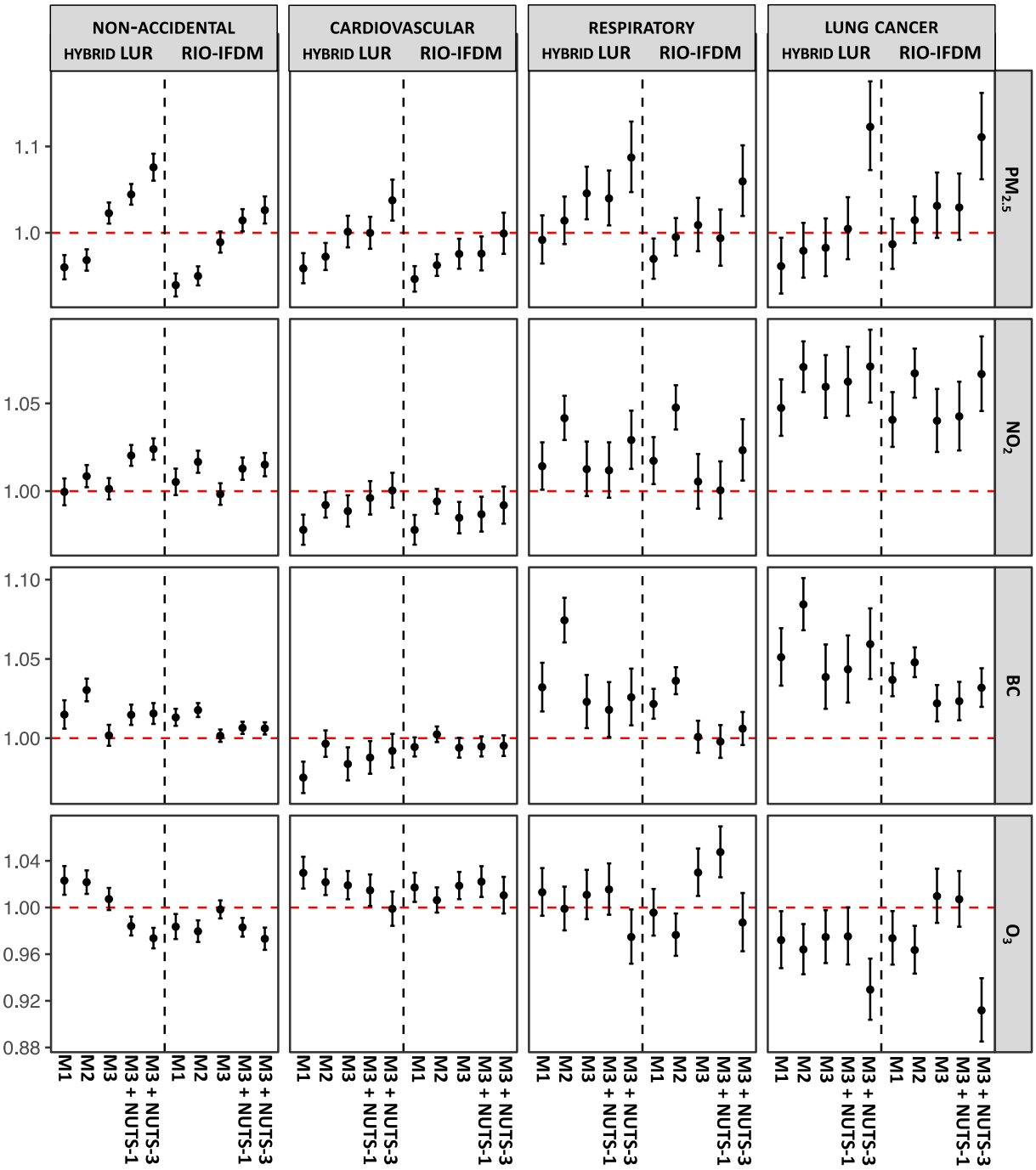


Fig. 1. Adjusted hazard ratios and 95% confidence intervals of the association between long-term air pollution exposure and mortality outcomes with increasing confounder adjustment and including random effects for neighbourhood and geographic subdivisions NUTS-1 or NUTS-3.
Note: reported HRs are expressed per increment increases; 5 μg/m^3 for $PM_{2.5}$, 10 μg/m^3 for NO_2, 0.5 10^{-5} m^{-1} (hybrid LUR) or μg/m^3 (RIO-IFDM) for BC, and 10 μg/m^3 for O_3. Model 1 (M1) stratified by sex and accounted for between-area variability by including a cluster term for neighbourhood. Model 2 (M2) M1 with additional adjustment for individual sociodemographic covariates (marital status, country of origin, education level and occupational status). Model 3 (M3) M2 with additional control for area-level socio-economic position indicators (mean income, unemployment, low education and ethnicity). M3 including area-level random effects for neighbourhood and NUTS-1 ($n = 3$; M3 + NUTS-1) or for neighbourhood and NUTS-3 ($n = 43$; M3 + NUTS-3).

outcomes. Effect estimates were sensitive to exposure assessment method, additional adjustment for geographical subdivisions (NUTS-1 or NUTS-3) of the country and differential adjustment for area-level socio-economic covariates. Mortality risk in relation to ambient air pollution was suggested to be highest among individuals younger than 65 years at baseline or with tertiary education. Overall, we observed most robust associations with lung cancer and both NO_2 or BC for both exposure methods, independently of alternative model specifications. Observed consistency of aforementioned results among exposure methods is an important finding, as each method may incorporate different degrees of measurement error. These potentially introduce bias to health effect estimates of which magnitude and direction is hard to quantify.

To our knowledge, only four other studies systematically compared potential heterogeneity in effect estimates using different exposure assessment methods when evaluating the association between long-

Table 3
Adjusted hazard ratios (HR) and 95% confidence intervals (95% CI) of the association between long-term air pollution exposure and mortality outcomes for single main and two-pollutant models.

	Pollutant[a]	Exposure	Single pollutant	Two-pollutant[c] model, adjusted for			
			Model 3[b]	$PM_{2.5}$	NO_2	BC	O_3
			HR (95% CI)	HR (95% CI)	HR (95% CI)	HR (95% CI)	HR (95% CI)
Non-accidental	$PM_{2.5}$	Hybrid LUR	**1.023 (1.011-1.035)**	–	**1.028 (1.014-1.043)**	**1.029 (1.015-1.044)**	**1.035 (1.021-1.050)**
		RIO-IFDM	0.989 (0.977-1.001)	–	**0.974 (0.953-0.996)**	**0.975 (0.958-0.992)**	**0.977 (0.961-0.993)**
	NO_2	Hybrid LUR	1.001 (0.995-1.007)	0.995 (0.987-1.002)	–	1.000 (0.988-1.013)	**1.013 (1.003-1.023)**
		RIO-IFDM	0.998 (0.992-1.004)	1.009 (0.999-1.020)	–	**0.984 (0.969-0.998)**	0.993 (0.984-1.003)
	BC	Hybrid LUR	1.002 (0.995-1.008)	0.993 (0.985-1.001)	1.002 (0.988-1.015)	–	1.010 (1.000-1.021)
		RIO-IFDM	1.002 (0.998-1.005)	**1.007 (1.002-1.013)**	**1.011 (1.002-1.021)**	–	1.002 (0.996-1.007)
	O_3	Hybrid LUR	1.007 (0.998-1.017)	**1.018 (1.007-1.029)**	**1.021 (1.006-1.036)**	**1.015 (1.001-1.029)**	–
		RIO-IFDM	0.998 (0.991-1.006)	**0.988 (0.979-0.998)**	0.992 (0.980-1.004)	1.000 (0.990-1.011)	–
Cardiovascular	$PM_{2.5}$	Hybrid LUR	1.001 (0.983-1.020)	–	1.016 (0.995-1.038)	**1.022 (1.001-1.044)**	1.018 (0.997-1.039)
		RIO-IFDM	**0.975 (0.958-0.993)**	–	1.001 (0.968-1.034)	0.976 (0.952-1.001)	0.991 (0.967-1.015)
	NO_2	Hybrid LUR	**0.989 (0.980-0.998)**	**0.985 (0.975-0.995)**	–	1.000 (0.983-1.018)	0.999 (0.985-1.013)
		RIO-IFDM	**0.985 (0.976-0.994)**	0.985 (0.968-1.001)	–	**0.967 (0.947-0.987)**	0.991 (0.976-1.005)
	BC	Hybrid LUR	**0.984 (0.973-0.994)**	**0.977 (0.965-0.989)**	0.983 (0.964-1.003)	–	0.990 (0.976-1.005)
		RIO-IFDM	0.994 (0.988-1.000)	1.000 (0.991-1.008)	1.014 (1.000-1.019)	–	1.001 (0.992-1.009)
	O_3	Hybrid LUR	**1.019 (1.007-1.031)**	**1.025 (1.011-1.038)**	1.018 (0.999-1.037)	1.012 (0.995-1.029)	–
		RIO-IFDM	**1.019 (1.007-1.030)**	1.015 (0.999-1.031)	1.010 (0.991-1.029)	**1.020 (1.004-1.036)**	–
Respiratory	$PM_{2.5}$	Hybrid LUR	**1.046 (1.016-1.077)**	–	**1.043 (1.009-1.079)**	1.033 (0.999-1.069)	**1.068 (1.034-1.103)**
		RIO-IFDM	1.009 (0.979-1.040)	–	1.000 (0.949-1.054)	1.014 (0.973-1.056)	**1.079 (1.032-1.129)**
	NO_2	Hybrid LUR	1.013 (0.997-1.028)	1.002 (0.985-1.020)	–	0.989 (0.962-1.016)	**1.047 (1.022-1.072)**
		RIO-IFDM	1.005 (0.990-1.021)	1.005 (0.979-1.033)	–	1.020 (0.986-1.055)	**1.060 (1.033-1.087)**
	BC	Hybrid LUR	**1.023 (1.006-1.040)**	1.013 (0.994-1.033)	**1.034 (1.004-1.064)**	–	**1.052 (1.030-1.075)**
		RIO-IFDM	1.001 (0.991-1.011)	0.998 (0.984-1.011)	0.989 (0.967-1.011)	–	**1.019 (1.006-1.032)**
	O_3	Hybrid LUR	1.011 (0.990-1.032)	**1.031 (1.007-1.055)**	**1.058 (1.025-1.093)**	**1.051 (1.023-1.079)**	–
		RIO-IFDM	**1.030 (1.010-1.051)**	**1.064 (1.034-1.096)**	**1.089 (1.054-1.126)**	**1.053 (1.026-1.081)**	–
Lung cancer	$PM_{2.5}$	Hybrid LUR	0.983 (0.950-1.017)	–	**0.907 (0.871-0.943)**	**0.930 (0.893-0.968)**	**0.956 (0.920-0.994)**
		RIO-IFDM	1.031 (0.994-1.070)	–	**0.895 (0.840-0.955)**	0.979 (0.933-1.028)	**1.081 (1.026-1.138)**
	NO_2	Hybrid LUR	**1.060 (1.042-1.078)**	**1.086 (1.065-1.107)**	–	**1.096 (1.064-1.129)**	**1.108 (1.078-1.139)**
		RIO-IFDM	**1.040 (1.022-1.058)**	**1.090 (1.057-1.124)**	–	**1.050 (1.013-1.089)**	**1.118 (1.086-1.151)**
	BC	Hybrid LUR	**1.039 (1.019-1.059)**	**1.062 (1.038-1.087)**	**0.954 (0.922-0.987)**	–	**1.041 (1.015-1.068)**
		RIO-IFDM	**1.022 (1.011-1.033)**	**1.027 (1.012-1.042)**	0.992 (0.969-1.016)	–	**1.042 (1.026-1.057)**
	O_3	Hybrid LUR	**0.975 (0.952-0.998)**	**0.962 (0.937-0.987)**	**1.080 (1.039-1.122)**	1.004 (0.973-1.036)	–
		RIO-IFDM	1.010 (0.987-1.033)	**1.044 (1.011-1.078)**	**1.125 (1.082-1.169)**	**1.059 (1.028-1.091)**	–

Note: statistically significant HRs are indicated in bold text (p-value < 0.05).
[a] reported HRs are expressed per increment increases; 5 μg/m^3 for $PM_{2.5}$, 10 μg/m^3 for NO_2, 0.5 10^{-5} m^{-1} (hybrid LUR) or μg/m^3 (RIO-IFDM) for BC, and 10 μg/m^3 for O3.
[b] Single pollutant main model (M3) stratified by sex and accounted for between-area variability by including a cluster term for neighbourhood, adjustment for individual sociodemographic covariates (marital status, country of origin, education level and occupational status) control for area-level socio-economic position indicators (mean income, unemployment, low education and ethnicity).
[c] Two-pollutant model: M3 with additional pollutant adjustment. Two-pollutant models were specified for all pollutants within the same exposure model (i.e. hybrid LUR and RIO-IFDM).

term exposure to ambient air pollution and various mortality outcomes using cohort data (Yap et al., 2012; Jerrett et al., 2016; Klompmaker et al., 2020; Gariazzo et al., 2021). All four aforementioned studies also detected variation in the effect estimates in terms of magnitude, direction or statistical significance depending on the applied exposure assessment method. In our study, observed variation in effect estimates only seemed to differ to a small degree between exposure models and might be explained by methodological differences (supplementary material S1). Although both models were of similar fine-scale spatial resolution, we generally found somewhat stronger associations with lowest compared with highest resolution models (100 × 100 m for hybrid LUR and 25 × 25 m for RIO-IFDM, respectively). These findings agree with those recently obtained by Gariazzo et al. (2021) for associations between both coarse PM or NO_2 and non-accidental, respiratory disease and cardiovascular disease mortality.

The study of Klompmaker et al. (2020), using Dutch administrative cohort data, was also part of the ELAPSE project. In line with expectations, our study similarly found moderate correlations for $PM_{2.5}$ and relatively strong correlations for NO_2 and BC between different exposure methods (Klompmaker et al., 2020). Comparably, differences in HRs for both NO_2 and BC between exposure models were smaller in minimally adjusted models (M1; i.e. including age and sex) versus fully adjusted models (M3), reflecting differential correlation patterns between pollutants and area-level SEP. Further, comparison of effect estimates based on the same hybrid LUR exposure model and non-accidental mortality were almost identical for associations between non-accidental mortality and $PM_{2.5}$ [HR 1.023 (95%CI 1.011-1.035) for the current (Belgian) and HR 1.030 (95%CI 1.019-1.041) for the Dutch administrative cohort (Klompmaker et al., 2020)]. Overall observed patterns with hybrid LUR exposure methods were similar in both the Belgian and Dutch administrative cohort, where strongest associations were observed for lung cancer and weakest for cardiovascular mortality (Klompmaker et al., 2020).

When study-specific between-area variability was additionally accounted for, associations in our study between $PM_{2.5}$, NO_2 and BC and mortality became stronger; hence, indicating that potential residual confounding does not necessarily lead to effect estimates biased upwards. This finding is consistent with a review reporting that more complete adjustment for area-level indicators tended to increase air pollution effect estimates rather than decrease (Vodonos et al., 2018). In Canadian cohort studies (Crouse et al., 2012, 2015), HRs also increased after adjustment for large geographical area of the country. Additional adjustment for geographical subdivisions (neighbourhood in addition to NUTS-1 or NUTS-3), reflected broad-scale spatial variation in health due to factors other than air pollution or included socio-economic covariates at individual and area-level. Previous research on spatial variability in mortality patterns in Belgium identified a clear north-south gradient across the country, where mortality rates generally are highest in the south and in former industrial areas (Deboosere and Gadeyne, 2002; Van Hemelrijck et al., 2016). Other possible

explanations for this geographic variation in health status have been proposed, such as differences in diagnostic and therapeutic practices, cultural and health-related behaviors and historical context (Deboosere and Gadeyne, 2002; Van Hemelrijck et al., 2016). Although we aimed to maximise the number of available relevant covariates in our study, no data on these specific factors was available for linkage to the Belgian administrative cohort. Therefore, we recognise that some important unobserved residual confounding may remain. With regard to country-wide spatial trends of air pollution, the aforementioned north-south gradient is inverse: observed pollutant levels are highest in the north and decrease towards the south of the country (Supplementary Fig. S3). In consequence, additional adjustment for between-area variability as random effects in our main model might have accentuated the generally small exposure contrasts between different area-levels (neighbourhood in addition to NUTS-1 or NUTS-3).

Consistent with the majority of prior research evaluating effect modification by age in the association of long-term exposure to air pollution (Huangfu and Atkinson, 2020; Chen and Hoek, 2020), our study confirmed earlier findings showing higher mortality risk in younger individuals (<65 years) with $PM_{2.5}$, NO_2 and BC. Current evidence on potential effect modification by education level with these pollutants is still limited and inconclusive. Two other participating administrative cohorts in the ELAPSE project evaluated effect modification by education level (Brunekreef et al., 2021). In accordance with our study findings, the Swiss cohort also detected strongest associations among higher educated compared to lower educated with $PM_{2.5}$, NO_2 and BC. Contrarily, the observed pattern was opposite in the Norwegian cohort. Exposure distributions of studied pollutants were nearly identical between different population subgroups by age or education level. Health and mortality risks are known to be generally higher among individuals with lower versus higher education levels, which is often referred to as the social gradient in health (Wilkinson and Marmot, 2003). This is also true for our study, where we found relative mortality risks to increase two- to three- fold between each category of education level. The social gradient among population subgroups has been attributed to several underlying health determinants, such as differences in health-related behaviors (e.g. tobacco and alcohol use, dietary habits or physical activity) or differential access to important resources (e.g. access to health care or basic housing conditions). While in our study we only observed higher mortality risks among younger or higher educated individuals, presumed mortality risks among older or lower educated individuals in relation to long-term exposure to air pollution may also be detected if other, potentially more influential health determinants could be mitigated. We speculate that the absence of such determinants in our data might partially explain observed null-trends for cardiovascular mortality in our main model.

When disentangling sensitivity of various area-level SEP indicators into separate models, we observed heterogeneity of patterns in effect estimates for different pollutants and mortality outcomes. This finding points to the multiplicity of the construct of (area-level) SEP, as well as its complex interplay with different air pollutants. Consequently, comprehensive explanation is not straightforward and deserves to be addressed further in future studies focussing on health and environmental inequalities.

Previous studies on the health effects of air pollution emphasised the importance of adjustment for SEP indicators at both individual and area-level since associations with health outcomes seemed to be independent (Roux, 2007; Temam et al., 2017; Vodonos et al., 2018). Additionally, it has been argued that adjustment for area-level SEP complementary to individual SEP might be of particular interest in studies where individuals' geographic location is important (Galobardes et al., 2007). Also, the inclusion of various SEP indicators to represent its different dimensions was suggested to be important (Galobardes et al., 2007; Pinault et al., 2016). Given the complexity of SEP and in order to reduce confounding as much as possible, our main model (M3), as has been defined a priori within the ELAPSE project, adjusted for as many individual and area-level SEP indicators as available. Although concerns for potential over-adjustment might be valid, a recent meta-analytic review on associations between $PM_{2.5}$ and several mortality outcomes observed that additional adjustment for area-level SEP unlikely results in upward bias (Vodonos et al., 2018). These findings are in line with our study, where effect estimates for $PM_{2.5}$ increased after area-level SEP adjustment with non-accidental (hybrid LUR), respiratory disease (hybrid LUR and RIO-IFDM) and lung cancer mortality (RIO-IFDM). However, we did not observe a similar pattern for the other pollutants under study.

Our study includes a number of limitations. First, and potentially most important, our study lacked individual information on health-related behaviors, such as tobacco and alcohol use, dietary habits or physical activity, as these have been identified as important determinants of mortality risk. However, we addressed this limitation, as far as possible, by indirectly adjusting our main models with information on smoking status and BMI using a survey representative of the study population. Such adjustment resulted mainly in stronger mortality associations with $PM_{2.5}$ for studied outcomes. Lack of adjustment for smoking status and BMI could not further explain observed weaker findings for cardiovascular mortality, nor could it explain apparent stronger findings for lung cancer mortality. A recent meta-analysis of cohort studies by Atkinson et al. (2018) also reported strongest associations with NO_2 and lung cancer. Another limitation of our study is that only time-fixed exposure for the year 2010 could be obtained for both exposure models. Although a decreasing trend in air pollution levels has been observed across Europe over the last years, we assumed its spatial distribution remained relatively stable over the follow-up period. Higher air pollution levels presumably result in larger exposure contrasts towards baseline. As such, using exposure for prior follow-up years may attenuate observed HRs, although this could not be evaluated. Additionally, individual and area-level covariates were not available for different time points over the follow-up period, which is a common limitation in most administrative cohorts. Furthermore, updates on residential history were not obtainable either.

5. Conclusion

Long-term term exposure to ambient air pollution was associated with higher mortality risk among nearly 5.5 million Belgian adults. We observed variability in the strength of our effect estimates by additional adjustment for geographic subdivisions of the country, area-level SEP covariates and to a limited extent exposure assessment method. Most robust and consistent associations were found between both NO_2 or BC and lung cancer mortality. Future studies should apply caution and carefully evaluate analytic strategies as exposure assessment method, different model specifications and covariate availability might influence both magnitude and direction of health effect estimates related to long-term air pollution exposure.

CRediT authorship contribution statement

B.B. and G.H.: principal investigators of the ELAPSE project; B.B., G.H., J.C. and M.S. ELAPSE project coordination. S.R., E.S., and K.K. statistical methodology ELAPSE project; K.d.H., J.C., G.H., W.L. and C.V.: exposure assessment. M.B.: conceptualization, resources, data curation, methodology, formal analysis, software and Writing-original draft; G.H., B.B., H.V. and P.D.: supervision; H.V., P.D., and A.V.N. funding. All authors read and critically revised the manuscript for the important intellectual content and approved the final version of the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors would like to thank IRCEL-CELINE (Belgian Interregional Environment Agency) for providing the air pollution estimates and Statbel (Directorate-general Statistics - Statistics Belgium) for geocoding the census data and facilitating several waves of data linkages during the exposure assessment process. Furthermore, we acknowledge the help of Johan Surkyn from Interface Demography VUB with data management as well as the support of Katrien De Troeyer with the preparation of the data demand. We are grateful for the input of Benoit Nemery from Centre for Environment and Health, Department of Public Health and Primary Care, KU Leuven for his comments/suggestions on early draft versions of the article. Computational resources and services were provided by the Shared ICT Services Centre funded by the Vrije Universiteit Brussel, the Flemish Supercomputer Center (VSC) and the Research Foundation - Flanders (FWO). The icons used for the graphical abstract were made available by the Noun Project (https://thenounproject.com) under a Free Creative Commons (CC) license [attributions: Belgium by Matthieu Rodrigues, Fien Robbe and Paul Aimé; pollution by callorine and jokokerto; air pollution by Eucalyp; factory by monkik; analysis by Rflor; conflict by Gregor Cresnar; mortality by Nithinan Tatah; health by Lakshisha]. We are grateful for the fruitful exchanges with the reviewers, which substantially helped improving this study.

Funding

Research described in this article was conducted under contract to the Health Effects Institute (HEI), an organization jointly funded by the United States Environmental Protection Agency (EPA) (Assistance Award No. R-82811201) and certain motor vehicle and engine manufacturers. The contents of this article do not necessarily reflect the views of HEI, or its sponsors, nor do they necessarily reflect the views and policies of the EPA or motor vehicle and engine manufacturers. Mariska Bauwelinck is funded by an individual PhD grant supported by the Research Foundation Flanders (FWO) [grant number 11A9718N].

Data statement

The research data is confidential.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2021.150091.

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