Environmental Research 238 (2023) 117223

Contents lists available at ScienceDirect

Environmental Research

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

Long-term exposure to air pollution and mortality in Scotland: A register-based individual-level longitudinal study

Mary Abed Al Ahad [a,*], Urška Demšar [a], Frank Sullivan [b], Hill Kulu [a]

[a] School of Geography and Sustainable Development, University of St Andrews, Scotland, United Kingdom
[b] School of Medicine, University of St Andrews, Scotland, United Kingdom

ARTICLE INFO

Keywords:
Air pollution
Mortality
Cardio-respiratory
Mental disorders
Scottish longitudinal study

ABSTRACT

Background: Air pollution is associated with several adverse health outcomes. However, heterogeneity in the size of effect estimates between cohort studies for long-term exposures exist and pollutants like SO_2 and mental/behavioural health outcomes are little studied. This study examines the association between long-term exposure to multiple ambient air pollutants and all-cause and cause-specific mortality from both physical and mental illnesses.

Methods: We used individual-level administrative data from the *Scottish-Longitudinal-Study (SLS)* on 202,237 individuals aged 17 and older, followed between 2002 and 2017. The SLS dataset was linked to annual concentrations of NO_2, SO_2, and particulate-matter (PM10, PM2.5) pollution at 1 km^2 spatial resolution using the individuals' residential postcode. We applied survival analysis to assess the association between air pollution and all-cause, cardiovascular, respiratory, cancer, mental/behavioural disorders/suicides, and other-causes mortality.

Results: Higher all-cause mortality was associated with increasing concentrations of PM2.5, PM10, NO_2, and SO_2 pollutants. NO_2, PM10, and PM2.5 were also associated with cardiovascular, respiratory, cancer and other-causes mortality. For example, the mortality hazard from respiratory diseases was 1.062 (95%CI = 1.028–1.096), 1.025 (95%CI = 1.005–1.045), and 1.013 (95%CI = 1.007–1.020) per 1 $\mu g/m^3$ increase in PM2.5, PM10 and NO_2 pollutants, respectively. In contrast, mortality from mental and behavioural disorders was associated with 1 $\mu g/m^3$ higher exposure to SO_2 pollutant (HR = 1.042; 95%CI = 1.015–1.069).

Conclusion: This study revealed an association between long-term (16-years) exposure to ambient air pollution and all-cause and cause-specific mortality. The results suggest that policies and interventions to enhance air quality would reduce the mortality hazard from cardio-respiratory, cancer, and mental/behavioural disorders in the long-term.

1. Introduction

The air we breathe is crucial for health. Previous epidemiological cohort studies from Europe and North America have shown that long-term exposure to ambient air pollution is associated with poor health outcomes and increased mortality from all-causes, but mostly from cardiovascular, respiratory, and lung cancer diseases (Abed Al Ahad et al., 2022, 2023; Beelen et al., 2014; Beverland et al., 2012; Crouse Dan et al., 2012, 2015; Dehbi et al., 2017; Fischer et al., 2015; Hvidtfeldt et al., 2019; Pinault et al., 2017; Pope et al., 2019; Raaschou-Nielsen et al., 2020; Rodopoulou et al., 2022; So et al., 2020; Zhang et al., 2021). For example, the ELAPSE project across eight European cohorts followed over an average of 20 years showed that higher exposures to particulate-matter with diameters of less than or equal to 2.5 μm (PM2.5), nitrogen dioxide (NO_2), and black carbon are associated with increased risk of almost all mortality outcomes including stroke, lung cancer, and Chronic Obstructive Pulmonary Disease (COPD), and with a 13% increase in natural deaths per 5 $\mu g/m^3$ increase in PM2.5 (Hvidtfeldt et al., 2021; Liu et al., 2021; Stafoggia et al., 2022; Strak et al., 2021; Wolf et al., 2021).

Likewise, studies from the Danish HERMES project have shown associations between long-term exposure to NO_2 and PM2.5 pollutants and higher hazards of cardiovascular mortality outcomes including stroke, myocardial infarction, and diabetes (Poulsen et al., 2023a; Poulsen

* Corresponding author.
E-mail address: maaa1@st-andrews.ac.uk (M. Abed Al Ahad).

https://doi.org/10.1016/j.envres.2023.117223
Received 28 July 2023; Received in revised form 16 September 2023; Accepted 19 September 2023
Available online 2 October 2023

et al., 2023b; Sørensen et al., 2022). In contrast, little research has been conducted on the association between long-term exposure to ambient air pollution and mental and behavioural health outcomes as per a recent systematic literature review (Dominski et al., 2021).

Despite the increasing evidence on the adverse air pollution associations with mortality and health, heterogeneity in the size of effect estimates between cohort studies for long-term exposures has been identified as per several systematic literature reviews and meta-analyses (Abed Al Ahad et al., 2020; Chen and Hoek, 2020; Hoek et al., 2013; Pope et al., 2020; Vodonos et al., 2018). These heterogeneities might be related to differences in air pollution exposure assessments (e.g., residential versus residential plus workplace assessments, assessments using high versus low spatial resolution, or baseline versus yearly assessments), exposure levels, study location, population composition (e.g., age, sex, socioeconomic status), and study methodology (Chen and Hoek, 2020; Vodonos et al., 2018). The heterogeneities in estimates also suggest the need for further studies to obtain more conclusive evidence on the association between air pollution and health.

Furthermore, literature in the last decade has been mostly concentrated on the health impacts of exposure to NO_2 and particulate-matter with diameters of less than or equal to 10 μm (PM10) or 2.5 μm (PM2.5), whereas other pollutants such as sulphur dioxide (SO_2) have been little studied (Abed Al Ahad et al., 2020; Pope et al., 2019; Vodonos et al., 2018). This could be due to the large decline in SO_2 emissions driven by the reduction in coal use in the energy sector and the desulfurization of cars and power plants in developed nations (O'Brien et al., 2023), making this pollutant of low priority compared to other pollutants. Regardless, studying the association between long-term exposure to SO_2 and mortality outcomes is important, given that SO_2 would still be harmful for human beings even at low exposures (O'Brien et al., 2023).

Taken together, this study investigates the association between long-term (16 years) exposure to four ambient air pollutants (NO_2, SO_2, PM10, and PM2.5) and all-cause and cause-specific mortality in Scotland. The associations between air pollution and mortality are examined distinguishing deaths related to cardiovascular, respiratory, cancer and other diseases as well as deaths related to mental/behavioural disorders/suicides. These associations are examined by linking longitudinal administrative individual-level data from a large Scottish cohort using the individuals' residential postcodes for each year between 2002 and 2017 to annual air pollution data modelled at 1 km^2 spatial resolution. Our study contributes to the evidence on air pollution and health by examining multiple air pollutants in relation to multiple mortality outcomes, providing insights into the specific mechanism of action of each pollutant in producing toxic effects.

2. Methods

2.1. Design and data

A prospective cohort longitudinal design was employed using individual-level data from the "*Scottish Longitudinal Study (SLS)*" (*Scottish Longitudinal Study*, Accessed November 08, 2021). The SLS is a large representative dataset of 5% of the Scottish population. It includes information from three linked censuses (1991, 2001, 2011) on individuals' socio-demographics and vital events including marriages, births, and mortality (up to 2013). The dataset includes central-register data on migration into or out of Scotland and on residential postcode histories (*Scottish Longitudinal Study*, Accessed November 08, 2021). To complement the SLS mortality data after 2013 through 2017, "*Public Health Scotland*" through the *"Electronic Data Research and Innovation Service (eDRIS)"* provided data on the year, month, and final underlying cause of death for SLS individuals from 2014 to 2017.

For this study, a cohort of 202,237 SLS individuals aged 17+ starting in 2002 was followed through 2017. Data was requested initially on all traced SLS individuals aged 16+ in the 2001 census (n = 205,732 individuals). We dropped 36 individuals because of missing gender and 1127 individuals (0.6%) because of missing postcode history. We also excluded observations for all individuals in 2001 due to no information on deaths that occurred prior to the census date on April 2001, which made the 2001 death rate incomparable to death rates in later years.

The SLS cohort structure relies on the 2001 and 2011 baseline Scottish censuses and on individuals' migration and mortality events. The possibilities of entering and exiting the cohort during the follow-up period (2002–2017) for 9 hypothetical individuals are illustrated in a Lexis-diagram (Fig. 1).

2.2. Variables

2.2.1. Mortality

Year of death was used to indicate whether individuals died in that year. Codes from the 10th Revision of International Statistical Classification of Diseases (ICD-10) were used to classify the main underlying cause of death as follows: cardiovascular (I00–I99), respiratory (J00-J99), cancer (C00–C97; D00-D48), and mental/behavioural disorders/suicide (F00–F99; X60-X84; Y10–Y34; Y87.0; Y87.2) (Supplementary Material Table 1).

In data quality checks, we compared the age-specific mortality rates (starting at age 20) of our SLS cohort to mortality rates in Scotland published by the Human Mortality Database (HMD) for the period of 2002–2017. Age-specific mortality rates are slightly lower for the SLS cohort compared to HMD for ages below 65 and above 84 (rate-ratio between 0.8 and 0.95; the difference does not exceed 20%; Supplementary material: Fig. 1).

2.2.2. Air pollution

Yearly air pollution data that combine all sources of air pollution including road traffic and industrial/combustion processes for NO_2, SO_2, PM10, and PM2.5 pollutants were obtained from the "Department-for-Environment-Food and Rural-Affairs (DEFRA)" (Department-for-Environment-Food-and-Rural-Affairs, 2020). These are raster data of mean annual concentrations of pollutants measured in $\mu g/m^3$, estimated using air dispersion models at 1 km^2 resolution, and projected using the UK-National Grid (Department-for-Environment-Food-and-Rural-Affairs, 2020). These data were linked to postcodes in Scotland received from "National-Records-of-Scotland" (National-Records-of-Scotland, 2019) that fell within the 1 km^2 raster cells for each year between 2002 and 2017. Fig. 2 shows the concentrations of NO_2, SO_2, PM10, and PM2.5 pollutants in 2017 across the residential postcodes in Scotland. In a second step, we linked the data file of matched yearly air pollution concentrations with postcodes with the data file of SLS real-time residential postcode histories. For individuals who changed their residential postcode within the same year, we kept the postcode with the highest monthly duration.

2.2.3. Socioeconomic and contextual covariates

Our study included individual-level socioeconomic covariates collected at the 2001 and 2011 censuses: gender, ethnicity, country of birth, marital status, education, and occupation (Supplementary material: Table 2). We also included place of residence, a time-varying contextual variable that classifies the individuals' residential postcodes into six rural-urban categories based on the data-zone where each postcode is located (Scottish-Government, 2021). We accounted for these socioeconomic and place of residence covariates because they are available in the SLS administrative data and are considered by relevant literature to affect the association between air pollution and mortality (Abed Al Ahad et al., 2020; Beelen et al., 2008; Cesaroni et al., 2013; Strak et al., 2021).

2.3. Analysis

We calculated risk-time (person-years at risk), all-cause and cause-specific death counts, and percentages by the main socioeconomic and

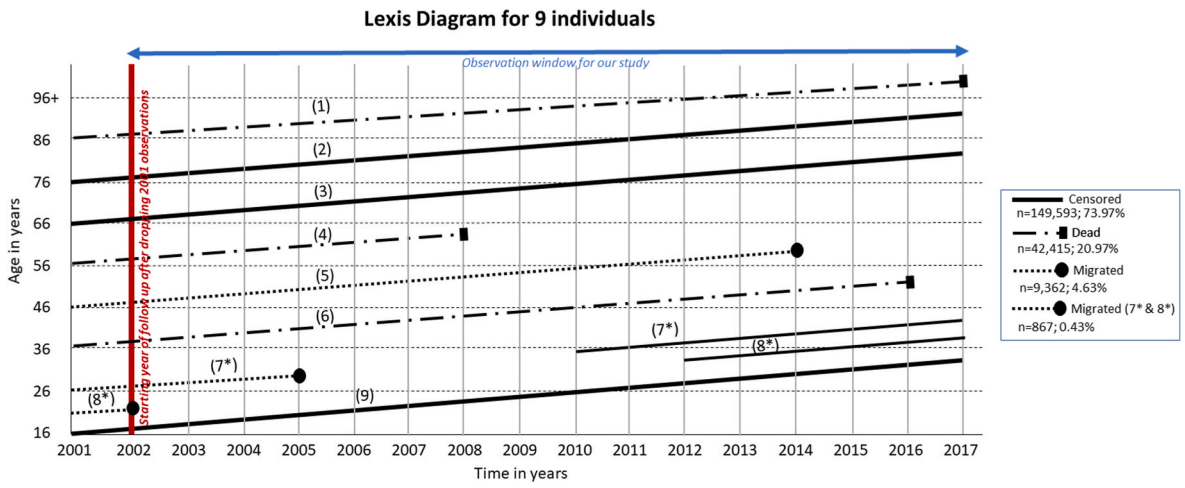

Fig. 1. A Lexis diagram showing the possibilities of entering and exiting the cohort for 9 hypothetical individuals.
Data source: Author's own calculations based on the Scottish Longitudinal Study data; The red line presents the starting year of follow-up (2002) after dropping the 2001 observations; Individuals can either be censored at the end of the study (individuals 2, 3, 9), or died (individuals 1, 4, 6), or migrated and didn't come back during the observation period of 2002–2017 (individual 5), or migrated and then came back to Scotland and thus to our study within the follow-up period (individuals 7 and 8). Thus, individual 7 was followed from 2002 to 2005 and then from 2010 to 2017 with years spent outside Scotland (2006–2009) due to migration being dropped from observation. Similarly, individual 8 was present in 2002 and then was followed from 2012 to 2017 with years spent outside Scotland (2003–2011) due to migration being dropped from observation. Thus, possibilities for entering and exiting the cohort can be summarised as follows: (1) individuals followed for the whole study period from 2002 to 2017 and then either censored, migrated or died in 2017; (2) individuals exit the cohort before 2017 because they died during the follow-up period (2002–2017); (3) individuals exit the cohort because of migrating outside of Scotland and not coming back during the follow-up period (2002–2017); and (4) individuals exit the cohort because of migrating outside of Scotland, but they come back to the cohort in later years within the follow-up period (2002–2017) due to returning to Scotland. In case individuals migrate out of Scotland and then return in the same year, this short-term migration is ignored because the individual stayed in Scotland for some months of the full calendar year. If an individual returns to Scotland from a previous year migration and then migrates again out of Scotland within the same year, the individuals' observation for that year is kept since some months out of the full calendar year have been spent in Scotland.

contextual covariates. We also calculated the correlation between the four pollutants. Given the high correlations between NO_2, PM10, and PM2.5 pollutants (Pearson's-coefficient $\geq$0.7; Table 2), the association of the four pollutants with all-cause and cause-specific mortality was assessed in separate models. SO_2 showed weak correlations (Pearson's-coefficient <0.5) with the other pollutants (Table 2), which enabled us to assess in a sensitivity analysis the association between NO_2, PM10, and PM2.5 and mortality in two-pollutant models adjusting for the SO_2 pollutant.

We used Cox proportional-hazards models with age as baseline to study the association between air pollution and all-cause and cause-specific (cardiovascular, respiratory, cancer, mental/behavioural disorders/suicide, and other causes) mortality.

We fitted three models. Model 1 included air pollution, gender, and dummies for calendar years. Model 2 additionally included socio-demographic and economic covariates collected in 2001 and 2011 censuses: ethnicity, country of birth, marital status, education, and occupation. Yearly varying place of residence was included in Model 3.

The association of all-cause and cause-specific mortality with the socioeconomic and contextual covariates is shown in Supplementary Material Tables 3–8 Results are presented as hazard ratios (HRs) with 95% confidence-intervals (CIs) per 1 $\mu g/m^3$ increase in pollutants, visualised in coefficient plots. The 1 $\mu g/m^3$ increase in air pollutants was chosen as a fixed increment to facilitate comparison with other studies (Poulsen et al., 2023a; Stafoggia et al., 2022; Vodonos et al., 2018; Zhang et al., 2021), given that other increment types (e.g., interquartile range) are specific to the population under study, and their comparison would be more complicated. Statistical significance is at a p-value of less than 0.05. Statistical analysis was conducted in $STATA_{16}$. Coefficient plots were constructed using ggplot in R-Studio. Spatial pre-processing was conducted in ArcGIS-Pro software.

2.4. Ethics

Ethical approval was granted on May 14, 2020, by the Ethics Committee of the researchers' university. Access to SLS data was approved by SLS board and access to linked data from Public Health Scotland was approved following Public Benefit and Privacy Panel for Health and Social Care (HSC-PBPP) application. No consent was required for this study because it is based on secondary data analysis. Data cleaning, management, and analysis were performed in SLS safe settings, and the study conformed to the Declaration of Helsinki principles.

3. Results

3.1. Risk-time and deaths

Our study included 202,237 SLS adult individuals followed over 16 years (2002–2017) with a total of 2,821,344 person-years at risk and 42,415 deaths distributed as: 13,459 (32%) cardiovascular, 5418 (13%) respiratory, 12,069 (28%) cancer, 2815 (7%) mental/behavioural disorders/suicide, and 8654 (20%) other-causes deaths (Table 1). Most individuals were females (53%), belonged to white ethnicity (96%), were born in Scotland (87%), were married (54%), had post-school/university education (29%), worked in white-collar high skilled (30%) or white-collar low skilled (27%) jobs, and lived in large urban (35%) areas (Table 1).

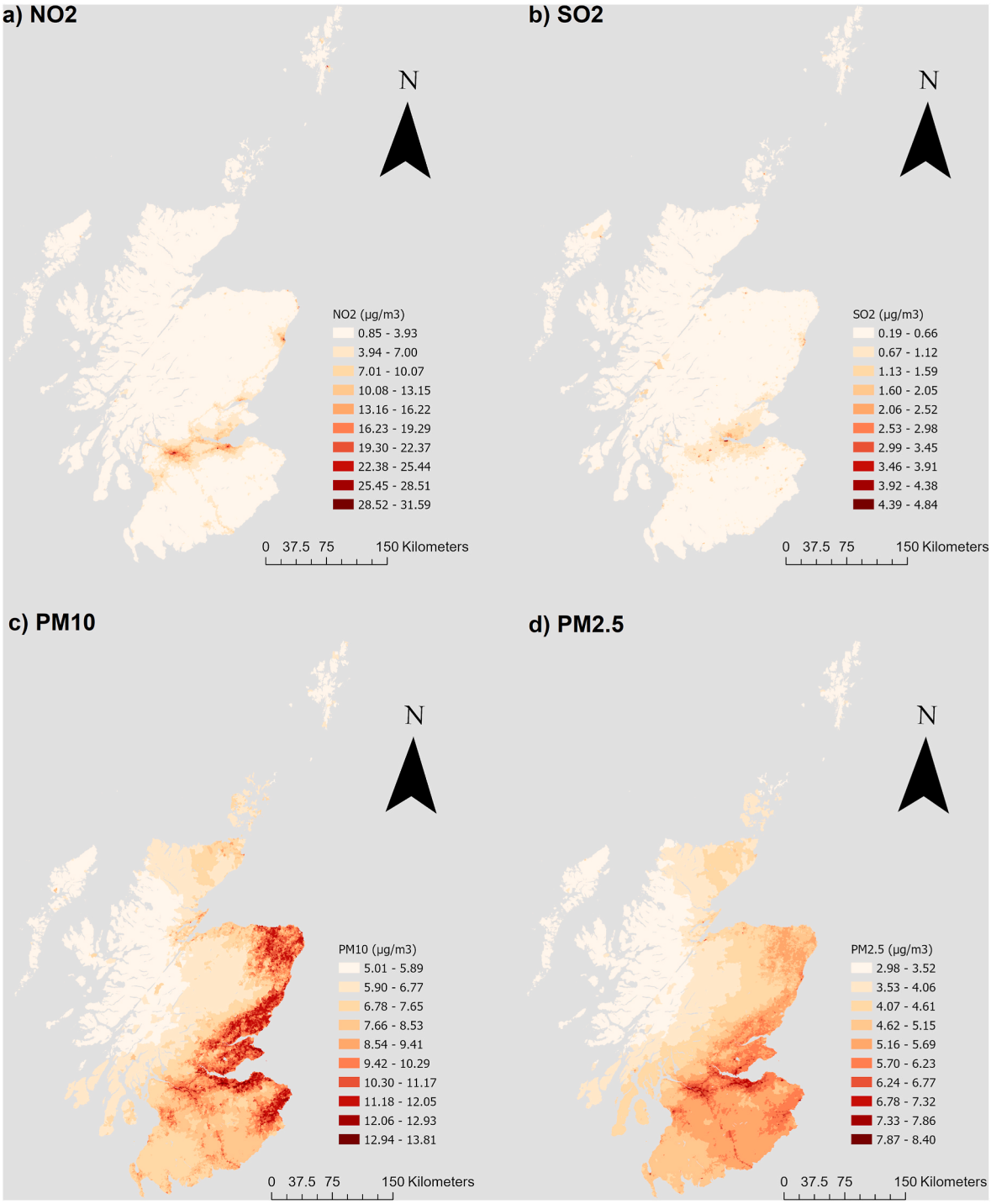

Fig. 2. Maps showing mean annual concentrations of NO_2, SO_2, PM10, and PM2.5 pollutants in 2017 across the residential postcodes in Scotland.
The map was constructed by the authors in ArcGIS Pro software using air pollution shapefiles for the year of 2017 downloaded from the DEFRA online data repository (Department-for-Environment-Food-and-Rural-Affairs, 2020) and postcode boundaries shapefiles downloaded from the National Records of Scotland (National-Records-of-Scotland, 2019). Both DEFRA and National Records of Scotland shapefiles are governed under the Open Government Licence v.3.0.

3.2. Air pollution

Fluctuations in air pollutants were observed from one year to another (2002–2017) with higher concentrations in the first three years (2002–2004) compared to later years (Supplementary material: Fig. 2). Across the follow-up time, the average concentrations of NO_2, SO_2, PM10, and PM2.5 pollutants were 11.9 (SD = 6.4), 1.9 (SD = 1.5), 11.3 (SD = 2.1), and 7.2 (SD = 1.6) µg/m^3, respectively. High correlations (Pearson's-coefficient $\geq$0.7) were noted between NO_2, PM10, and PM2.5, which could be related to the source of emission and chemical reactivity of pollutants (Table 2).

Table 1
Person-years at risk and the number of death events by the study covariates.

	Risk Time	%	All-cause death		Cardiovascular death		Respiratory death		Cancer death		Mental/ behavioural disorders/ suicide death		Other-causes death	
Covariates			Deaths	%	Deaths	%	Deaths	%	Deaths	%	Deaths	%	Deaths	%
Age														
<40	741537	26.3	671	1.6	70	0.2	15	0.0	94	0.2	198	0.5	294	0.7
40–44	283663	10.1	495	1.2	88	0.2	24	0.1	108	0.3	84	0.2	191	0.5
45–49	295294	10.5	768	1.8	143	0.3	34	0.1	254	0.6	89	0.2	248	0.6
50–54	284779	10.1	1158	2.7	260	0.6	58	0.1	411	1.0	86	0.2	343	0.8
55–59	266092	9.4	1729	4.1	456	1.1	140	0.3	708	1.7	65	0.2	360	0.9
60–64	240244	8.5	2477	5.8	637	1.5	233	0.6	1032	2.4	80	0.2	495	1.2
65–69	212892	7.6	3742	8.8	1048	2.5	387	0.9	1569	3.7	65	0.2	673	1.6
70–74	176893	6.3	5037	11.9	1523	3.6	626	1.5	1962	4.6	120	0.3	806	1.9
75–79	140549	5.0	6595	15.6	2144	5.1	884	2.1	2175	5.1	261	0.6	1131	2.7
80–84	98432	3.5	7546	17.8	2629	6.2	1101	2.6	1875	4.4	491	1.2	1450	3.4
85–89	53647	1.9	6521	15.4	2363	5.6	953	2.3	1248	2.9	617	1.5	1340	3.2
90–94	21341	0.8	4115	9.7	1539	3.6	665	1.6	507	1.2	474	1.1	930	2.2
95+	5981	0.2	1561	3.7	559	1.3	298	0.7	126	0.3	185	0.4	393	0.9
Year														
2002	201948	7.2	2755	6.5	1058	2.5	307	0.7	724	1.7	120	0.3	546	1.3
2003	197896	7.0	2865	6.8	1043	2.5	356	0.8	762	1.8	154	0.4	550	1.3
2004	194046	6.9	2711	6.4	988	2.3	344	0.8	691	1.6	155	0.4	533	1.3
2005	190522	6.8	2660	6.3	922	2.2	337	0.8	743	1.8	142	0.3	516	1.2
2006	187002	6.6	2634	6.2	886	2.1	331	0.8	745	1.8	151	0.4	521	1.2
2007	183570	6.5	2767	6.5	909	2.1	348	0.8	783	1.9	178	0.4	549	1.3
2008	180183	6.4	2716	6.4	845	2.0	355	0.8	753	1.8	171	0.4	592	1.4
2009	176723	6.3	2548	6.0	805	1.9	310	0.7	763	1.8	154	0.4	516	1.2
2010	173710	6.2	2563	6.0	797	1.9	340	0.8	708	1.7	182	0.4	536	1.3
2011	170814	6.1	2447	5.8	788	1.9	312	0.7	693	1.6	173	0.4	481	1.1
2012	168036	6.0	2571	6.1	767	1.8	337	0.8	763	1.8	187	0.4	517	1.2
2013	164831	5.8	2505	5.9	740	1.7	337	0.8	775	1.8	193	0.5	460	1.1
2014	162183	5.8	2581	6.1	715	1.7	324	0.8	783	1.9	203	0.5	556	1.3
2015	159473	5.7	2689	6.3	784	1.9	364	0.9	773	1.8	206	0.5	562	1.3
2016	156533	5.6	2632	6.2	706	1.7	364	0.9	757	1.8	211	0.5	594	1.4
2017	153874	5.5	2771	6.5	706	1.7	352	0.8	853	2.0	235	0.6	625	1.5
Gender														
Male	1323609	46.9	19935	47.0	6361	15.0	2397	5.7	6126	14.4	1173	2.8	3878	9.1
Female	1497735	53.1	22480	53.0	7098	16.7	3021	7.1	5943	14.0	1642	3.9	4776	11.3
Ethnicity														
White	2695450	95.5	40061	94.5	12671	29.9	5089	12.0	11555	27.2	2658	6.3	8088	19.1
Not-white	125894	4.5	2354	5.6	788	1.9	329	0.8	514	1.2	157	0.4	566	1.3
Country of birth														
Born in Scotland	2448385	86.8	37491	88.4	11850	27.9	4838	11.4	10773	25.4	2496	5.9	7534	17.8
Born in rest of UK	257551	9.1	3244	7.7	1050	2.5	362	0.9	915	2.2	198	0.5	719	1.7
Born outside UK	115408	4.1	1680	4.0	559	1.3	218	0.5	381	0.9	121	0.3	401	1.0
Marital status														
Married	1517571	53.8	18534	43.7	5658	13.3	2061	4.9	6506	15.3	903	2.1	3406	8.0
Single never married	758808	26.9	5129	12.1	1512	3.6	599	1.4	1136	2.7	505	1.2	1377	3.3
Divorced/separated/widowed	536131	19.0	18292	43.1	6129	14.5	2697	6.4	4344	10.2	1371	3.2	3751	8.8
No response	8834	0.3	460	1.1	160	0.4	61	0.1	83	0.2	36	0.1	120	0.3
Education														
No educational qualification	849560	30.1	18473	43.6	5470	12.9	2454	5.8	5684	13.4	1151	2.7	3714	8.8
Intermediate school qualification	640152	22.7	3909	9.2	992	2.3	374	0.9	1368	3.2	292	0.7	883	2.1
High school qualification	377028	13.4	1795	4.2	475	1.1	157	0.4	650	1.5	120	0.3	393	0.9
Post-school/university qualification	814050	28.9	4667	11.0	1288	3.0	382	0.9	1744	4.1	301	0.7	952	2.2
*Still a student/Not recoded/No response	140554	5.0	13571	32.0	5234	12.3	2051	4.8	2623	6.2	951	2.2	2712	6.4
Occupation														
White collar high skilled	843133	29.9	6027	14.2	1723	4.1	569	1.3	2194	5.2	357	0.8	1184	2.8
White collar low skilled	765422	27.1	6711	15.8	1846	4.4	736	1.7	2284	5.4	438	1.0	1407	3.3
Blue collar high skilled	312312	11.1	4161	9.8	1255	3.0	467	1.1	1344	3.2	249	0.6	846	2.0
Blue collar low skilled	649796	23.0	9517	22.4	2731	6.4	1252	3.0	3068	7.2	599	1.4	1867	4.4
Not applicable: students/never worked	209152	7.4	13037	30.7	4933	11.6	2009	4.7	2341	5.5	1034	2.4	2720	6.4
No response	41529	1.5	2962	7.0	971	2.3	385	0.9	838	2.0	138	0.3	630	1.5
Place of residence														
Large Urban areas	982209	34.8	15251	36.0	4726	11.1	2025	4.8	4343	10.2	1019	2.4	3138	7.4
Other urban areas	817733	29.0	12442	29.3	3905	9.2	1659	3.9	3504	8.3	863	2.0	2511	5.9
Accessible small towns	207817	7.4	3059	7.2	994	2.3	387	0.9	868	2.1	169	0.4	641	1.5
Remote small towns	68031	2.4	1265	3.0	413	1.0	151	0.4	351	0.8	84	0.2	266	0.6
Accessible Rural areas	530751	18.8	7185	16.9	2323	5.5	844	2.0	2078	4.9	480	1.1	1460	3.4
Remote rural areas	214803	7.6	3213	7.6	1098	2.6	352	0.8	925	2.2	200	0.5	638	1.5
Total	**2821344**	**100**	**42415**	**100**	**13459**	**31.7**	**5418**	**12.8**	**12069**	**28.5**	**2815**	**6.6**	**8654**	**20.4**

Data source: Author's own calculations based on the Scottish Longitudinal Study data; *Still a student/Not recoded/no response: The counts and percentages of the two categories of Still a student and Not recoded/no response were combined due to low counts; Percentages might not add up to 100 due to rounding.

Table 2
Description of air pollution exposure.

	NO_2 (μg/m^3)	SO_2 (μg/m^3)	PM10 (μg/m^3)	PM2.5 (μg/m^3)
Mean	11.9	1.9	11.3	7.2
Standard deviation	6.4	1.5	2.1	1.6
Median	11.2	1.6	11.2	7.1
Interquartile Range	9.4	1.3	2.8	2.3
Correlation matrix of air pollutants				
	NO_2 (μg/m^3)	SO_2 (μg/m^3)	PM10 (μg/m^3)	PM2.5 (μg/m^3)
NO_2 (μg/m^3)	1.0			
SO_2 (μg/m^3)	0.3	1.0		
PM10 (μg/m^3)	**0.7**	0.4	1.0	
PM2.5 (μg/m^3)	**0.7**	0.3	**0.9**	1.0

Strong correlations with correlation coefficient ≥0.7 are highlighted in bold; Data source: Author's own calculations based on the Scottish Longitudinal Study data.

3.3. Air pollution and mortality associations

Results showed higher hazard ratios of all-cause mortality with increasing concentrations of PM2.5 (HR = 1.035; 95%CI = 1.023–1.047), PM10 (HR = 1.016; 95%CI = 1.009–1.023), NO_2 (HR = 1.009; 95%CI = 1.007–1.012), and SO_2 (HR = 1.009; 95%CI = 1.002–1.016) pollutants (Fig. 3). Higher hazard ratios for cardiovascular, respiratory, cancer and other-causes mortality were also shown with increasing concentrations of NO_2, SO_2 (only in models 1 and 2), PM10 and PM2.5 pollutants. For example, the mortality hazard for respiratory diseases in model 3 was 1.062 (95%CI = 1.028–1.096), 1.025 (95%CI = 1.005–1.045), and 1.013 (95%CI = 1.007–1.020) per 1 μg/m^3 increase in PM2.5, PM10, and NO_2 pollutants, respectively. Mortality from mental/behavioural disorders/suicides was mainly associated with higher exposure to SO_2 (HR = 1.042; 95%CI = 1.015–1.069) pollutant (Fig. 3). Separating mental/behavioural disorders from suicide mortality still showed a similar pattern of associations; though the association between suicide mortality and SO_2 was not significant due to the low suicides count (n = 417; Supplementary material: Fig. 3).

Similar results were noticed in two-pollutant models. The exceptions were cardiovascular and cancer mortality that did not show a significant association with PM2.5 after adjusting for SO_2 (Supplementary material: Fig. 4). Thus, the effect of PM2.5 on cardiovascular and cancer mortality may largely be the consequence of exposure to other pollutants that co-exist with PM2.5 in the atmosphere such as SO_2 (Ku et al., 2017) and their post-inhalation interactions within the human body (Gładka et al., 2018).

3.3.1. Sensitivity analysis

In a sensitivity analysis, we refitted models 1–3 replacing yearly air pollution with average cumulative air pollution (CAP) that was calculated following the methods of Bentayeb et al. (2015) (Bentayeb et al., 2015). For each individual, we calculated the average pollutant concentration from the baseline year (2002) to each year of follow-up before death or censoring (e.g., exposure in 2006 was calculated as the mean of annual concentrations from 2002 to 2006; in 2007, from 2002 to 2007).

We observed positive associations between higher exposure to average CAP and all-cause and cause-specific mortality. However, stronger associations were noted for average CAP, which supports that long-term cumulative exposures have an exacerbating effect on health (Supplementary material: Fig. 5). Nevertheless, the differences between average CAP and yearly pollution effects were not large and this could be related to the low mobility of individuals during the 16 years of follow-up: 54% of individuals did not change the postcode and 32% moved within the same data-zone or council area.

4. Discussion

Using large individual-level administrative data linked to 1 km^2 air pollution data at the individuals' residential postcode between 2002 and 2017, this study supports an association between long-term exposure to NO_2, SO_2, PM10 and PM2.5 pollutants and all-cause, cardiovascular, respiratory, cancer, mental/behavioural disorders, suicides, and other-causes mortality in Scotland. The highest death rates were observed from respiratory causes, especially with higher exposure to long-term PM2.5, which was expected given that air pollution enters mainly the

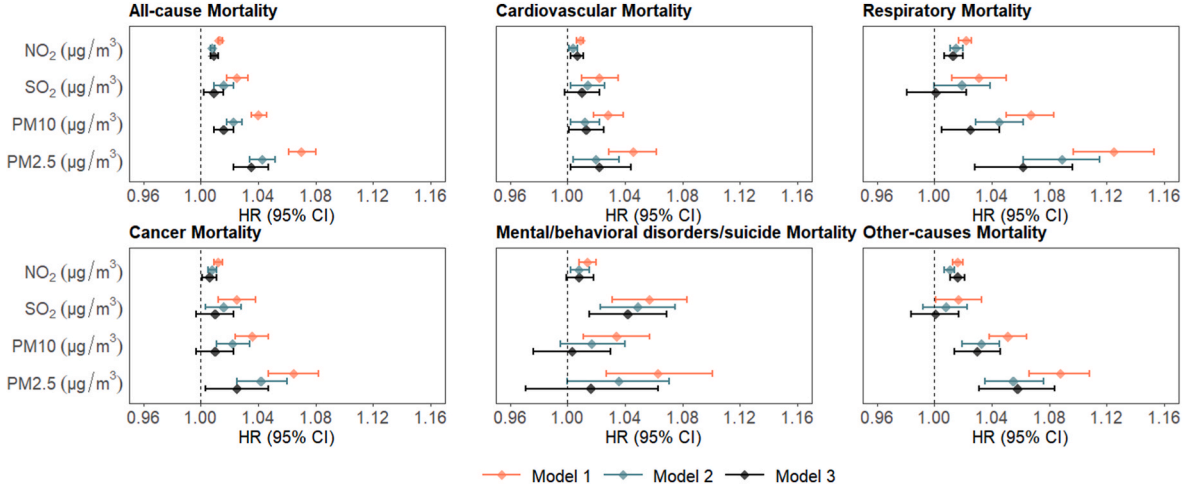

Fig. 3. The association of all-cause and cause-specific mortality with NO_2, SO_2, PM10, and PM2.5 air pollutants in separate Cox Proportional-Hazard models (N = 202,237 individuals and 2,821,344 person-years at risk).
Data source: Author's own calculations based on the Scottish Longitudinal Study data; The dashed line is placed at HR = 1 as a cut-off for statistically insignificant results; Model 1 is adjusted for gender and calendar year dummies; Model 2 = Model 1 + ethnicity + country of birth + marital status + education + occupation; Model 3 = Model 2 + Place of residence. Results are presented as HRs with 95%CIs per 1 μg/m^3 increase in air pollutants. Models 1 to 3 include the same individuals (N = 202,237 individuals and 2,821,344 person-years at risk).

human body through air-breathing, causing damage to the nasal cavity, upper respiratory airways, and lung tissues (Abed Al Ahad et al., 2020; Manisalidis et al., 2020).

Our results in terms of the direction of the associations are consistent with previous studies from North America, Europe, and South-Korea (Beelen et al., 2014; Carey et al., 2013; Crouse Dan et al., 2015; Crouse Dan et al., 2012; Dehbi et al., 2017; Fischer et al., 2015; Hansell et al., 2016; Hvidtfeldt et al., 2021; Hvidtfeldt et al., 2019; Lepeule et al., 2012; Liu et al., 2021; Min et al., 2018; Pinault et al., 2017; Pope et al., 2019; Poulsen et al., 2023a; Poulsen et al., 2023b; Pun et al., 2017; Raaschou-Nielsen et al., 2020; Rodopoulou et al., 2022; So et al., 2020; Stafoggia et al., 2022; Strak et al., 2021; Wolf et al., 2021; Yuchi et al., 2020; Zhang et al., 2021) and with systematic literature reviews and meta-analyses that investigated the long-term effect of air pollution on all-cause and cause-specific mortality (Chen and Hoek, 2020; Hoek et al., 2013; Pope et al., 2020; Vodonos et al., 2018). However, some of our estimates (e.g., HRs of the association between PM2.5 and all-cause, cardiovascular, and respiratory mortality) were larger than what other studies and systematic literature reviews have found. For example, in a systematic literature review of 75 studies from around the world, Pope et al. (2020) found that the random effects meta-estimates for all-cause mortality per 10 $\mu g/m^3$ increase in PM2.5 correspond to a hazard ratio of 1.09 (95%CI 1.07–1.11) in North America, 1.12 (95%CI 1.06–1.19) in Europe, and 1.07 (95%CI 1.04–1.11) in Asia (Pope et al., 2020). Similarly, a systematic literature review by Vodonos el al. (2018) reported for every 1 $\mu g/m^3$ increase in PM2.5, a 1.29% (95%CI 1.09–1.50), 1.46% (95%CI 1.25–1.67), and 1.13% (95%CI 0.85–1.41) increase in all-cause, cardiovascular, and respiratory mortality, respectively (Vodonos et al., 2018). On the other hand, the hazard ratios for the association between NO_2 and all-cause mortality were comparable to the ELAPSE project findings (HR 1.09; 95%CI 1.07–1.10 per 10 $\mu g/m^3$ increase in NO_2) (Strak et al., 2021) and the hazard ratios for the association between NO_2 and respiratory diseases mortality were comparable to a National English Cohort study (HR 1.15; 95%CI 1.10–1.20 per 10.7 $\mu g/m^3$ increase in NO_2) (Carey et al., 2013).

The elevated estimates in our study could be attributed to the differences in population size, study location, air pollution exposure assessment and level, and methodological differences such as residual confounding (Chen and Hoek, 2020). For example, our models adjusted only for the socio-demographic and economic characteristics of individuals (e.g., age, gender, education, marital status, ethnicity, country of birth, and occupation) and for the time trend (i.e., year dummies) and place of residence (i.e., rural-urban area classifications). However, our models did not account for individual lifestyle covariates such as smoking, exercise, alcohol consumption, or body mass index that may affect the association between air pollution and mortality (Beelen et al., 2008; Stafoggia et al., 2022; Strak et al., 2021; Weichenthal et al., 2014) due to the unavailability of this information in register-based data. Adjusting for these lifestyle covariates would likely alter the magnitude of association estimates slightly in the range of 1–2% increase or decrease, depending on the cause of death as shown in other studies (Abed Al Ahad et al., 2023; Carey et al., 2013; Chen et al., 2013; Crouse Dan et al., 2015; Fischer et al., 2015; Nieuwenhuijsen et al., 2018). Similarly, our models did not account for environmental factors at the place of residence such as noise pollution or the lack of green spaces. Nevertheless, this is unlikely to have a tremendous effect on the association between air pollutants and mortality outcomes with estimates being little attenuated by 0–3% increase or decrease as reported by previous studies (Nieuwenhuijsen et al., 2018; Sørensen et al., 2022; Yuchi et al., 2020).

Our study also supported differences in the effect of the four pollutants on cause-specific mortality. Whilst NO_2 was associated with all mortality causes, particulate-matter, especially PM2.5 was mainly related to respiratory, cardiovascular and cancer mortality, while SO_2 was associated with mental and behavioural disorders mortality. This could be attributed to the specific mechanism of action of each pollutant in producing toxic effects depending on its chemical and physical properties, which results in different diseases and mortality outcomes. Literature has shown that NO_2 is an irritant of the respiratory system that can penetrate deeply into the lungs (Costa et al., 2014; Manisalidis et al., 2020). Exposure to high concentrations of NO_2 (>2 ppm) affect the immune system by altering the function of T-lymphocytes and natural-killer cells (Manisalidis et al., 2020). Long-term exposure to NO_2 is also related to ventricular-hypertrophy in humans (Manisalidis et al., 2020). This increases the risk for cardiovascular, respiratory, and lung cancer mortality as shown in our study and other observational studies (Cesaroni et al., 2013; Fischer et al., 2015; Liu et al., 2021; Wolf et al., 2021). Exposure to NO_2 is also linked to mental and behavioural disorders due to the formation of reactive-oxygen species (ROS) and free radicals, which results in neuronal injury and neurological disorders (Kilian and Kitazawa, 2018; Yan et al., 2015).

Particulate-matter with larger diameters (e.g., PM10) will be deposited in nasal cavities and upper airways following inhalation. Particulate-matter with smaller diameters (e.g., PM2.5) may penetrate more deeply the respiratory system reaching alveoli and bloodstream (Costa et al., 2014; Manisalidis et al., 2020). Once inside the body, particulate-matter will initiate oxidative stress and the formation of ROS, resulting in respiratory, cardiovascular, immune, and central nervous system dysfunctions (Costa et al., 2014; Manisalidis et al., 2020).

Chronic exposure to SO_2 can disrupt the signal transmission and synaptic communications between neurons and initiate oxidative stress resulting in neurodegeneration and neuronal dysfunction (Ku et al., 2017; Manisalidis et al., 2020). This leads to various neurodegenerative, psychological, and behavioural complications including Alzheimer's and Parkinson's diseases (Ku et al., 2017; Manisalidis et al., 2020), cognitive impairment (Kilian and Kitazawa, 2018), and depression (Borroni et al., 2022).

The emission source of the four pollutants can also explain the observed differences. Traffic exhaust is the main source of NO_2 (Grazuleviciene et al., 2004). Particulate-matter results from both traffic and industrial processes as well as from domestic sources such as wood burning and wood stoves and from natural processes (e.g., forest fires and dust). Particulate-matter can stay for long time in the atmosphere due to their tiny dimensions and can spread over long distances through atmospheric transport, depending on factors related to weather, topography, coastal areas, and proximity to natural sources, among others (Jyethi, 2016; Malek et al., 2006; Manisalidis et al., 2020; Wood et al., 2023). Thus, higher concentrations of NO_2 are expected in urban areas and around busy roads in general rather than being restricted to certain industrial neighbourhoods, and particulate-matter pollution is expected to be scattered, covering large areas beyond its emission sources. In contrast, SO_2 originates from industries and power plants (Vestreng et al., 2007), which are restricted to specific urban and rural areas. Fig. 2 supports these expectations by showing higher concentrations of NO_2 and SO_2 in the urban Central Belt and in busy coastal cities like Aberdeen, while PM10 and PM2.5 are scattered across the whole of Scotland. Fig. 2 also shows some clustering of SO_2 in rural areas in places of local industries and energy production facilities. This further suggests that the place of residence (urban versus rural) plays a crucial role in the intensity and duration of exposure to ambient air pollution and its associated morbidity and mortality. Adjusting our analysis for the place of residence (model 3), reduced the magnitude of associations between mortality and all the four pollutants. This also indicates that living near factories and power plants could play a role in the observed association between SO_2 and mental/behavioural disorders mortality. Some studies have shown that areas near industries and power plants are more deprived and are disproportionately occupied by people of colour and lower socioeconomic status (Downey and Van Willigen, 2005). This is because those areas have high air and noise pollution, and lack positive environmental factors such as parks, trees, and open spaces (Downey and Van Willigen, 2005). This increases the risk of mental and

behavioural illness in a direct way due to higher exposure to air and noise pollution and indirectly due to the anxiety experienced from deprivation, individuals' perceptions of neighbourhood disorder, and personal powerlessness (Downey and Van Willigen, 2005; Marques and Lima, 2011).

4.1. Strengths and limitations

An important strength of this article is that it used a large administrative individual-level cohort from Scotland over a long period of 16 years to investigate the association between mortality and air pollution exposure assessed and linked at 1 km^2 spatial scale. Administrative data are usually of high quality, and they possess advantage over other types of data (e.g., surveys) by providing continuous longitudinal information on residential histories at the postcode level, on emigrations and immigrations, and on mortality and births vital events. Knowing the exact postcode histories of individuals over the 16 years of follow-up is essential in the assessment of individual's air pollution exposure. Besides, the linkage of modelled air pollution data at 1 km^2 resolution provides a uniform assessment of exposure across the postcodes in Scotland, which would not be the case for unmodelled station-based pollution data. Furthermore, the SLS administrative-based data consists of a 5% representative sample of the total Scottish population based on the three censuses of 1991, 2001, and 2011, which ensures representation of all population sub-groups, reduces selection bias, and provides enough statistical power to observe associations. However, the usage of administrative data comes with its limitations related to the unavailability of important lifestyle covariates that were shown to affect the association between air pollution and mortality such as smoking, alcohol consumption, body-mass-index, and exercise. This may contribute to residual confounding as discussed previously. To overcome this limitation, future research would have to investigate the possibility of linking administrative data to survey data that contains information on lifestyle factors. Nevertheless, we adjusted for several commonly used potential confounders including socio-demographic, economic, and rural-urban confounders, which reduces the confounding by other risk factors.

Another strength of the present study is that it investigated the association between multiple air pollutants including the less studied SO_2 pollutant and several cause-specific mortality outcomes. This is important to show that air pollution is associated with both physical and mental illnesses mortality and to reveal differences in mortality outcomes based on exposures to specific pollutants. For example, our study showed that SO_2 is mainly associated with mortality from mental/behavioural disorders, while the other three pollutants were mainly associated with mortality from cardiovascular, respiratory, and cancer diseases. Furthermore, our study revealed that despite the relatively low concentrations of SO_2 in Scotland, it is still associated with an increased mortality hazard, particularly for mental and behavioural diseases, which warrant further investigation.

Finally, bias from exposure misclassification and selection cannot be excluded. First, our cohort included a 5% representative sample of all adult individuals (age 16+) who were present in Scotland at the 2001 census. This may introduce selection bias by excluding individuals who became adults after 2001 census or who entered Scotland at later years through immigration. However, following a cohort design by including adult individuals present at the onset of the study and not allowing new entries allows a lengthier follow-up time for everyone and reduces heterogeneities between individuals and the bias that may arise from periods of rapid population change. Second, the SLS cohort was followed over a period of 16 years starting the year 2002; thus bias may result from previous lifetime exposures to air pollution at different residences. Third, we assessed the individuals' exposure to ambient air pollution using the residential postcode, which does not necessarily equate to the true personal exposure. In reality, an exposure scenario is more complex involving exposure indoors, at workplace, during leisure activities and through commuting patterns. Thus, future research would benefit from integrating air pollution exposure at the residence and workplace (e.g., by using census data on journey-to-work flows or real-time GPS data) and from considering both ambient and indoor air pollution exposures. Finally, we assessed the association between air pollution and mortality on a yearly rather than monthly or daily basis, which did not allow for seasonal variations in air pollution.

5. Conclusion

This study contributed to the evidence that long-term exposure to ambient air pollution is associated with mortality. The results suggest that policies and interventions to enhance air quality would reduce the mortality hazard from both physical (e.g., cardiovascular, respiratory, and cancer) and mental/behavioural illnesses in the long-term.

Author contribution statement

Mary Abed Al Ahad: Conceptualization, Investigation, Methodology, Data curation, Formal Analysis, Writing-Original Draft, Writing-Review and Editing, Visualization, Project administration. Hill Kulu, Urška Demšar and Frank Sullivan: Conceptualization, Funding acquisition, Supervision, Writing-Review and Editing.

Ethical considerations

This paper is part of a PhD project that was granted ethical approval on the May 14, 2020 by the School of Geography and Sustainable Development Ethics Committee, acting on behalf of the University Teaching and Research Ethics Committee (UTREC) at the University of St Andrews. Access to the SLS data was approved by the SLS manager following a detailed application and access to the linked data from Public Health Scotland via the Electronic Data Research and Innovation Service (eDRIS) was approved following a detailed Public Benefit and Privacy Panel for Health and Social Care (HSC-PBPP) application. The SLS team have already obtained all the needed consent and approvals for the data processing and analysis. Based on the SLS data policy and the sensitivity of the used data, all data cleaning, management, and analysis was performed in the safe settings of the SLS in Ladywell House in Edinburgh to ensure individuals' confidentiality and safe and secure data storage and access.

Funding

This study is funded by the St Leonard's interdisciplinary PhD scholarship, School of Geography and Sustainable Development, and School of Medicine, University of St Andrews, Scotland, UK. Mary Abed Al Ahad's and Hill Kulu's research is also part of the MigrantLife project that has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (Grant agreement No. 834103). The funding body has no role in the study design, data analysis and data interpretation. Everything presented in this article is conducted solely by the authors.

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.

Data availability

The authors do not have permission to share data.

Acknowledgements

The help provided by staff of the Longitudinal Studies Centre – Scotland (LSCS) for the Scottish Longitudinal Study (SLS) data is acknowledged. The LSCS is supported by the ESRC/JISC, the Scottish Funding Council, the Chief Scientist's Office and the Scottish Government. The authors alone are responsible for the interpretation of the data. Census output is Crown copyright and is reproduced with the permission of the Controller of HMSO and the Queen's Printer for Scotland.

The help provided by the Electronic Data Research and Innovation Service (eDRIS) in obtaining approvals for the Public Benefit and Privacy Panel for Health and Social Care (HSC-PBPP) application and in the Public Health Scotland data provision and linkages is also acknowledged. We would also like to acknowledge the Max Planck Institute for Demographic Research and their International Max Planck Research School for Population, Health and Data Science (IMPRS-PHDS) for providing resources to carry out the research presented in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2023.117223.

References

Abed Al Ahad, M., Demšar, U., Sullivan, F., Kulu, H., 2022. Does long-term air pollution exposure affect self-reported health and limiting long term illness disproportionately for ethnic minorities in the UK? A census-based individual level analysis. Applied Spatial Analysis and Policy. https://doi.org/10.1007/s12061-022-09471-1.

Abed Al Ahad, M., Demšar, U., Sullivan, F., Kulu, H., 2023. The spatial–temporal effect of air pollution on individuals' reported health and its variation by ethnic groups in the United Kingdom: a multilevel longitudinal analysis. BMC Publ. Health 23 (1), 897. https://doi.org/10.1186/s12889-023-15853-y.

Abed Al Ahad, M., Sullivan, F., Demšar, U., Melhem, M., Kulu, H., 2020. The effect of air-pollution and weather exposure on mortality and hospital admission and implications for further research: a systematic scoping review. PLoS One 15 (10), e0241415. https://doi.org/10.1371/journal.pone.0241415.

Beelen, R., Hoek, G., van den Brandt Piet, A., Goldbohm, R.A., Fischer, P., Schouten Leo, J., Jerrett, M., Hughes, E., Armstrong, B., Brunekreef, B., 2008. Long-term effects of traffic-related air pollution on mortality in a Dutch cohort (NLCS-AIR study). Environ. Health Perspect. 116 (2), 196–202. https://doi.org/10.1289/ehp.10767.

Beelen, R., Stafoggia, M., Raaschou-Nielsen, O., Andersen, Z.J., Xun, W.W., Katsouyanni, K., Dimakopoulou, K., Brunekreef, B., Weinmayr, G., Hoffmann, B., Wolf, K., Samoli, E., Houthuijs, D., Nieuwenhuijsen, M., Oudin, A., Forsberg, B., Olsson, D., Salomaa, V., Lanki, T., Hoek, G., 2014. Long-term exposure to air pollution and cardiovascular mortality: an analysis of 22 European cohorts. Epidemiology 25 (3), 368–378. https://doi.org/10.1097/ede.0000000000000076.

Bentayeb, M., Wagner, V., Stempfelet, M., Zins, M., Goldberg, M., Pascal, M., Larrieu, S., Beaudeau, P., Cassadou, S., Eilstein, D., Filleul, L., Le Tertre, A., Medina, S., Pascal, L., Prouvost, H., Quénel, P., Zeghnoun, A., Lefranc, A., 2015. Association between long-term exposure to air pollution and mortality in France: a 25-year follow-up study. Environ. Int. 85, 5–14. https://doi.org/10.1016/j.envint.2015.08.006.

Beverland, I.J., Cohen, G.R., Heal, M.R., Carder, M., Yap, C., Robertson, C., Hart, C.L., Agius, R.M., 2012. A comparison of short-term and long-term air pollution exposure associations with mortality in two cohorts in Scotland. Environ. Health Perspect. 120 (9), 1280–1285. https://doi.org/10.1289/ehp.1104509.

Borroni, E., Pesatori, A.C., Bollati, V., Buoli, M., Carugno, M., 2022. Air pollution exposure and depression: a comprehensive updated systematic review and meta-analysis. Environ. Pollut. 292, 118245 https://doi.org/10.1016/j.envpol.2021.118245.

Carey, I.M., Atkinson, R.W., Kent, A.J., van Staa, T., Cook, D.G., Anderson, H.R., 2013. Mortality associations with long-term exposure to outdoor air pollution in a national English cohort. Am. J. Respir. Crit. Care Med. 187 (11), 1226–1233. https://doi.org/10.1164/rccm.201210-1758OC.

Cesaroni, G., Badaloni, C., Gariazzo, C., Stafoggia, M., Sozzi, R., Davoli, M., Forastiere, F., 2013. Long-term exposure to urban air pollution and mortality in a cohort of more than a million adults in Rome. Environ. Health Perspect. 121 (3), 324–331. https://doi.org/10.1289/ehp.1205862.

Chen, H., Goldberg, M.S., Burnett, R.T., Jerrett, M., Wheeler, A.J., Villeneuve, P.J., 2013. Long-term exposure to traffic-related air pollution and cardiovascular mortality. Epidemiology 24 (1), 35–43. http://www.jstor.org/stable/41739716.

Chen, J., Hoek, G., 2020. Long-term exposure to PM and all-cause and cause-specific mortality: a systematic review and meta-analysis. Environ. Int. 143, 105974 https://doi.org/10.1016/j.envint.2020.105974.

Costa, S., Ferreira, J., Silveira, C., Costa, C., Lopes, D., Relvas, H., Borrego, C., Roebeling, P., Miranda, A.I., Paulo Teixeira, J., 2014. Integrating health on air quality assessment—review Report on health risks of two major European outdoor air pollutants: PM and NO2. J. Toxicol. Environ. Health, Part A B 17 (6), 307–340. https://doi.org/10.1080/10937404.2014.946164.

Crouse Dan, L., Peters Paul, A., Hystad, P., Brook Jeffrey, R., van Donkelaar, A., Martin Randall, V., Villeneuve Paul, J., Jerrett, M., Goldberg Mark, S., Pope, C.A., Brauer, M., Brook Robert, D., Robichaud, A., Menard, R., Burnett Richard, T., 2015. Ambient PM2.5, O3, and NO2 exposures and associations with mortality over 16 Years of follow-up in the Canadian census health and environment cohort (CanCHEC). Environ. Health Perspect. 123 (11), 1180–1186. https://doi.org/10.1289/ehp.1409276.

Crouse Dan, L., Peters Paul, A., van Donkelaar, A., Goldberg Mark, S., Villeneuve Paul, J., Brion, O., Khan, S., Atari Dominic, O., Jerrett, M., Pope, C.A., Brauer, M., Brook Jeffrey, R., Martin Randall, V., Stieb, D., Burnett Richard, T., 2012. Risk of nonaccidental and cardiovascular mortality in relation to long-term exposure to low concentrations of fine particulate matter: a Canadian national-level cohort study. Environ. Health Perspect. 120 (5), 708–714. https://doi.org/10.1289/ehp.1104049.

Dehbi, H.-M., Blangiardo, M., Gulliver, J., Fecht, D., de Hoogh, K., Al-Kanaani, Z., Tillin, T., Hardy, R., Chaturvedi, N., Hansell, A.L., 2017. Air pollution and cardiovascular mortality with over 25years follow-up: a combined analysis of two British cohorts. Environ. Int. 99, 275–281. https://doi.org/10.1016/j.envint.2016.12.004.

Department-for-Environment-Food-and-Rural-Affairs, 2020. Modelled Background Pollution Data. https://uk-air.defra.gov.uk/data/pcm-data.

Dominski, F.H., Lorenzetti Branco, J.H., Buonanno, G., Stabile, L., Gameiro da Silva, M., Andrade, A., 2021. Effects of air pollution on health: a mapping review of systematic reviews and meta-analyses. Environ. Res. 201, 111487 https://doi.org/10.1016/j.envres.2021.111487.

Downey, L., Van Willigen, M., 2005. Environmental stressors: the mental health impacts of living near industrial activity. J. Health Soc. Behav. 46 (3), 289–305. https://doi.org/10.1177/002214650504600306.

Fischer, P.H., Marra, M., Ameling, C.B., Hoek, G., Beelen, R., de Hoogh, K., Breugelmans, O., Kruize, H., Janssen, N.A., Houthuijs, D., 2015. Air pollution and mortality in seven million adults: the Dutch environmental longitudinal study (DUELS). Environ. Health Perspect. 123 (7), 697–704. https://doi.org/10.1289/ehp.1408254.

Gładka, A., Rymaszewska, J., Zatoński, T., 2018. Impact of air pollution on depression and suicide. Int. J. Occup. Med. Environ. Health 31 (6), 711–721. https://doi.org/10.13075/ijomeh.1896.01277.

Grazuleviciene, R., Maroziene, L., Dulskiene, V., Malinauskiene, V., Azaraviciene, A., Laurinaviciene, D., Jankauskiene, K., 2004. Exposure to urban nitrogen dioxide pollution and the risk of myocardial infarction. Scand. J. Work. Environ. Health 30 (4), 293–298. https://doi.org/10.5271/sjweh.797.

Hansell, A., Ghosh, R.E., Blangiardo, M., Perkins, C., Vienneau, D., Goffe, K., Briggs, D., Gulliver, J., 2016. Historic air pollution exposure and long-term mortality risks in England and Wales: prospective longitudinal cohort study. Thorax 71 (4), 330–338. https://doi.org/10.1136/thoraxjnl-2015-207111.

Hoek, G., Krishnan, R.M., Beelen, R., Peters, A., Ostro, B., Brunekreef, B., Kaufman, J.D., 2013. Long-term air pollution exposure and cardio- respiratory mortality: a review. Environ. Health 12 (1), 43. https://doi.org/10.1186/1476-069X-12-43.

Hvidtfeldt, U.A., Severi, G., Andersen, Z.J., Atkinson, R., Bauwelinck, M., Bellander, T., Boutron-Ruault, M.-C., Brandt, J., Brunekreef, B., Cesaroni, G., Chen, J., Concin, H., Forastiere, F., van Gils, C.H., Gulliver, J., Hertel, O., Hoek, G., Hoffmann, B., de Hoogh, K., Fecht, D., 2021. Long-term low-level ambient air pollution exposure and risk of lung cancer – a pooled analysis of 7 European cohorts. Environ. Int. 146, 106249 https://doi.org/10.1016/j.envint.2020.106249.

Hvidtfeldt, U.A., Sørensen, M., Geels, C., Ketzel, M., Khan, J., Tjønneland, A., Overvad, K., Brandt, J., Raaschou-Nielsen, O., 2019. Long-term residential exposure to PM2.5, PM10, black carbon, NO2, and ozone and mortality in a Danish cohort. Environ. Int. 123, 265–272. https://doi.org/10.1016/j.envint.2018.12.010.

Jyethi, D.S., 2016. Air quality: global and Regional emissions of particulate matter, SOx, and NOx. In: Kulshrestha, U., Saxena, P. (Eds.), Plant Responses to Air Pollution. Springer Singapore, pp. 5–19. https://doi.org/10.1007/978-981-10-1201-3_2.

Kilian, J., Kitazawa, M., 2018. The emerging risk of exposure to air pollution on cognitive decline and Alzheimer's disease - evidence from epidemiological and animal studies. Biomed. J. 41 (3), 141–162. https://doi.org/10.1016/j.bj.2018.06.001.

Ku, T., Chen, M., Li, B., Yun, Y., Li, G., Sang, N., 2017. Synergistic effects of particulate matter (PM2.5) and sulfur dioxide (SO2) on neurodegeneration via the microRNA-mediated regulation of tau phosphorylation. Toxicology Research 6 (1), 7–16. https://doi.org/10.1039/c6tx00314a.

Lepeule, J., Laden, F., Dockery, D., Schwartz, J., 2012. Chronic exposure to fine particles and mortality: an extended follow-up of the Harvard Six Cities study from 1974 to 2009. Environ. Health Perspect. 120 (7), 965–970. https://doi.org/10.1289/ehp.1104660.

Liu, S., Jørgensen, J.T., Ljungman, P., Pershagen, G., Bellander, T., Leander, K., Magnusson, P.K.E., Rizzuto, D., Hvidtfeldt, U.A., Raaschou-Nielsen, O., Wolf, K., Hoffmann, B., Brunekreef, B., Strak, M., Chen, J., Mehta, A., Atkinson, R.W., Bauwelinck, M., Varraso, R., Andersen, Z.J., 2021. Long-term exposure to low-level air pollution and incidence of chronic obstructive pulmonary disease: the ELAPSE project. Environ. Int. 146, 106267 https://doi.org/10.1016/j.envint.2020.106267.

Malek, E., Davis, T., Martin, R.S., Silva, P.J., 2006. Meteorological and environmental aspects of one of the worst national air pollution episodes (January, 2004) in Logan, Cache Valley, Utah, USA. Atmos. Res. 79 (2), 108–122. https://doi.org/10.1016/j.atmosres.2005.05.003.

Manisalidis, I., Stavropoulou, E., Stavropoulos, A., Bezirtzoglou, E., 2020. Environmental and health impacts of air pollution: a review. Front. Public Health 8, 14. https://doi.org/10.3389/fpubh.2020.00014, 14.

Marques, S., Lima, M.L., 2011. Living in grey areas: industrial activity and psychological health. J. Environ. Psychol. 31 (4), 314–322. https://doi.org/10.1016/j.jenvp.2010.12.002.

Min, J.-y., Kim, H.-J., Min, K.-b., 2018. Long-term exposure to air pollution and the risk of suicide death: a population-based cohort study. Sci. Total Environ. 628–629, 573–579. https://doi.org/10.1016/j.scitotenv.2018.02.011.

National-Records-of-Scotland, 2019. Scottish Postcode Directory Files. https://www.nrscotland.gov.uk/statistics-and-data/geography/our-products/scottish-postcode-directory/2019-2.

Nieuwenhuijsen, M.J., Gascon, M., Martinez, D., Ponjoan, A., Blanch, J., Garcia-Gil, M. D., Ramos, R., Foraster, M., Mueller, N., Espinosa, A., Cirach, M., Khreis, H., Dadvand, P., Basagaña, X., 2018. Air pollution, noise, Blue space, and green space and Premature mortality in Barcelona: a mega cohort. Int. J. Environ. Res. Publ. Health 15 (11). https://doi.org/10.3390/ijerph15112405.

O'Brien, E., Masselot, P., Sera, F., Roye, D., Breitner, S., Ng Chris Fook, S., de Sousa Zanotti Stagliorio Coelho, M., Madureira, J., Tobias, A., Vicedo-Cabrera Ana, M., Bell Michelle, L., Lavigne, E., Kan, H., Gasparrini, A., null, n., 2023. Short-term association between sulfur dioxide and mortality: a multicountry analysis in 399 cities. Environ. Health Perspect. 131 (3), 037002 https://doi.org/10.1289/EHP11112.

Pinault, L.L., Weichenthal, S., Crouse, D.L., Brauer, M., Erickson, A., Donkelaar, A.v., Martin, R.V., Hystad, P., Chen, H., Finès, P., Brook, J.R., Tjepkema, M., Burnett, R.T., 2017. Associations between fine particulate matter and mortality in the 2001 Canadian census health and environment cohort. Environ. Res. 159, 406–415. https://doi.org/10.1016/j.envres.2017.08.037.

Pope, C.A., Coleman, N., Pond, Z.A., Burnett, R.T., 2020. Fine particulate air pollution and human mortality: 25+ years of cohort studies. Environ. Res. 183, 108924 https://doi.org/10.1016/j.envres.2019.108924.

Pope, C.A., Lefler Jacob, S., Ezzati, M., Higbee Joshua, D., Marshall Julian, D., Kim, S.-Y., Bechle, M., Gilliat Kurtis, S., Vernon Spencer, E., Robinson Allen, L., Burnett Richard, T., 2019. Mortality risk and fine particulate air pollution in a large, representative cohort of U.S. Adults. Environ. Health Perspect. 127 (7), 077007 https://doi.org/10.1289/EHP4438.

Poulsen, A.H., Sørensen, M., Hvidtfeldt, U.A., Frohn, L.M., Ketzel, M., Christensen, J.H., Brandt, J., Massling, A., Khan, J., Lassen, C.F., Raaschou-Nielsen, O., 2023a. Air pollution and myocardial infarction; effect modification by sociodemographic and environmental factors. A cohort study from Denmark. Environ. Res. 229, 115905 https://doi.org/10.1016/j.envres.2023.115905.

Poulsen, A.H., Sørensen, M., Hvidtfeldt Ulla, A., Christensen Jesper, H., Brandt, J., Frohn Lise, M., Ketzel, M., Andersen, C., Raaschou-Nielsen, O., 2023b. Source-specific air pollution including ultrafine particles and risk of myocardial infarction: a nationwide cohort study from Denmark. Environ. Health Perspect. 131 (5), 057010 https://doi.org/10.1289/EHP10556.

Pun, V.C., Kazemiparkouhi, F., Manjourides, J., Suh, H.H., 2017. Long-term PM2.5 exposure and respiratory, cancer, and cardiovascular mortality in older US adults. Am. J. Epidemiol. 186 (8), 961–969. https://doi.org/10.1093/aje/kwx166.

Raaschou-Nielsen, O., Thorsteinson, E., Antonsen, S., Holst, G.J., Sigsgaard, T., Geels, C., Frohn, L.M., Christensen, J.H., Brandt, J., Pedersen, C.B., Hvidtfeldt, U.A., 2020. Long-term exposure to air pollution and mortality in the Danish population a nationwide study. eClinicalMedicine 28. https://doi.org/10.1016/j.eclinm.2020.100605.

Rodopoulou, S., Stafoggia, M., Chen, J., de Hoogh, K., Bauwelinck, M., Mehta, A.J., Klompmaker, J.O., Oftedal, B., Vienneau, D., Janssen, N.A.H., Strak, M., Andersen, Z.J., Renzi, M., Cesaroni, G., Nordheim, C.F., Bekkevold, T., Atkinson, R., Forastiere, F., Katsouyanni, K., Hoek, G., 2022. Long-term exposure to fine particle elemental components and mortality in Europe: results from six European administrative cohorts within the ELAPSE project. Sci. Total Environ. 809, 152205 https://doi.org/10.1016/j.scitotenv.2021.152205.

Scottish-Government, 2021. Urban Rural Classification (6-Fold). https://statistics.gov.scot/data/urban-rural-classification.

Scottish Longitudinal Study. https://sls.lscs.ac.uk/. (Accessed 8 November 2021).

So, R., Jørgensen, J.T., Lim, Y.-H., Mehta, A.J., Amini, H., Mortensen, L.H., Westendorp, R., Ketzel, M., Hertel, O., Brandt, J., Christensen, J.H., Geels, C., Frohn, L.M., Sisgaard, T., Bräuner, E.V., Jensen, S.S., Backalarz, C., Simonsen, M.K., Loft, S., Andersen, Z.J., 2020. Long-term exposure to low levels of air pollution and mortality adjusting for road traffic noise: a Danish Nurse Cohort study. Environ. Int. 143, 105983 https://doi.org/10.1016/j.envint.2020.105983.

Sørensen, M., Poulsen, A.H., Hvidtfeldt, U.A., Brandt, J., Frohn, L.M., Ketzel, M., Christensen, J.H., Im, U., Khan, J., Münzel, T., Raaschou-Nielsen, O., 2022. Air pollution, road traffic noise and lack of greenness and risk of type 2 diabetes: a multi-exposure prospective study covering Denmark. Environ. Int. 170, 107570 https://doi.org/10.1016/j.envint.2022.107570.

Stafoggia, M., Oftedal, B., Chen, J., Rodopoulou, S., Renzi, M., Atkinson, R.W., Bauwelinck, M., Klompmaker, J.O., Mehta, A., Vienneau, D., Andersen, Z.J., Bellander, T., Brandt, J., Cesaroni, G., de Hoogh, K., Fecht, D., Gulliver, J., Hertel, O., Hoffmann, B., Janssen, N.A.H., 2022. Long-term exposure to low ambient air pollution concentrations and mortality among 28 million people: results from seven large European cohorts within the ELAPSE project. Lancet Planet. Health 6 (1), e9–e18. https://doi.org/10.1016/S2542-5196(21)00277-1.

Strak, M., Weinmayr, G., Rodopoulou, S., Chen, J., de Hoogh, K., Andersen, Z.J., Atkinson, R., Bauwelinck, M., Bekkevold, T., Bellander, T., Boutron-Ruault, M.-C., Brandt, J., Cesaroni, G., Concin, H., Fecht, D., Forastiere, F., Gulliver, J., Hertel, O., Hoffmann, B., Samoli, E., 2021. Long term exposure to low level air pollution and mortality in eight European cohorts within the ELAPSE project: pooled analysis. BMJ 374, n1904. https://doi.org/10.1136/bmj.n1904.

Vestreng, V., Myhre, G., Fagerli, H., Reis, S., Tarrasón, L., 2007. Twenty-five years of continuous sulphur dioxide emission reduction in Europe. Atmos. Chem. Phys. 7 (13), 3663–3681. https://doi.org/10.5194/acp-7-3663-2007.

Vodonos, A., Awad, Y.A., Schwartz, J., 2018. The concentration-response between long-term PM2.5 exposure and mortality; A meta-regression approach. Environ. Res. 166, 677–689. https://doi.org/10.1016/j.envres.2018.06.021.

Weichenthal, S., Hoppin, J.A., Reeves, F., 2014. Obesity and the cardiovascular health effects of fine particulate air pollution. Obesity 22 (7), 1580–1589. https://doi.org/10.1002/oby.20748.

Wolf, K., Hoffmann, B., Andersen, Z.J., Atkinson, R.W., Bauwelinck, M., Bellander, T., Brandt, J., Brunekreef, B., Cesaroni, G., Chen, J., de Faire, U., de Hoogh, K., Fecht, D., Forastiere, F., Gulliver, J., Hertel, O., Hvidtfeldt, U.A., Janssen, N.A.H., Jørgensen, J.T., Ljungman, P.L.S., 2021. Long-term exposure to low-level ambient air pollution and incidence of stroke and coronary heart disease: a pooled analysis of six European cohorts within the ELAPSE project. Lancet Planet. Health 5 (9), e620–e632. https://doi.org/10.1016/S2542-5196(21)00195-9.

Wood, M., Wood, C., Styring, P., Jones, C.R., Smith, J.K., Day, M., Chakraborty, R., Mensah, G., 2023. Perceptions of accountability and trust in the regulatory governance of wood burning stove sustainability: survey evidence from the post-Brexit UK. Energy Pol. 177, 113549 https://doi.org/10.1016/j.enpol.2023.113549.

Yan, W., Ji, X., Shi, J., Li, G., Sang, N., 2015. Acute nitrogen dioxide inhalation induces mitochondrial dysfunction in rat brain. Environ. Res. 138, 416–424. https://doi.org/10.1016/j.envres.2015.02.022.

Yuchi, W., Sbihi, H., Davies, H., Tamburic, L., Brauer, M., 2020. Road proximity, air pollution, noise, green space and neurologic disease incidence: a population-based cohort study. Environ. Health 19 (1), 8. https://doi.org/10.1186/s12940-020-0565-4.

Zhang, Z., Wang, J., Kwong, J.C., Burnett, R.T., van Donkelaar, A., Hystad, P., Martin, R. V., Bai, L., McLaughlin, J., Chen, H., 2021. Long-term exposure to air pollution and mortality in a prospective cohort: the Ontario Health Study. Environ. Int. 154, 106570 https://doi.org/10.1016/j.envint.2021.106570.