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Long-term exposure to ambient air pollution and the hospital admission burden in Scotland: A 16-year prospective population cohort study

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Title: Long-term exposure to ambient air pollution and the hospital admission burden in Scotland: A 16-year prospective population cohort study

Mary Abed Al Ahad, PhD[1]; Urška Demšar, PhD[1]; Frank Sullivan, FRSE, FRCP, FRCGP[2]; Hill Kulu, PhD[1]

[1] School of Geography and Sustainable Development, University of St Andrews, Scotland, United Kingdom.

[2] School of Medicine, University of St Andrews, Scotland, United Kingdom.

Correspondence should be addressed to
Mary Abed Al Ahad
School of Geography and Sustainable Development,
University of St Andrews,
Scotland, United Kingdom
Email: maaa1@st-andrews.ac.uk

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Ethical considerations: This paper is part of a PhD project that was granted ethical approval on the 14th of May 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.

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Transparency declaration: The corresponding author affirms that this manuscript is an honest, accurate, and transparent account of the study being reported; that no important aspects of the study have been omitted; and that any discrepancies from the study as planned (and, if relevant, registered) have been explained.

Data availability statement: Data underlying this study is confidential and is not publicly available due to ethical and legal restrictions. We are using the "Scottish Longitudinal Study" dataset which contains linked census, vital events, and education data for a five per cent sample of the population of Scotland. These data are protected by a copyright license and only available for licensed researchers in the UK following a detailed application and security checks. Researchers must also pass a Safe Researcher Training which equip them with the needed knowledge and information to analyse data in safe settings. Further information on how to access the SLS data are available on the following web page: https://sls.lscs.ac.uk/

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Title: Long-term exposure to ambient air pollution and the hospital admission burden in Scotland: A 16-year prospective population cohort study

Abstract

Objectives: Air pollution is considered a major threat for global health and is associated with various health outcomes. Previous research on the long-term exposure to ambient air pollution and health has been mostly focused on mortality and is characterised with heterogeneities in the size of effect estimates between studies and a little consideration for pollutants like SO_2 and mental/behavioural or infectious diseases outcomes. In this study, we investigate the association between long-term exposure to ambient air pollution and all-cause and cause-specific hospital admissions.

Design: This is a prospective cohort study.

Setting: Individual-level data from the "*Scottish Longitudinal Study (SLS)*" are linked to yearly concentrations of four pollutants (NO_2, SO_2, PM10, PM2.5) at 1 Km^2 spatial resolution using the individual's residential postcode for each year between 2002 and 2017.

Participants: The study includes 202,237 adult individuals aged 17 and older.

Outcome measures: The associations between air pollution and all-cause, cardiovascular, respiratory, infectious, mental/behavioural disorders, and other-causes hospital admissions are examined using multilevel mixed-effects negative binomial regression.

Results: Higher exposure to NO_2, PM10, and PM2.5 is associated with higher incidence of all-cause, cardiovascular, respiratory, and infectious hospital admissions. The incidence rate for respiratory hospital admissions increased by 4.2% (95%CI=2.1%-6.3%) and 1.2% (95%CI=0.8%-1.7%) per 1 $\mu g/m^3$ increase in PM2.5 and NO_2 pollutants, respectively. SO_2 was mainly associated with respiratory hospital admissions (IRR=1.016; 95%CI=1.004-1.027) and NO_2 was related to higher incidence of mental/behavioural disorders hospital admissions (IRR=1.021; 95%CI=1.011-1.031). Average cumulative exposure to air pollution showed stronger positive associations with higher rates of hospital admissions.

Conclusion: This study supports an association between long-term (16-years) exposure to ambient air pollution and increased all-cause and cause-specific hospital admissions for both physical and mental/behavioural illnesses. The results suggest that interventions on air pollution through stricter environmental regulations could help ease the hospital-care burden in Scotland in the long-term.

Keywords: Air pollution, hospital admissions, long-term, cardio-respiratory, mental disorders, Scottish Longitudinal Study.

Strengths and limitations of this study

- This study utilises 16 years (2002-2017) of administrative prospective cohort individual-level data from Scotland and links it to high-resolution 1 km^2 air pollution data at the residential postcode to investigate the association between long-term exposure to air pollution and all-cause and cause-specific hospital admissions, focusing on admissions related to physical illness such as cardiovascular, respiratory, and infectious diseases as well as on mental and behavioural disorders.
- This study attempted to develop previous research by contributing to the existing evidence on air pollution and health through the examination of multiple air pollutants (i.e., NO_2, SO_2, PM10, and PM2.5) in relation to multiple hospital admission outcomes over prolonged period of time.
- The limitations of this study included following individuals for 16 years starting the year of 2002; thus, bias may result from earlier life-time exposures to air pollution.
- The assessment of air pollution exposure was done at the place of residence. However, individuals are exposed to air pollution not only at the place of residence, but also at the workplace, during daily outdoor activities, and through commuting patterns.
- We could not account for some important lifestyle covariates (e.g., smoking, alcohol consumption, and exercise) due to the unavailability of this information in administrative data.

1. Introduction

Air pollution is considered by the World Health Organisation as one of the largest environmental health risks in the 21st century [1]. Air pollution results in poor health and in increased hospital admissions, mortality, and doctor visits, mostly for cardiovascular, respiratory, and cancer diseases [2-8]. For example, in Italy, long-term exposure to NO_2 (nitrogen dioxide) and PM2.5 (particulate-matter diameter ≤2.5 µm) was associated with increased hospital admissions for circulatory diseases, myocardial infarction, lung cancer, kidney cancer, and lower-respiratory tract infections [9]. Results from the "Effects of Low-Level Air Pollution: A Study in Europe (ELAPSE)" project have shown elevated asthma, chronic obstructive pulmonary disease (COPD), and stroke incidence with higher long-term exposure to NO_2, PM2.5, and black carbon pollutants [10-12], and elevated lung cancer incidence with higher exposure to PM2.5 [13]. Similarly, the Danish "Health Effects of Air Pollution Components, Noise and Socioeconomic Status (HERMES)" project found an association between long-term exposure to PM2.5 and higher risks of stroke and myocardial infarction [14-16], and between NO_2 pollutant and higher diabetes risk [17]. A similar story was also shown with short-term exposures to PM10 (particulate-matter diameter ≤10 µm) and PM2.5 pollutants and increased respiratory hospital admissions in Poland [18].

Although the association between long-term exposure to air pollution and health is well-documented, most research is focused on mortality outcomes [4 7 19-32]. This is because of the ease of access to mortality databases, the less strict ethical considerations, and the straightforward analysis of mortality that occurs only once in the individual's life [2].

Studies that investigate the association between long-term air pollution and health outcomes other than mortality often estimate a combined risk of mortality with the other health indicators such as hospital admissions or doctoral prescriptions and focus only on analysing the first hospital admission [12 14 16]. Besides, variations in the magnitude of effect estimates among studies have been identified in numerous systematic literature reviews and meta-analyses [2 33-36]. These discrepancies may be attributed to differences in the assessment of air pollution exposure, such as residential versus combined residential and workplace assessments, high versus low spatial resolution, or baseline versus annual assessments. Other contributing factors include variations in exposure levels, outcome measurements, study locations, population characteristics (e.g., age, sex, socioeconomic status), and study methodologies [35 36]. The differences in estimates also underscore the necessity for further research to obtain more conclusive evidence regarding the association between air pollution and health.

Additionally, over the past decade, the majority of literature has concentrated on investigating the health implications of NO_2, PM10, and PM2.5 exposure, with limited attention given to other pollutants like sulphur dioxide (SO_2) [2 23 35]. This lack of emphasis on SO_2 may be attributed to a substantial decrease in its emissions, driven by the diminished use of coal in the energy sector and the desulfurization efforts in cars and power plants in developed nations [37]. Consequently, SO_2 has become a lower priority compared to other pollutants. Nonetheless, investigating the link between prolonged exposure to SO_2 and health outcomes, such as hospital admissions, remains crucial as even at reduced levels, SO_2 can still pose harm to human health [37].

Finally, despite the literature availability on air pollution in relation to cardiovascular and respiratory diseases [2 3], other health complications such as mental/behavioural disorders have not been thoroughly studied [38 39]. A recent study has also found an association between short-term exposure to PM2.5 and hospital admissions for rarely studied infectious diseases such as sepsis, kidney failure, urinary tract and skin infections [40]. This suggests the need for more studies that investigate the association between air pollution and less studied health outcomes such as infectious diseases and mental/behavioural disorders.

Taken collectively, this study examines the association between long-term exposure to air pollution and all-cause and cause-specific hospital admissions. We distinguish between hospital admissions related to cardiovascular, respiratory, infectious, mental/behavioural disorders, and other illnesses. In examining these associations, we will be relying on administrative longitudinal individual-level data from a large Scottish cohort that will be linked to yearly 1 km^2 air pollution data using the individuals' residential postcodes for each year between 2002 and 2017. Our study attempts to develop previous research by contributing to the existing evidence on air pollution and health through the examination of multiple air pollutants (i.e., NO_2, SO_2, PM10, and PM2.5) in relation to multiple hospital admission outcomes over time.

2. Methods

2.1. Design, sample, and structure

We used individual-level longitudinal prospective-cohort data from the Scottish Longitudinal Study (SLS). This is a representative dataset on 5% of the Scottish population which includes information from three linked censuses (1991, 2001, 2011) on individuals' socio-demographics, vital events records on marriages, births, and mortality (up to 2013), and migration and residential histories at the postcode level [7]. To supplement SLS mortality data after 2013 through 2017, data on the individuals' year and month of death were obtained from Public Health Scotland (PHS) via Electronic Data Research and Innovation Service (eDRIS) [7].

For this study, we followed 202,237 individuals aged 17^+ with a total of 2,810,414 person-years between 2002 and 2017. Initially, information was sought for all identified individuals in the SLS aged 16 and above during the 2001 census (totalling 205,732 individuals). However, 36 individuals were excluded due to the absence of gender data, and 1,127 individuals (constituting 0.55%) were excluded due to missing postcode history. We also dropped 2001 observations (n=204,569) due to missing data on deaths that occurred prior to the census date (April 2001), which made 2001 death rate incomparable to the death rates at later years [7]. The SLS cohort structure and the possibilities of entering and exiting the study between 2002 and 2017 are illustrated in a Lexis-diagram (Figure 1).

2.2. Variables

2.2.1. Hospital admissions

The month, year, and main underlying cause of hospital admissions were obtained from PHS and linked to SLS data by eDRIS using the individual's unique identification number. We then calculated the yearly count of all-cause and cause-specific hospital admissions for each SLS individual. Individuals who did not go to the hospital in a certain year were given a count of zero. The International Statistical Classification of Diseases, 10th Revision (ICD-10) codes of the main underlying cause of hospital admission were used to determine the cause-specific outcomes (Supplementary material Table 1) as follows: cardiovascular (I00-I99), respiratory (J00-J99), infectious (A00-B99), and mental/behavioural disorders (F00-F99).

2.2.2. Air pollution

Annual air pollution data encompassing all sources, including road traffic and industrial/combustion processes for NO_2, SO_2, PM10, and PM2.5, was acquired from the "Department for Environment Food and Rural Affairs (DEFRA)" [41]. These data consist of raster representations indicating the average annual concentrations of pollutants measured in $\mu g/m^3$. Air dispersion models were utilized to estimate these concentrations at a spatial resolution of 1 Km^2 on the UK National Grid [41]. These data were in turn linked to postcodes in Scotland obtained from the National Records of Scotland that fell within the 1 Km^2 raster cells for each year between 2002 and 2017. Figure 2 describes 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 annual air pollution concentrations with postcodes with the data file of SLS residential postcode histories. Where individuals changed residential postcodes during a certain year, the postcode with the lengthiest monthly duration within that year was the one used [7].

2.2.3. Study covariates

The association between air pollution and hospital admissions is influenced by several factors: (1) socioeconomic (e.g. age, gender, income, education, occupation, ethnicity, country of birth, economic activity) [2 8 42]; (2) individual-lifestyle (e.g. pre-existing diseases, smoking, alcohol consumption, exercise, obesity) [8 43]; (3) contextual (e.g. neighbourhood, deprivation, rural-urban classifications) [43 44]; and (4) environmental (e.g. season, temperature, humidity, rainfall, wind) [45].

Accordingly, the following individual-level baseline socioeconomic covariates collected at the 2001 and 2011 censuses were included in our study: age, squared age (age^2; to account for possible non-linear age effects), gender, ethnicity, country of birth, marital status, education, and occupation (Supplementary material Table 2). We additionally included a yearly-varying place of residence variable that classifies the individuals' residential postcodes into six rural-urban categories, based on the data-zone where the postcode is located. Calendar year dummies were also included for each year between 2002 and 2017 to control for the time trend.

2.3. Analysis

All-cause and cause-specific hospital admission counts, socioeconomic and place of residence covariates were described using frequencies, percentages, means, and variances. The mean and correlation between the four pollutants were also calculated. Given the high correlations between NO_2, PM10, and PM2.5 (Pearson's coefficient ≥ 0.7), the association of the four pollutants with all-cause and cause-specific hospital admissions was assessed in separate models. SO_2 showed weak correlations (Pearson's coefficient <0.5) with the other pollutants, which enabled us to assess in a sensitivity analysis the association between NO_2, PM10, and PM2.5 and hospital admissions in two-pollutant models adjusting for SO_2.

We used multilevel mixed-effects negative binomial regression with a random intercept for individuals to study the association between air pollution and all-cause and cause-specific (cardiovascular, respiratory, infectious, mental/behavioural disorders, and other-causes) hospital admissions. The negative binomial model was used because around 85% of annual individual observations did not include an admission into a hospital (a skewed distribution with a high number of zeros). Therefore, the variance of the count of hospital admissions is greater than the mean (Table 1), and the overdispersion parameter (α) for all hospital admission outcomes is greater than zero (Supplementary material Tables 4-9). This makes the negative binomial regression that can account for overdispersion in hospital admission counts more appropriate than Poisson regression [46]. In a sensitivity analysis, we treated the hospital admission outcomes as binary variables (0=Not admitted to hospital; 1=Admitted to hospital) and used multilevel mixed-effects logistic regression for analysis.

Three stepwise models were developed: Model 1 included the air pollution independent variable and controlled for age, age^2, gender and calendar year dummies; Model 2 controlled additionally for ethnicity, country of birth, marital status, education, and occupation; and Model 3 included the place of residence covariate.

The association of all-cause and cause-specific hospital admissions with the socioeconomic and place of residence covariates is shown in Supplementary material Tables 4-15. Results of the multilevel negative binomial regression are presented as incidence rate ratios (IRRs) with 95% confidence intervals (CIs) per 1 $\mu g/m^3$ increase in pollutants and visualised in coefficient plots. Statistical significance is at a p-value of less than 0.05. Statistical analysis was conducted in $STATA_{16}$. Coefficient plots using ggplot package were performed in R Studio. Spatial pre-processing was conducted in ArcGIS-Pro software.

2.3.1. Additional analysis

To assess the impact of cumulative air pollution (CAP) exposure from year to year and across the different places of residence between 2002 and 2017, we repeated models 1 to 3 replacing the yearly air pollution variable with average CAP exposure. Following the methods of Bentayeb et al. (2015) [47], the CAP variable was calculated as the average of cumulative yearly exposure before censoring or death. Thus, for every individual, we computed the mean pollutant concentration from the baseline year (2002) to each year of follow-up (e.g., exposure in 2004 was calculated as the average of annual concentrations from 2002 to 2004; in 2005, from 2002 to 2005, etc).

2.4. Ethics

On May 14th, 2020, ethical clearance was obtained from the Ethics Committee of the University of St Andrews. Approval for accessing SLS data was granted by the SLS board, and access to linked data from PHS was authorized through the application to the Public Benefit and Privacy Panel for Health and Social Care (HSC-PBPP). Consent was not deemed necessary for this study as it relied on secondary data analysis. The tasks of data cleaning, management, and analysis were conducted within the secure settings of the SLS. Final outputs were cleared following a thorough screening protocol. Information classified as potentially disclosive such as full dates of birth, death and hospital admissions were not given for analysis. Instead, the researcher had access to the month and year of those events.

3. Results

3.1. Hospital admissions description

Around 15% of person-years involved an admission into a hospital. The mean of all-cause hospital admissions was 0.3 (variance=1.6) with 8.6% of yearly individual observations including one hospital admission, 2.9% including two admissions, and 3.5% including 3 or more admissions. The mean of cardiovascular, respiratory, infectious, mental/behavioural disorders, and other-causes hospital admission count was 0.04 (variance=0.14), 0.03 (variance=0.1), 0.005 (variance=0.01), 0.003 (variance=0.01), and 0.26 (variance=1.18), respectively (Table 1).

3.2. Study covariates description

Most individuals were females (53%), belonged to white ethnicity (~95%), were born in Scotland (~87%), were married (~55%), had a post-school/university education (24% in 2002-2010; 34% in 2011-2017), worked in white collar high skilled (27% in 2002-2010; 33% in 2011-2017) or white collar low skilled (25% in 2002-2010; 29% in 2011-2017) jobs, and lived in large urban (35%) areas (Table 2).

3.3. Air pollution description

Fluctuations in air pollutant levels were observed across the years 2002 to 2017, with higher concentrations recorded in the initial three years (2002-2004) compared to subsequent years (Supplementary material Figure 1). Over the period from 2002 to 2017, the mean 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 (Supplementary material Table 3).

Significant correlations (Pearson's coefficient $\geq$ 0.7) were observed among NO_2, PM10, and PM2.5, potentially attributed to the atmospheric chemical reactions involving these pollutants (Supplementary material Table 3).

3.4. The association of air pollution with hospital admissions

Results revealed higher incidence of all-cause hospital admissions per 1 μg/m^3 increase in NO_2 (Model 2: IRR=1.005, 95%CI=1.004-1.006) and PM2.5 (Model 2: IRR=1.005, 95%CI=1.000-1.010) pollutants (Figure 3). Higher incidence rate ratios for cardiovascular (except for model 3), respiratory, and infectious hospital admissions were also shown with increasing concentrations of NO_2, PM10 (except for model 3) and PM2.5 pollutants. After adjusting for socioeconomic variables and place of residence (model 3), the incidence rate for respiratory hospital admissions increased by 4.2% (95%CI=2.1%-6.3%) and 1.2% (95%CI=0.8%-1.7%) per 1 μg/m^3 increase in PM2.5 and NO_2, respectively. Higher exposure to SO_2 was associated with higher rates of respiratory hospital admissions only in models 1 and 2. Hospital admissions for mental/behavioural disorders were associated with higher exposure to NO_2 (IRR=1.021; 95%CI=1.011-1.031). Contrary to our expectations, higher exposure to SO_2 was associated with lower incidence rates for all-cause, mental/behavioural disorders, and other-causes hospital admissions in models 2 and 3 (Figure 3).

In a sensitivity analysis considering hospital admissions as binary (yes/no) outcomes, we observed similar results whereby a higher exposure to NO_2, PM10, and PM2.5 pollutants was associated with higher odds of cardiovascular, respiratory, and infectious hospital admissions. An exception was the absence of an association between NO_2 and PM2.5 pollutants and all-cause hospital admission treated as a binary (yes/no) outcome (Supplementary material Figure 4). Similar results were observed in two-pollutant models, which include SO_2 and one of the other three pollutants in the same model (Supplementary material Figures 2 and 5).

3.4.1. Average CAP results

Stronger positive associations were noticed in the analysis of average CAP effect on hospital admissions compared to the analysis of yearly air pollution effects. Higher average CAP concentrations for NO_2, PM10, and PM2.5 pollutants were associated with higher incidence rate ratios for all-cause, cardiovascular, respiratory, infectious, mental/behavioural disorders, and other-causes hospital admissions. Cumulative exposure to SO_2 was associated with higher rates of respiratory hospital admissions in all three models. The incidence rate for respiratory hospital admissions increased by 12.6% (95%CI=9.9%-15.5%), 6.8% (95%CI=5.1%-8.5%), 2.8% (95%CI=1.1%-4.6%), and 2.1% (95%CI=1.7%-2.6%) per 1 μg/m^3 increase in average cumulative exposure to PM2.5, PM10, SO_2 and NO_2 pollutants, respectively. Higher cumulative exposure to SO_2 is not associated anymore with a lower incidence of mental/behavioural disorders hospital admissions (Supplementary material Figure 3). Similar results were noted when hospital admissions were treated as binary (yes/no) outcomes (Supplementary material Figure 6). This shows that long-term average cumulative exposure to air pollution has a greater effect on both physical and mental health outcomes, resulting in higher rates of hospital admissions.

4. Discussion

This study used a large and representative census-based individual-level cohort data linked to 1 km^2 resolution air pollution at the postcode level between 2002 and 2017. Analysis supported an association between long-term exposure to NO_2, SO_2, PM10 and PM2.5 pollutants and higher rates of all-cause, cardiovascular, respiratory, infectious, mental/behavioural disorders, and other-causes hospital admissions. The direction of these positive associations is concordant with previous studies investigating the long-term effects of different air pollutants on all-cause

[8 48 49], cardiovascular [9 12 16 48], respiratory [9-11 49], and mental/behavioural disorders [50] hospital admissions.

Given the differences in population size, study location, air pollution exposure assessment and level, outcomes measurement, and methodology, we cannot compare directly the magnitude of our estimates to the estimates from other studies. Rather, we can conclude that our findings are in line with what previous literature has suggested with some noted heterogenieties. Some of these heterogenities might be due to residual confounding from unobserved factors. For example, our models adjusted only for socio-demographic and economic factors of individuals (e.g., age, squared age, gender, education, marital status, ethnicity, country of birth, and occupation), as well as for the time trend (i.e., year dummies) and place of residence (i.e., rural-urban area classifications). However, lifestyle covariates at the individual level, such as smoking, exercise, alcohol consumption, or body mass index, which could influence the relationship between air pollution and hospital admissions, were not considered due to their unavailability in the SLS register-based data. Accounting for these lifestyle covariates could result in a slight adjustment of association estimates, typically within the range of a 1–2% increase or decrease, depending on the specific outcome, as indicated by other studies [4 6 25 51-53]. Similarly, our models did not incorporate environmental factors at the place of residence, such as noise pollution or the absence of green spaces. However, the impact on association magnitudes is anticipated to be minimal, with estimates showing a marginal attenuation of 0-3% increase or decrease, as documented in previous studies [17 53 54]. The adjustment of our models for the individual-level socioeconomic and rural-urban covariates might also absorb some of the residual confounding due to the interconnections between the individuals' socioeconomic circumstances, their lifestyle, and their surrounding environment.

As for the positive association between long-term exposure to NO_2, PM10, and PM2.5 and infectious hospital admissions, the literature on this outcome is scarce. Yet, one study examining the association between short-term exposure to PM2.5 air pollution and hospital admissions for infectious diseases such as sepsis, urinary tract and skin infections corroborate our findings [40].

Our study showed that yearly exposures to different air pollutants can be associated with different hospital admission outcomes. For example, NO_2 was associated with all hospital admission outcomes, SO_2 was related to respiratory hospital admissions, while PM10 and PM2.5 were associated with respiratory and infectious hospital admissions. This could be related to the mechnisims of action of specific pollutants in producing toxic effects. Gaseous pollutants (e.g., NO_2 and SO_2) are irritants of the respiratory system that can penetrate deep in the lungs inducing respiratory irritation, mucus production, coughing, wheezing, bronchoconstriction, airways inflammation, bronchospasm and pulmonary-edema [2 55 56]. Long-term exposure to NO_2 is also related to the weakening of the immune system and to cardiovscular problems such as ventricle hypertrophy [55]. Additionally, NO_2 exposure can trigger neuronal injury and neurological disorders through the formation of Reactive Oxygen Species (ROS) and free radicals [57 58].

Despite the harmful effect of gaseous air pollutants (e.g., NO_2 and SO_2) on health, particulate-matter especially particles with smaller diameters (e.g. PM2.5) have the greatest effect as shown in our study and particularly on respiratory health. Particulate matter can penetrate deeply into the respiratory system through air breathing reaching alveoli and blood stream. This will initiate the oxidative stress mechanism and the production of ROS affecting various systems in the human body including the respiratory, cardiovascular, immune, and neural systems [2 55 56].

We also observed elevated estimates for average cumulative compared to yearly air pollution exposures in relation to hospital admissions, particularly in relation to mental and behavioural disorders admissions. Whilst yearly exposure to SO_2 showed an unexpected negative association with mental/behavioural disorders hospital admissions, average cumulative exposure to SO_2 did not show this association. Higher exposure to cumulative PM10 and PM2.5 pollutants was also associated with a higher incidence of mental/behavioural disorders hospital admissions, while this association was not observed for yearly PM10 and PM2.5 exposures. This shows that the average accumulation of air pollution exposures across time and through different places of residence has a greater effect on health, especially for mental and behavioural complications that take time to show-up.

Finally, adjusting our analysis for the place of residence (model 3), reduced the magnitude of associations between hospital admission outcomes and all the four pollutants. This 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 illness. For example, air pollution emission sources are more abundant in urban areas and factors that can absorb the air pollution emissions (e.g., green spaces) are less available. Confirming to this, Figure 2 shows higher concentrations of traffic-related (i.e., NO_2) and industrial (i.e., SO_2) air pollution in the urban Central Belt of Scotland and in large cities. Figure 2 also shows high concentrations of PM10 and PM2.5 in major cities and along the east coast because particulate-matter pollution originates from both traffic and industrial sources and can travel for long distances based on the wind direction and other metereological and topological factors [59-61].

Despite the strengths of this study, it has some limitations. First, individuals were followed for 16 years (2002-2017); thus, bias may result from previous life-time exposures to air pollution at different residences. As shown in our analysis, average CAP exposure across the 16 years of study period had a greater effect on hospital admission rates compared to yearly exposures, particularly for mental/behavioural disorders.

Second, the individuals' exposure to ambient air pollution was assessed at a yearly rather than monthly or daily basis which did not allow for seasonal variations, and the residential postcode was used as a proxy for the individual's exposure to air pollution. This does not necessarily equate to the true personal exposure, which can happen indoors, at the workplace, during daily outdoor activities, and through commuting patterns. Yet, the emergence of real-time GPS data would create an opportunity for future research to analyse real-time exposure to ambient air pollution by knowing the real-time location of individuals.

Finally, we could not account for some important lifestyle covariates (e.g., smoking or exercise) as discussed previously due to the unavailability of this information in the SLS census-based data. However, using administrative data has its advantages including high quality large representative data, less selection bias, and the provision of continuous longitudinal information on residential postcode histories, emigrations and immigrations, and mortality and births vital events. Knowing the exact postcode histories of individuals between

2002 and 2017 as provided in the SLS census-based data was also essential to obtain accurate assessments of individual's residential air pollution exposure.

5. Conclusion

This study supported an association between long-term exposure to air pollution and all-cause and cause-specific hospital admissions. Air pollution was associated with higher rates of hospital admissions for both physical (e.g., respiratory, cardiovascular, and infectious) and mental/behavioural diseases. Policies and interventions on air pollution through stricter environmental regulations, long-term planning, and the shifting toward renewable energy could eventually help ease the hospital-care burden in Scotland in the long-term.

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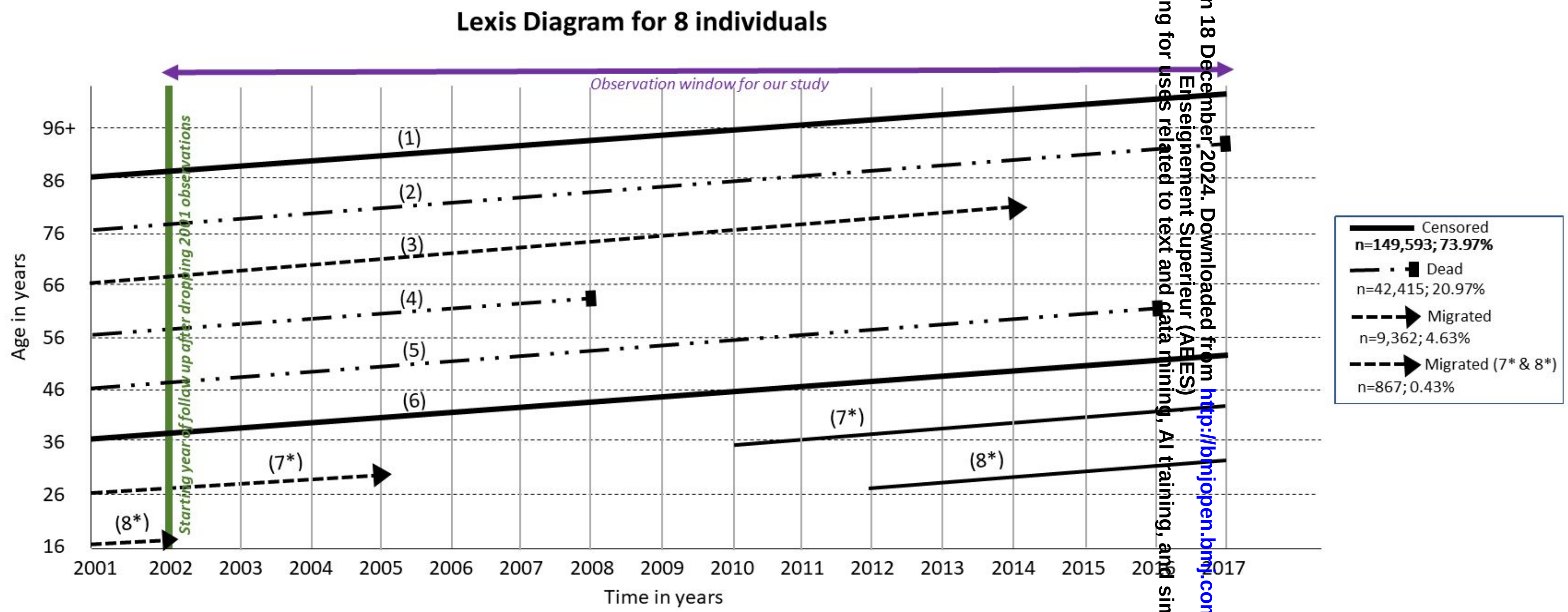
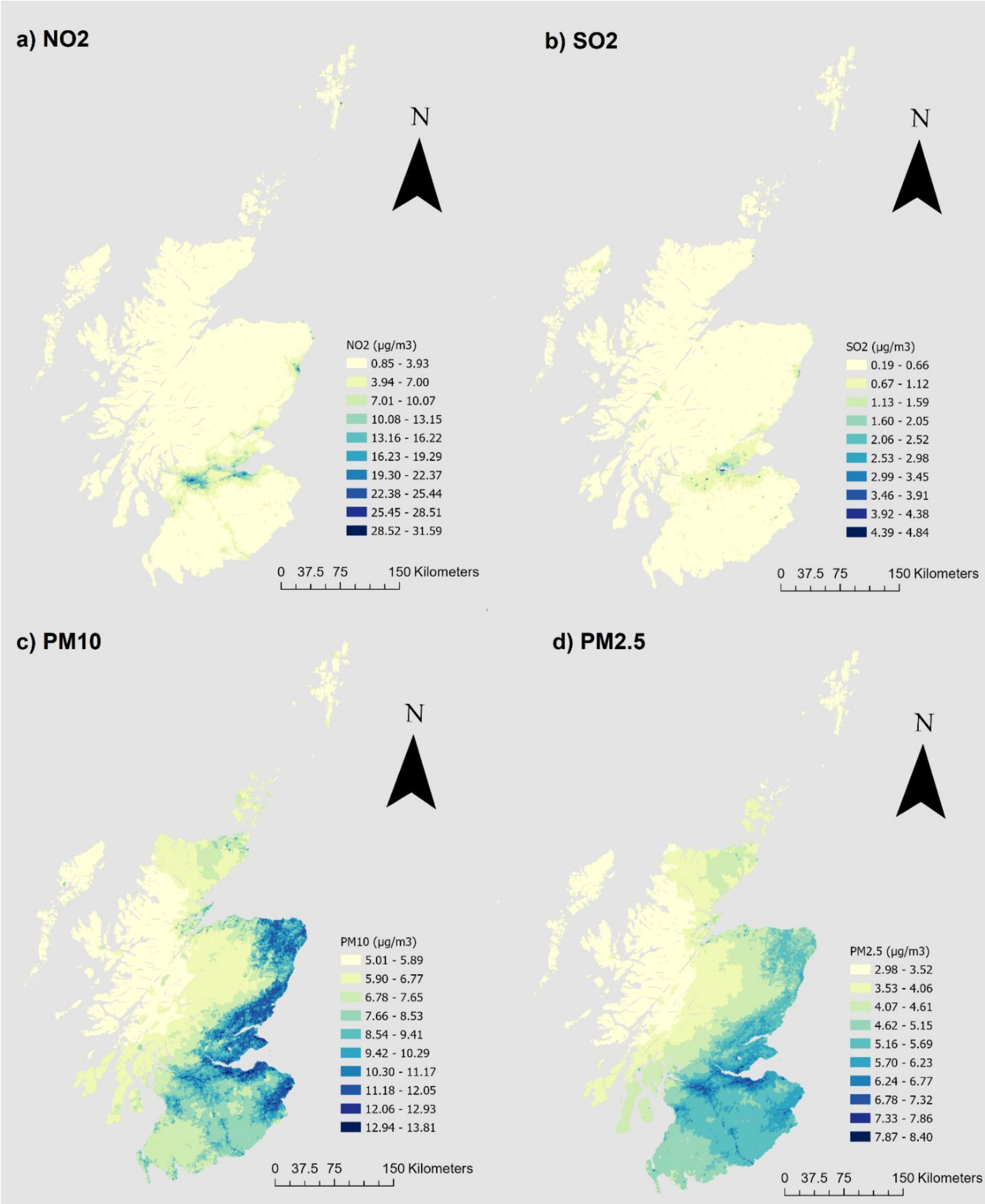
Figure 1: Possibilities of entering and exiting the cohort for 8 hypothetical individuals demonstrated in a Lexis-diagram.



Numbers and percentages in the diagram key are the author's own calculations based on the Scottish Longitudinal Study data. The green vertical line represents the starting year of follow-up (2002) after dropping the 2001 observations; Individuals can either be followed-up until the last year of observation which is 2017 where they are censored (e.g., individuals 1 and 6), or can die (e.g., individuals 2, 4, and 5), or can migrate without returning to Scotland during the observation period 2002-2017 (e.g., individual 3), or can migrate and then return to Scotland and thus to our study within the follow-up period (e.g., individuals 7 and 8). In this context, individual 7 is being followed between 2002 and 2005 and then between 2010 and 2017, inclusive. The years spent by individual 7 outside Scotland (2006-2009) due to migration are dropped from the analysis. A similar situation is experienced by individual 8 who was present in 2002 and then was followed from 2012 to 2017 with years spent abroad (2003-2011) due to migration being removed from the analysis. This lexis diagram further reveals that individuals can enter and exit the cohort based on four scenarios. First, individuals can be followed for the whole study period (2002-2017) and then either be censored, migrate, or die in 2017. Second, individuals can exit the cohort before 2017 due to death at any year during the follow-up period (2002-2017). Third, individuals can exit the cohort due to migration out of Scotland, without returning during the follow-up time (2002-2017). Fourth, individuals can exit the cohort due to out migration, but then they re-enter the cohort in later years due to returning to Scotland within the follow-up time (2002-2017). If individuals migrate out of Scotland and then return in the same year, this short-term migration is disregarded because the individual stayed in Scotland for some months of the full calendar year. If an individual comes back to Scotland from a previous year migration and then migrates out again within the same year, the individuals' observation for that year is kept because some months out of the full calendar year have been spent in Scotland.

Figure 2: Four maps illustrating the 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 [41] and postcode boundaries shapefiles obtained from the National Records of Scotland. Both DEFRA and National Records of Scotland shapefiles are governed under the Open Government Licence v.3.0.

Table 1: Description of hospital admissions (N=2,810,414 observations)

	Frequency	%	Mean	Variance
All-cause hospital admission			0.33	1.64
0	2388584	85		
1	241717	8.6		
2	80813	2.9		
3+	99300	3.5		
Cardiovascular hospital admission			0.04	0.14
0	2753992	98		
1	29432	1.1		
2	13091	0.5		
3+	13899	0.5		
Respiratory hospital admission			0.03	0.10
0	2773192	98.7		
1	19685	0.7		
2	9538	0.3		
3+	7999	0.3		
Infectious hospital admission			0.005	0.01
0	2802217	99.7		
1	5174	0.2		
2	1937	0.1		
3+	1086	0.04		
Mental/behavioural disorders hospital admission			0.003	0.01
0	2804737	99.8		
1	3521	0.1		
2	1263	0.04		
3+	893	0.03		
Other-causes hospital admission			0.26	1.18
0	2448665	87.1		
1	225980	8.0		
2	66976	2.4		
3+	68793	2.5		

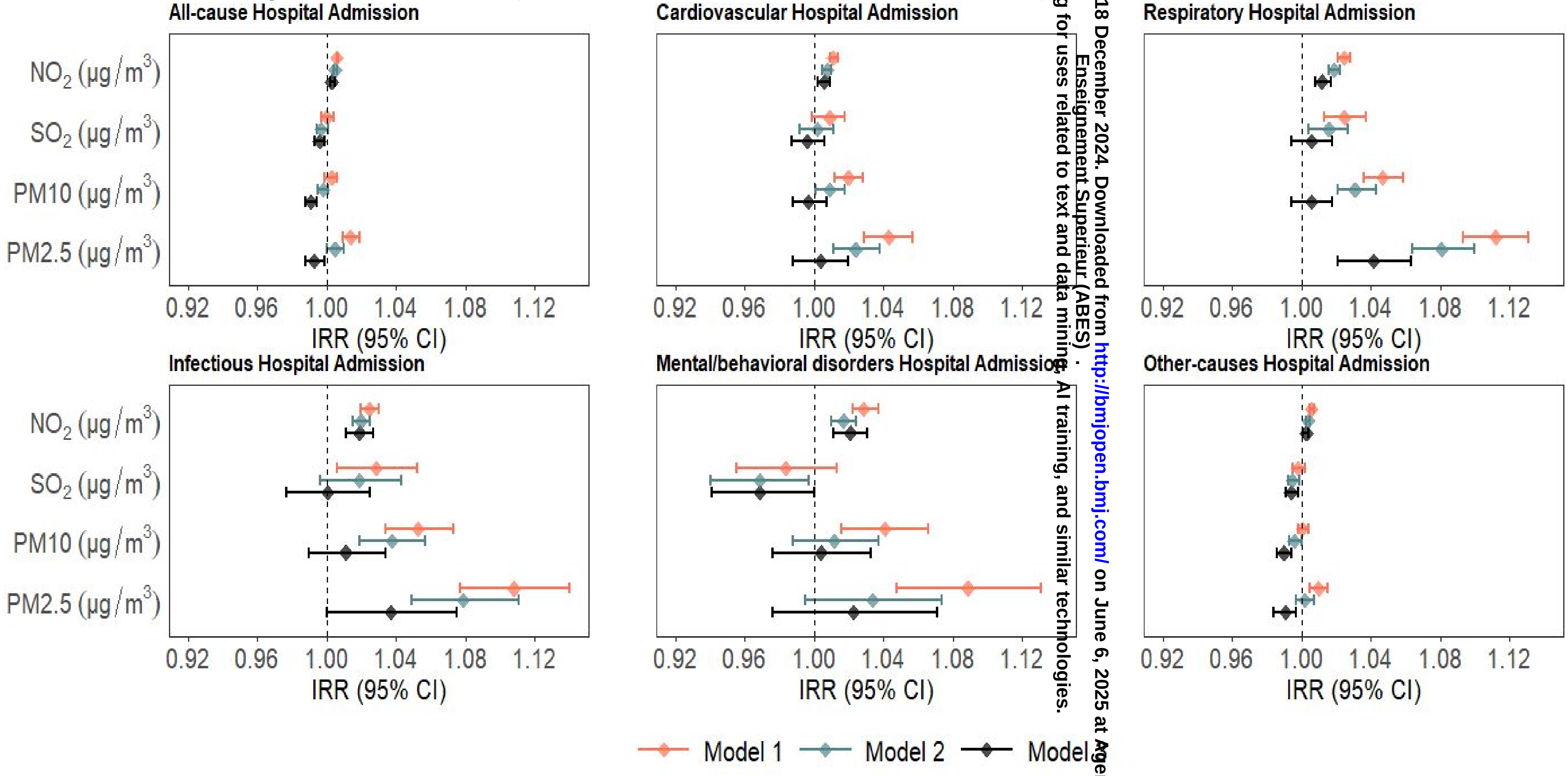
Data source: Author's own calculations based on the Scottish Longitudinal Study data.

Table 2: Description of socioeconomic study covariates

		Census-fixed socioeconomic covariates (N=202,237 individuals)			
		2002-2010		**2011-2017**	
		Frequency	**%**	**Frequency**	**%**
Gender	Male	94859	46.9	80282	46.9
	Female	107314	53.1	90753	53.1
Ethnicity	White	192485	95.2	163571	95.6
	Not-white	9688	4.8	7464	4.4
Ethnicity-3 categories	White	192485	95.2	163571	95.6
	Pakistani/Bangladeshi/Indian	1525	0.8	1323	0.8
	Other ethnicities	8163	4.0	6141	3.6
Country of birth	Born in Scotland	173229	85.7	149018	87.1
	Born in rest of UK	19649	9.7	15340	9.0
	Not born in UK	9295	4.6	6677	3.9
Marital Status	Married	104386	51.6	93867	54.9
	Single never married	58396	28.9	38979	22.8
	Divorced/separated/widowed	38481	19.0	37770	22.1
	No response	910	0.5	419	0.2
Education	No educational qualification	60311	29.8	53223	31.1
	Intermediate school	44854	22.2	36561	21.4
	High school	27844	13.8	20343	11.9
	Post-school/university	48251	23.9	58781	34.4
	Still a student	688	0.3	53	0.0
	No response/not recoded	20225	10.0	2074	1.2
Occupation	White collar high skilled	54299	26.9	55595	32.5
	White collar low skilled	50325	24.9	49202	28.8
	Blue collar high skilled	20530	10.2	20500	12.0
	Blue collar low skilled	46718	23.1	38173	22.3
	Not applicable: students/never worked	25535	12.6	5793	3.4
	No response	4766	2.4	1772	1.0
Total		202173	100	171035	100
		Yearly varying covariates (N=2,810,414 observations)			
Age		Mean=52.53	SD=17.57		
		Frequency	**%**		
Place of residence	Large Urban areas	977697	34.8		
	Other urban areas	815048	29.0		
	Accessible small towns	207083	7.4		
	Remote small towns	67776	2.4		
	Accessible Rural areas	528929	18.8		
	Remote rural areas	213881	7.6		

Data source: Author's own calculations based on the Scottish Longitudinal Study data.

Figure 3: The association of all-cause and cause-specific hospital admissions with NO_2, SO_2, PM10, and PM2.5 air pollutants in separate multilevel mixed-effects negative binomial models (N=202,237 individuals and 2,810,414 observations).



Data source: Author's own calculations based on the Scottish Longitudinal Study data; The dashed line is placed at IRR=1 as a cut-off for statistically insignificant results; Model 1 is adjusted for age, age^2, gender and calendar year dummies; Model 2= Model 1 + ethnicity + country of birth + marital status + education + occupation; Model 3= Model 2 + place of residence.

Supplemental Material

Contents

ICD-10 codes for classification of the main cause of hospital admissions

Table 1: Classification of the cause-specific hospital admission outcomes based on the ICD-10 codes of the main underlying cause of hospital admission

Cause-specific hospital admission outcomes	**ICD-10 codes of the main underlying cause of hospital admission**
Cardiovascular	I00-I99
Respiratory	J00-J99
Infectious	A00-B99
Mental and behavioural disorders including dementia, mental retardation, schizophrenia, schizotypal, delusional disorders, mood disorders, neurotic, stress-related and somatoform disorders, and mental and behavioural disorders due to psychoactive substance use and alcohol	F00-F99
Other causes hospital admission	All other causes of hospital admission excluding cardiovascular, respiratory, infectious, and mental/behavioural disorders causes

ICD-10 codes are accessed from the WHO. (2016). International Statistical Classification of Diseases and Related Health Problems 10th Revision. https://icd.who.int/browse10/2016/en

Socioeconomic and contextual covariates description

Table 2: Description of the socioeconomic and contextual covariates included in the study

Covariates	Description
Age	Age was calculated using the individuals' month and year of birth as per the below equation. For example, if an individual is born in June (month=06) 1982, he/she will be given the age of 19.5 at the beginning of the year 2002 and will age by one year with each additional year of follow-up. $Age_i = Year_{2002-2017} - (M\ birth_i \times (1 \div 12) + Y\ birth_i)$ Where Age_i is the individual's age; $Year_{2002-2017}$ is the year of follow-up ranging between 2002 and 2017; $M\ birth_i$ is the month of birth for individual i; and $Y\ birth_i$ is the year of birth for individual i.
Age^2	We also considered the possible non-linear effect of individuals' age and introduced a square term of age as an additional covariate following the approach of other researchers (Liu et al., 2021; Pereira Gray et al., 2017).
Gender	1=male; 2=female
Ethnicity	1=White; 2=Not-white
Country of birth	1=born in Scotland; 2=born in rest of UK; 3=born outside UK
Marital status	1=married; 2=single never married; 3=divorced/separated/widowed; 4=No response
Education	1=No educational qualification; 0=Intermediate school [reference category]; 2=High school qualification; 3=Post-school/university; 4=Still a student; 5=Not recoded/No response
Occupation	1=White collar high skilled: Managers, professionals, Associate professionals; 2=White collar low skilled: Administrative, service, care and shop sales; 3=Blue collar high skilled: Skilled trades occupations; 4=Blue collar low skilled: Process, Plant, Machine operatives and elementary occupations; 5=Not applicable: students/never worked; 6=No response
Place of residence	1=Large Urban areas: Settlements of 125,000 people and over; 2=other urban areas: Settlements of 10,000 to 124,999 people; 3=Accessible small towns: Settlements of 3,000 to 9,999 people, and within 30 minute drive time of a Settlement of 10,000 or more; 4=Remote small towns: Settlements of 3,000 to 9,999 people, and with drive time of over 30 minutes to a Settlement of 10,000 or more; 5=Accessible Rural areas: Areas with a population of less than 3,000 people, and within 30 minute drive time of a Settlement of 10,000 or more; and 6=Remote rural areas: Areas with a population of less than 3,000 people, and with drive time of over 30 minutes to a Settlement of 10,000 or more (Scottish-Government, 2021).

Citations:

Liu, Y., Zhu, K., Li, R.-L., Song, Y., & Zhang, Z.-J. (2021). Air Pollution Impairs Subjective Happiness by Damaging Their Health. *International journal of environmental research and public health*, *18*(19), 10319. https://doi.org/10.3390/ijerph181910319

Pereira Gray, D., Henley, W., Chenore, T., Sidaway-Lee, K., & Evans, P. (2017). What is the relationship between age and deprivation in influencing emergency hospital admissions? A model using data from a defined, comprehensive, all-age cohort in East Devon, UK. *BMJ Open*, *7*(2), e014045. https://doi.org/10.1136/bmjopen-2016-014045

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

Description of air pollution

Figure 1: The average exposure to NO_2, SO_2, PM10, and PM2.5 air pollutants from the year of 2002 to 2017

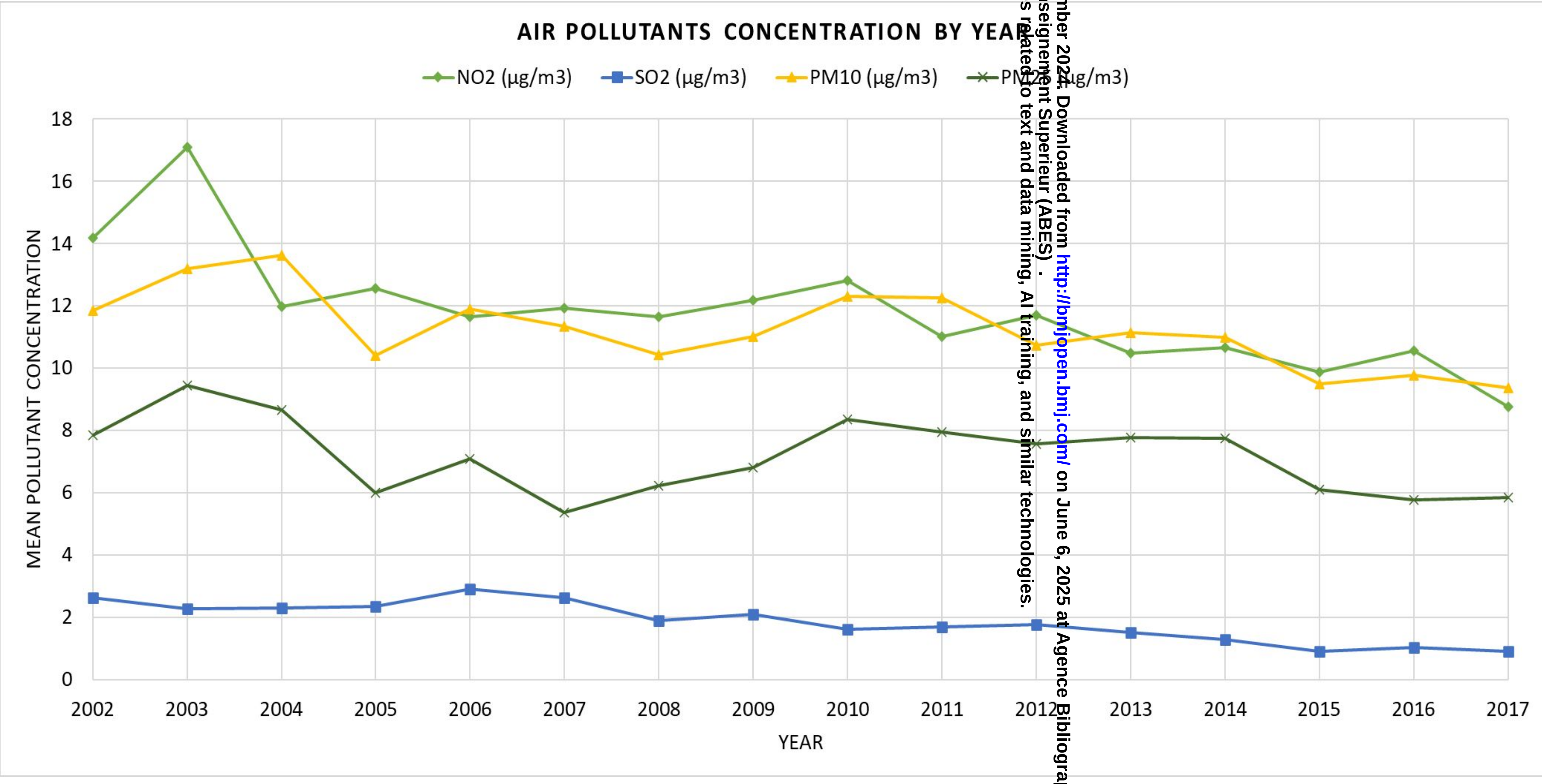


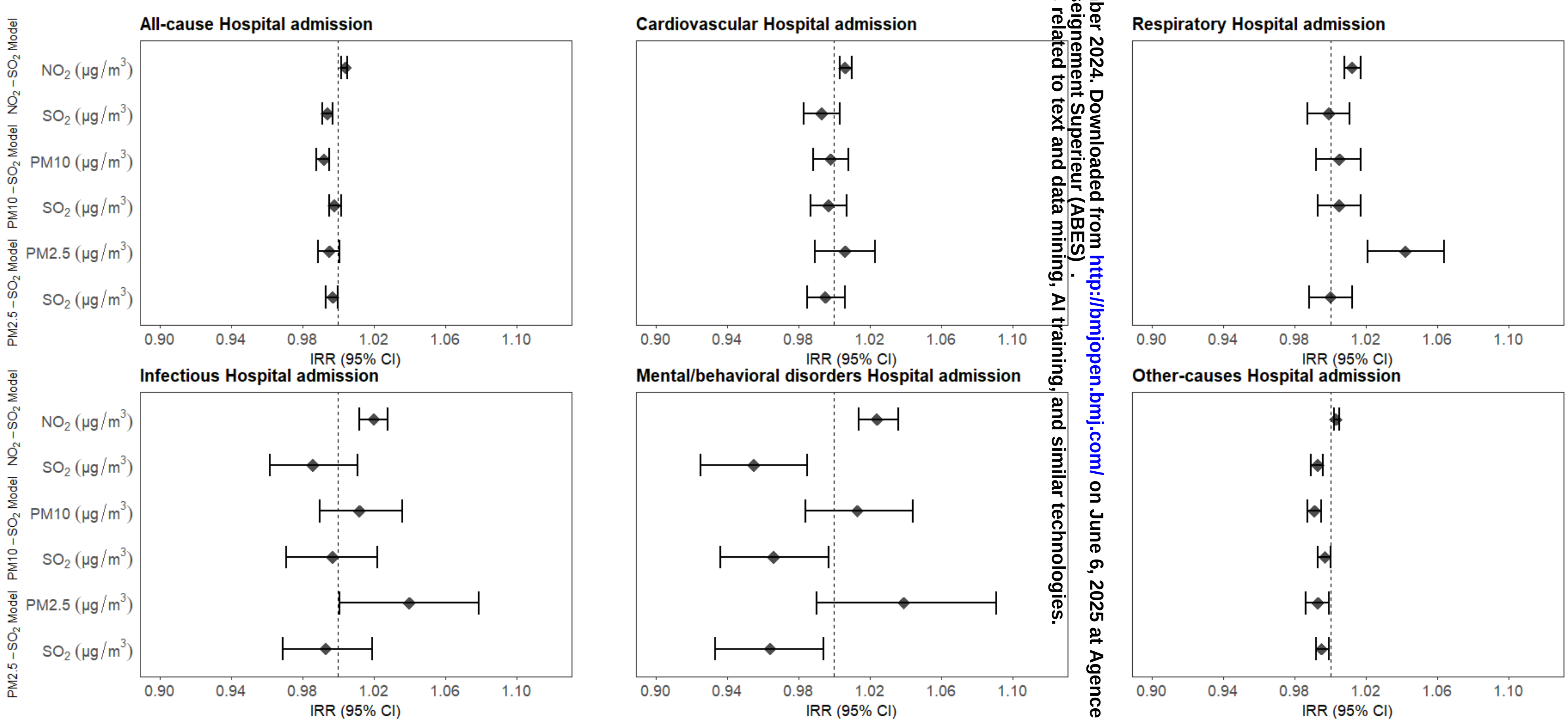
Table 3: Description of air pollution.

	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.

The association between air pollution and hospital admissions in two-pollutant models

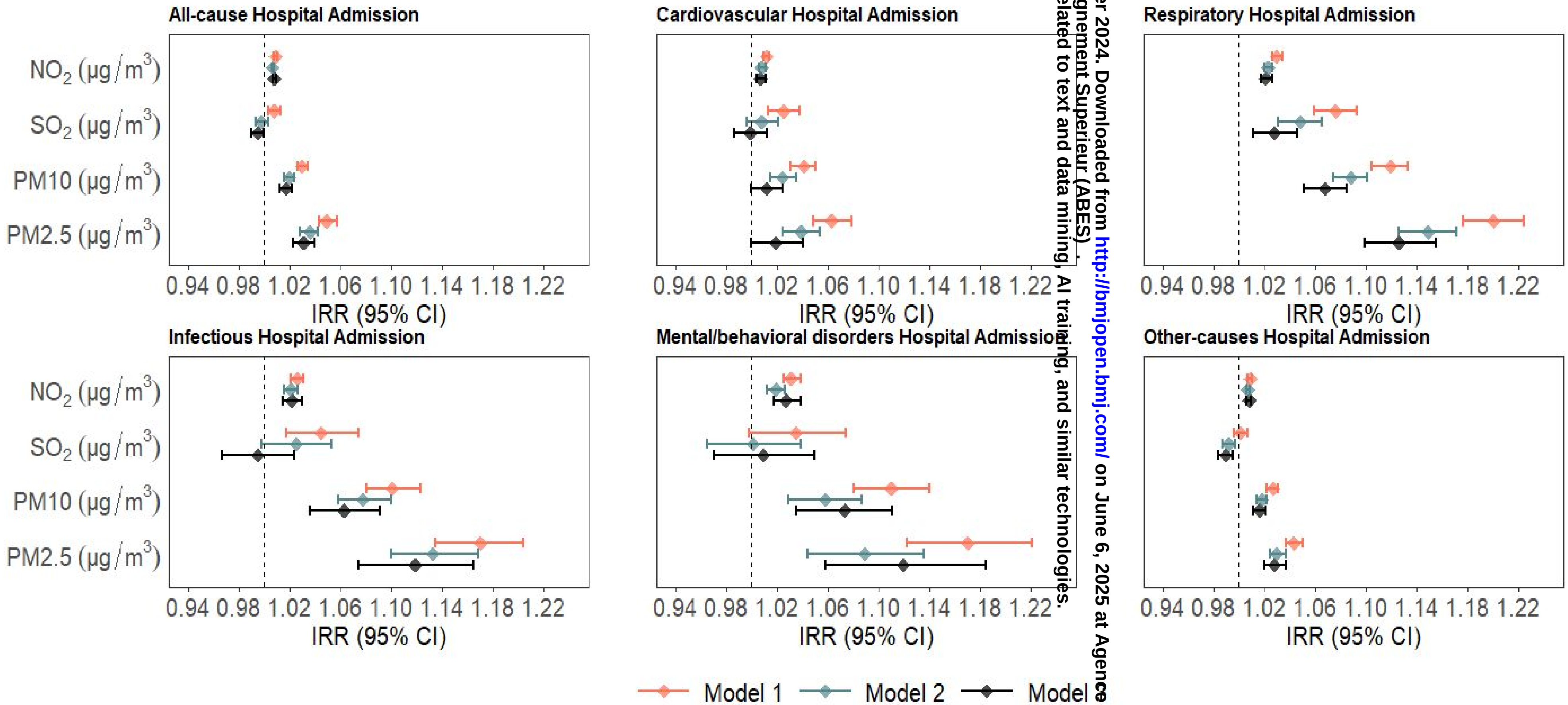
Figure 2: The association of all-cause and cause-specific hospital admissions with NO_2, SO_2, PM10, and PM2.5 air pollutants in two-pollutant models (N=202,237 individuals and 2,810,414 observations).



Data source: Author's own calculations based on the Scottish Longitudinal Study data; The dashed line is placed at IRR=1 as a cut-off for statistically insignificant results; The two-pollutant models which include SO_2 + one of the other three pollutants are adjusted for age, age^2, gender, calendar year dummies, ethnicity, country of birth, marital status, education, occupation, and place of residence.

The association between cumulative air pollution (CAP) exposure and hospital admissions

Figure 3: The association of all-cause and cause-specific hospital admissions with average cumulative exposure to NO_2, SO_2, PM10, and PM2.5 air pollutants (N=202,237 individuals and 2,810,414 observations).



Data source: Author's own calculations based on the Scottish Longitudinal Study data; The dashed line is placed at IRR=1 as a cut-off for statistically insignificant results; Model 1 is adjusted for age, age^2, gender and calendar year dummies; Model 2= Model 1 + ethnicity + country of birth + marital status + education + occupation; Model 3= Model 2 + Place of residence.

The association between hospital admissions and the socioeconomic and contextual covariates

Table 4: The association of all-cause hospital admissions with the socioeconomic and contextual covariates

Covariates	IRR	Lower 95% CI	Upper 95% CI	P-value
Age	0.970	0.968	0.972	0.000
Age2	1.001	1.001	1.001	0.000
Gender: Male				
Female	0.996	0.981	1.010	0.571
Year dummies: 2002				
2003	0.981	0.961	1.000	0.053
2004	0.998	0.978	1.018	0.812
2005	1.017	0.997	1.038	0.096
2006	1.040	1.020	1.061	0.000
2007	1.088	1.066	1.110	0.000
2008	1.129	1.106	1.152	0.000
2009	1.156	1.132	1.179	0.000
2010	1.160	1.137	1.184	0.000
2011	1.173	1.150	1.198	0.000
2012	1.214	1.189	1.239	0.000
2013	1.246	1.221	1.272	0.000
2014	1.274	1.247	1.301	0.000
2015	1.318	1.291	1.346	0.000
2016	1.346	1.318	1.375	0.000
2017	1.345	1.317	1.374	0.000
Ethnicity: White				
Not-White	1.047	1.011	1.084	0.011
Country of birth: Born in Scotland				
Born in rest of UK	0.865	0.845	0.886	0.000
Born outside UK	0.805	0.775	0.836	0.000
Marital Status: Married				
Single never married	0.970	0.953	0.988	0.001
Divorced/separated/widowed	1.127	1.110	1.143	0.000
No response	1.204	1.078	1.344	0.001
Education: Intermediate school qualification				
No qualification	1.157	1.138	1.176	0.000
High school qualification	0.877	0.860	0.894	0.000
Post-school/university qualification	0.845	0.830	0.860	0.000
Still a student	0.641	0.551	0.745	0.000
No response	0.845	0.814	0.877	0.000

Occupation: White collar high skilled				
White collar low skilled	1.069	1.052	1.087	0.000
Blue collar high skilled	1.117	1.093	1.141	0.000
Blue collar low skilled	1.178	1.157	1.199	0.000
NA: students/never worked	1.157	1.121	1.194	0.000
No response	2.699	2.566	2.840	0.000
Place of residence: Large Urban areas				
Other urban areas	0.973	0.959	0.987	0.000
Accessible small towns	0.932	0.911	0.952	0.000
Remote small towns	0.963	0.931	0.997	0.034
Accessible Rural areas	0.903	0.889	0.918	0.000
Remote rural areas	0.966	0.944	0.989	0.004
Overdispersion parameter (α)	2.49	2.48	2.51	

Table 5: The association of cardiovascular hospital admissions with the socioeconomic and contextual covariates

Covariates	**IRR**	**Lower 95% CI**	**Upper 95% CI**	**P-value**
Age	1.083	1.076	1.090	0.000
Age2	1.000	1.000	1.000	0.949
Gender: Male				
Female	0.560	0.541	0.579	0.000
Year dummies: 2002				
2003	0.943	0.887	1.002	0.059
2004	0.925	0.869	0.984	0.013
2005	0.901	0.847	0.959	0.001
2006	0.852	0.800	0.907	0.000
2007	0.858	0.806	0.914	0.000
2008	0.872	0.818	0.928	0.000
2009	0.902	0.847	0.960	0.001
2010	0.883	0.829	0.941	0.000
2011	0.885	0.830	0.943	0.000
2012	0.884	0.829	0.943	0.000
2013	0.885	0.829	0.943	0.000
2014	0.895	0.839	0.955	0.001
2015	0.874	0.820	0.933	0.000
2016	0.849	0.796	0.907	0.000
2017	0.833	0.779	0.890	0.000
Ethnicity: White				
Not-White	1.100	1.016	1.191	0.019
Country of birth: Born in Scotland				
Born in rest of UK	0.906	0.858	0.957	0.000
Born outside UK	0.844	0.773	0.921	0.000
Marital Status: Married				

Single never married	0.938	0.893	0.984	0.009
Divorced/separated/widowed	1.192	1.151	1.235	0.000
No response	1.026	0.803	1.310	0.840
Education: Intermediate school qualification				
No qualification	1.227	1.176	1.280	0.000
High school qualification	0.870	0.822	0.921	0.000
Post-school/university qualification	0.787	0.749	0.827	0.000
Still a student	0.716	0.373	1.373	0.314
No response	0.982	0.892	1.081	0.713
Occupation: White collar high skilled				
White collar low skilled	1.050	1.004	1.099	0.035
Blue collar high skilled	1.143	1.082	1.206	0.000
Blue collar low skilled	1.217	1.162	1.275	0.000
NA: students/never worked	1.177	1.079	1.283	0.000
No response	3.059	2.733	3.424	0.000
Place of residence: Large Urban areas				
Other urban areas	0.973	0.938	1.009	0.145
Accessible small towns	0.939	0.887	0.993	0.029
Remote small towns	0.917	0.838	1.003	0.058
Accessible Rural areas	0.884	0.848	0.922	0.000
Remote rural areas	0.894	0.844	0.947	0.000
Overdispersion parameter (α)	12.79	12.55	13.03	

Table 6: The association of respiratory hospital admissions with the socioeconomic and contextual covariates

Covariates	**IRR**	**Lower 95% CI**	**Upper 95% CI**	**P-value**
Age	0.898	0.891	0.904	0.000
Age2	1.001	1.001	1.002	0.000
Gender: Male				
Female	0.786	0.751	0.822	0.000
Year dummies: 2002				
2003	1.056	0.976	1.142	0.174
2004	1.091	1.008	1.181	0.031
2005	1.180	1.091	1.277	0.000
2006	1.255	1.160	1.357	0.000
2007	1.410	1.305	1.524	0.000
2008	1.582	1.464	1.709	0.000
2009	1.519	1.404	1.642	0.000
2010	1.541	1.425	1.667	0.000
2011	1.736	1.604	1.879	0.000
2012	1.867	1.725	2.020	0.000
2013	2.045	1.890	2.212	0.000

2014	2.129	1.967	2.304	0.000
2015	2.592	2.397	2.802	0.000
2016	2.849	2.635	3.081	0.000
2017	3.223	2.981	3.484	0.000
Ethnicity: White				
Not-White	1.112	1.004	1.232	0.043
Country of birth: Born in Scotland				
Born in rest of UK	0.748	0.692	0.809	0.000
Born outside UK	0.752	0.668	0.845	0.000
Marital Status: Married				
Single never married	1.043	0.980	1.110	0.185
Divorced/separated/widowed	1.353	1.293	1.416	0.000
No response	1.235	0.921	1.655	0.158
Education: Intermediate school qualification				
No qualification	1.416	1.341	1.496	0.000
High school qualification	0.815	0.758	0.877	0.000
Post-school/university qualification	0.693	0.650	0.740	0.000
Still a student	0.559	0.316	0.989	0.046
No response	0.766	0.685	0.856	0.000
Occupation: White collar high skilled				
White collar low skilled	1.132	1.066	1.202	0.000
Blue collar high skilled	1.317	1.224	1.416	0.000
Blue collar low skilled	1.552	1.460	1.651	0.000
NA: students/never worked	1.789	1.622	1.974	0.000
No response	8.220	7.187	9.402	0.000
Place of residence: Large Urban areas				
Other urban areas	0.922	0.881	0.966	0.001
Accessible small towns	0.833	0.774	0.895	0.000
Remote small towns	0.854	0.763	0.956	0.006
Accessible Rural areas	0.760	0.720	0.802	0.000
Remote rural areas	0.714	0.661	0.771	0.000
Overdispersion parameter (α)	7.07	6.89	7.26	

Table 7: The association of infectious hospital admissions with the socioeconomic and contextual covariates

Covariates	**IRR**	**Lower 95% CI**	**Upper 95% CI**	**P-value**
Age	0.938	0.926	0.949	0.000
Age2	1.001	1.001	1.001	0.000
Gender: Male				
Female	1.057	0.987	1.132	0.111
Year dummies: 2002				
2003	0.871	0.723	1.049	0.145

2004	0.993	0.827	1.192	0.937
2005	1.115	0.931	1.335	0.236
2006	1.262	1.057	1.507	0.010
2007	1.342	1.125	1.601	0.001
2008	1.185	0.990	1.419	0.065
2009	1.384	1.159	1.653	0.000
2010	1.504	1.261	1.794	0.000
2011	1.543	1.291	1.844	0.000
2012	1.849	1.552	2.202	0.000
2013	2.996	2.535	3.541	0.000
2014	3.848	3.267	4.533	0.000
2015	4.033	3.424	4.749	0.000
2016	4.315	3.664	5.082	0.000
2017	4.862	4.131	5.724	0.000
Ethnicity: White				
Not-White	1.212	1.044	1.408	0.012
Country of birth: Born in Scotland				
Born in rest of UK	0.896	0.799	1.004	0.059
Born outside UK	1.121	0.951	1.322	0.174
Marital Status: Married				
Single never married	1.169	1.064	1.284	0.001
Divorced/separated/widowed	1.228	1.139	1.325	0.000
No response	1.206	0.750	1.939	0.439
Education: Intermediate school qualification				
No qualification	1.268	1.158	1.387	0.000
High school qualification	0.844	0.751	0.950	0.005
Post-school/university qualification	0.826	0.746	0.915	0.000
Still a student	0.184	0.050	0.679	0.011
No response	0.876	0.721	1.065	0.184
Occupation: White collar high skilled				
White collar low skilled	1.144	1.040	1.259	0.006
Blue collar high skilled	1.239	1.099	1.397	0.000
Blue collar low skilled	1.313	1.187	1.453	0.000
NA: students/never worked	1.579	1.339	1.861	0.000
No response	3.122	2.468	3.950	0.000
Place of residence: Large Urban areas				
Other urban areas	0.995	0.923	1.071	0.885
Accessible small towns	0.861	0.763	0.973	0.016
Remote small towns	0.770	0.632	0.937	0.009
Accessible Rural areas	0.808	0.738	0.884	0.000
Remote rural areas	0.729	0.642	0.828	0.000
Overdispersion parameter (α)	40.81	37.36	44.58	

Table 8: The association of mental/behavioural disorders hospital admissions with the socioeconomic and contextual covariates

Covariates	**IRR**	**Lower 95% CI**	**Upper 95% CI**	**P-value**
Age	0.939	0.925	0.954	0.000
Age2	1.001	1.001	1.001	0.000
Gender: Male				
Female	0.578	0.524	0.638	0.000
Year dummies: 2002				
2003	0.994	0.819	1.207	0.954
2004	0.921	0.756	1.121	0.410
2005	0.941	0.771	1.147	0.545
2006	0.990	0.813	1.206	0.923
2007	1.072	0.881	1.305	0.485
2008	1.045	0.858	1.274	0.662
2009	1.149	0.944	1.399	0.166
2010	1.269	1.043	1.545	0.017
2011	1.387	1.137	1.692	0.001
2012	1.538	1.263	1.873	0.000
2013	1.655	1.360	2.014	0.000
2014	1.799	1.479	2.188	0.000
2015	1.904	1.567	2.314	0.000
2016	2.456	2.028	2.974	0.000
2017	2.763	2.284	3.343	0.000
Ethnicity: White				
Not-White	1.218	0.985	1.507	0.068
Country of birth: Born in Scotland				
Born in rest of UK	0.740	0.623	0.880	0.001
Born outside UK	0.619	0.476	0.806	0.000
Marital Status: Married				
Single never married	2.723	2.382	3.113	0.000
Divorced/separated/widowed	2.676	2.410	2.972	0.000
No response	3.874	2.211	6.788	0.000
Education: Intermediate school qualification				
No qualification	1.412	1.241	1.607	0.000
High school qualification	0.958	0.810	1.134	0.620
Post-school/university qualification	0.758	0.650	0.884	0.000
Still a student	0.313	0.069	1.423	0.133
No response	0.875	0.684	1.119	0.288
Occupation: White collar high skilled				
White collar low skilled	1.341	1.161	1.548	0.000
Blue collar high skilled	1.563	1.320	1.851	0.000
Blue collar low skilled	1.723	1.488	1.994	0.000

NA: students/never worked	2.676	2.152	3.326	0.000
No response	7.897	5.914	10.545	0.000
Place of residence: Large Urban areas				
Other urban areas	0.862	0.777	0.956	0.005
Accessible small towns	0.743	0.625	0.882	0.001
Remote small towns	1.233	0.975	1.558	0.080
Accessible Rural areas	0.672	0.592	0.762	0.000
Remote rural areas	1.081	0.920	1.271	0.345
Overdispersion parameter (α)	13.25	12.30	14.26	

Table 9: The association of other-causes hospital admissions with the socioeconomic and contextual covariates

Covariates	**IRR**	**Lower 95% CI**	**Upper 95% CI**	**P-value**
Age	0.978	0.976	0.980	0.000
Age2	1.001	1.001	1.001	0.000
Gender: Male				
Female	1.078	1.062	1.094	0.000
Year dummies: 2002				
2003	0.976	0.956	0.997	0.027
2004	0.995	0.974	1.016	0.632
2005	1.017	0.995	1.039	0.123
2006	1.046	1.024	1.068	0.000
2007	1.092	1.068	1.115	0.000
2008	1.135	1.111	1.160	0.000
2009	1.164	1.139	1.189	0.000
2010	1.166	1.141	1.191	0.000
2011	1.174	1.148	1.200	0.000
2012	1.215	1.188	1.242	0.000
2013	1.237	1.210	1.265	0.000
2014	1.258	1.231	1.287	0.000
2015	1.289	1.261	1.318	0.000
2016	1.300	1.271	1.330	0.000
2017	1.278	1.249	1.308	0.000
Ethnicity: White				
Not-White	1.039	1.002	1.077	0.040
Country of birth: Born in Scotland				
Born in rest of UK	0.876	0.854	0.897	0.000
Born outside UK	0.815	0.784	0.847	0.000
Marital Status: Married				
Single never married	0.971	0.953	0.990	0.003
Divorced/separated/widowed	1.109	1.092	1.126	0.000
No response	1.234	1.100	1.384	0.000

Education: Intermediate school qualification				
No qualification	1.139	1.119	1.158	0.000
High school qualification	0.877	0.859	0.895	0.000
Post-school/university qualification	0.857	0.841	0.873	0.000
Still a student	0.661	0.565	0.773	0.000
No response	0.848	0.815	0.882	0.000
Occupation: White collar high skilled				
White collar low skilled	1.067	1.049	1.085	0.000
Blue collar high skilled	1.103	1.078	1.128	0.000
Blue collar low skilled	1.156	1.135	1.178	0.000
NA: students/never worked	1.152	1.114	1.191	0.000
No response	2.343	2.222	2.471	0.000
Place of residence: Large Urban areas				
Other urban areas	0.971	0.957	0.986	0.000
Accessible small towns	0.931	0.910	0.952	0.000
Remote small towns	0.980	0.946	1.016	0.283
Accessible Rural areas	0.906	0.891	0.921	0.000
Remote rural areas	0.982	0.958	1.005	0.130
Overdispersion parameter (α)	2.57	2.55	2.59	

Supplementary Tables 4 to 9 describe the association of all-cause and cause-specific hospital admissions with the socioeconomic and contextual covariates. The calculated IRRs and 95%CIs are the author's own calculations based on the Scottish Longitudinal Study (SLS) data (*Scottish Longitudinal Study*, Accessed 08 November 2021).

Lower incidence rate ratios were observed for all-cause, cardiovascular, respiratory, infectious, mental/behavioural disorders, and other-causes hospital admissions among females (except for all-cause, infectious and other-causes hospital admissions), people born in rest of UK or outside UK compared to Scottish-born, single never married compared to married (except for infectious and mental hospital admissions), people who have high school or post-school/university education compared to people who have intermediate school education, and people who live in towns or rural areas compared to those living in large urban areas.

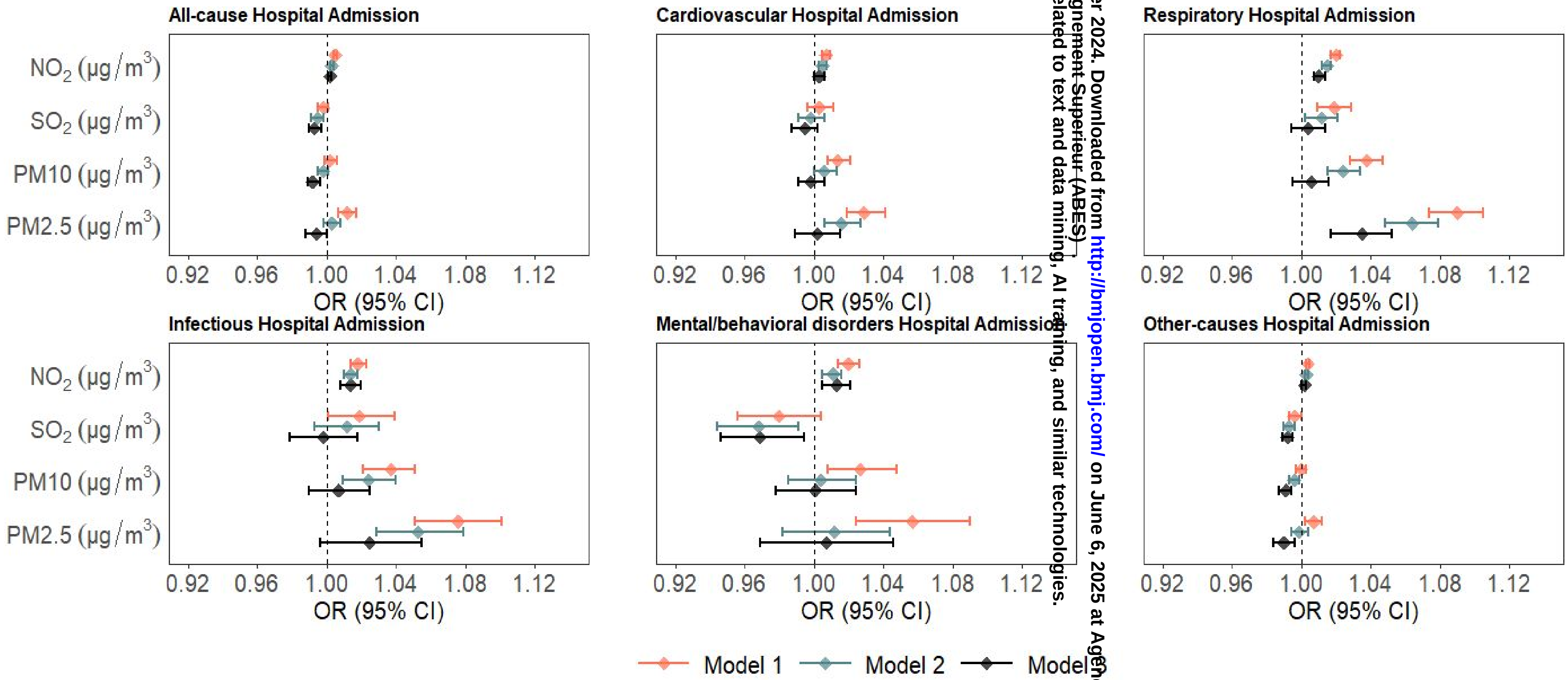
In contrast, higher incidence rate ratios were observed for all-cause, cardiovascular, respiratory, infectious, mental/behavioural disorders, and other-causes hospital admissions among not-white compared to white ethnicity, divorced/separated/widowed compared to married, people with no educational qualification compared to people with intermediate school education, and people who work in white collar low skilled, blue collar high skilled, and blue collar low skilled jobs compared to people working in white collar high skilled jobs.

Citation:

Scottish Longitudinal Study. (Accessed 08 November 2021). https://sls.lscs.ac.uk/

The association between air pollution and hospital admissions binary (yes/no) outcome

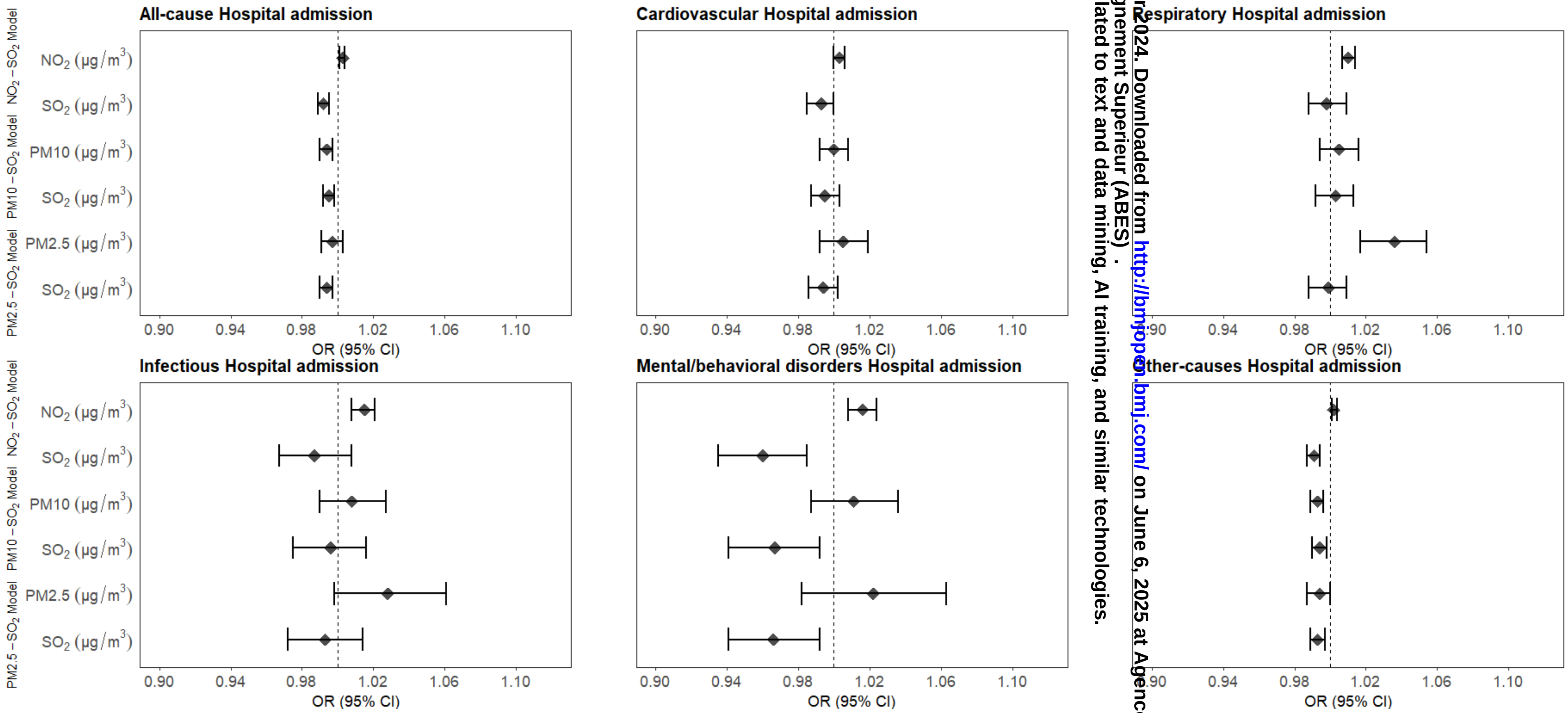
Figure 4: The association of all-cause and cause-specific hospital admissions binary (yes/no) outcome with NO_2, SO_2, PM10, and PM2.5 air pollutants in separate multilevel mixed-effects logistic models (N=202,237 individuals and 2,810,414 observations).



Data source: Author's own calculations based on the Scottish Longitudinal Study data; The dashed line is placed at OR=1 as a cut-off for statistically insignificant results; Model 1 is adjusted for age, age^2, gender and calendar year dummies; Model 2= Model 1 + ethnicity + country of birth + marital status + education + occupation; Model 3= Model 2 + Place of residence.

The association between air pollution and hospital admissions binary (yes/no) outcome in two-pollutant models

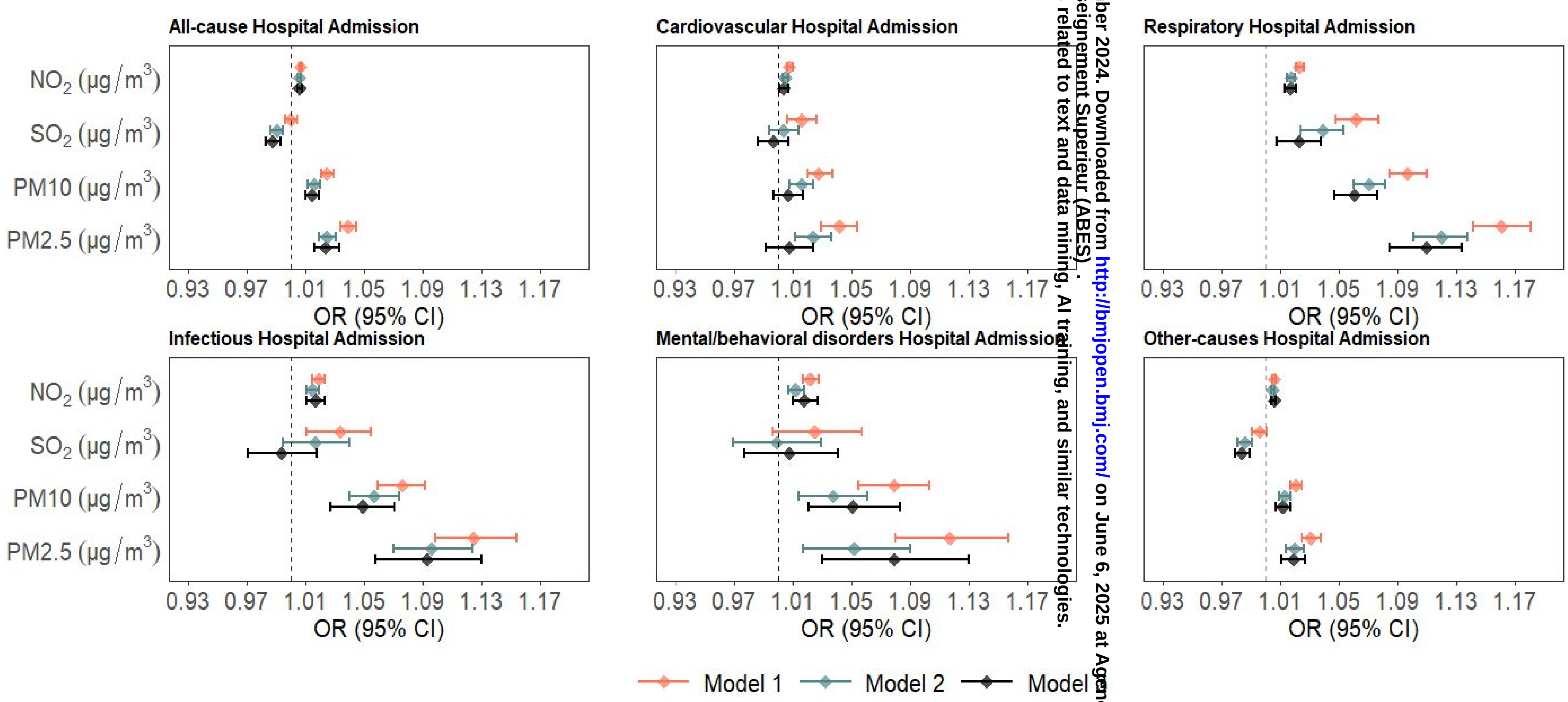
Figure 5: The association of all-cause and cause-specific hospital admissions binary (yes/no) outcome with NO_2, SO_2, PM10, and PM2.5 air pollutants in two-pollutant models (N=202,237 individuals and 2,810,414 observations).



Data source: Author's own calculations based on the Scottish Longitudinal Study data; The dashed line is placed at OR=1 as a cut-off for statistically insignificant results; The two-pollutant models which include SO_2 + one of the other three pollutants are adjusted for age, age2, gender, calendar year dummies, ethnicity, country of birth, marital status, education, occupation, and Place of residence.

The association between cumulative air pollution (CAP) exposure and hospital admissions binary (yes/no) outcome

Figure 6: The association of all-cause and cause-specific hospital admissions binary (yes/no) outcome with average CAP exposure to NO_2, SO_2, PM10, and PM2.5 air pollutants in separate multilevel mixed-effects logistic models (N=202,237 individuals and 2,810,414 observations).



Data source: Author's own calculations based on the Scottish Longitudinal Study data; The dashed line is placed at OR=1 as a cut-off for statistically insignificant results; Model 1 is adjusted for age, age^2, gender and calendar year dummies; Model 2= Model 1 + ethnicity + country of birth + marital status + education + occupation; Model 3= Model 2 + Place of residence.

The association between hospital admissions binary (yes/no) outcome and the socioeconomic and contextual covariates

Table 10: The association of all-cause hospital admissions binary (yes/no) outcome with the socioeconomic and contextual covariates

Covariates	OR	Lower 95% CI	Upper 95% CI	P-value
Age	0.970	0.968	0.972	0.000
Age2	1.001	1.001	1.001	0.000
Gender: Male				
Female	1.033	1.019	1.047	0.000
Year dummies: 2002				
2003	0.991	0.971	1.011	0.360
2004	1.009	0.989	1.030	0.389
2005	1.031	1.010	1.052	0.003
2006	1.052	1.031	1.074	0.000
2007	1.079	1.057	1.101	0.000
2008	1.124	1.101	1.147	0.000
2009	1.148	1.125	1.172	0.000
2010	1.132	1.109	1.156	0.000
2011	1.154	1.129	1.178	0.000
2012	1.185	1.160	1.210	0.000
2013	1.168	1.143	1.193	0.000
2014	1.180	1.155	1.206	0.000
2015	1.197	1.171	1.223	0.000
2016	1.162	1.136	1.187	0.000
2017	1.124	1.099	1.149	0.000
Ethnicity: White				
Not-White	1.043	1.009	1.079	0.014
Country of birth: Born in Scotland				
Born in rest of UK	0.878	0.858	0.898	0.000
Born outside UK	0.824	0.795	0.854	0.000
Marital Status: Married				
Single never married	0.948	0.931	0.965	0.000
Divorced/separated/widowed	1.123	1.107	1.139	0.000
No response	1.207	1.085	1.343	0.001
Education: Intermediate school qualification				
No qualification	1.158	1.139	1.177	0.000
High school qualification	0.873	0.856	0.890	0.000
Post-school/university qualification	0.854	0.839	0.869	0.000
Still a student	0.641	0.553	0.744	0.000

No response	0.924	0.891	0.959	0.000
Occupation: White collar high skilled				
White collar low skilled	1.072	1.055	1.090	0.000
Blue collar high skilled	1.119	1.096	1.143	0.000
Blue collar low skilled	1.174	1.153	1.195	0.000
NA: students/never worked	1.182	1.146	1.220	0.000
No response	2.362	2.247	2.482	0.000
Place of residence: Large Urban areas				
Other urban areas	0.982	0.968	0.996	0.010
Accessible small towns	0.941	0.921	0.962	0.000
Remote small towns	1.015	0.981	1.050	0.401
Accessible Rural areas	0.907	0.893	0.921	0.000
Remote rural areas	0.989	0.966	1.011	0.318

Table 11: The association of cardiovascular hospital admissions binary (yes/no) outcome with the socioeconomic and contextual covariates

Covariates	**OR**	**Lower 95% CI**	**Upper 95% CI**	**P-value**
Age	1.070	1.064	1.075	0.000
Age2	1.000	1.000	1.000	0.196
Gender: Male				
Female	0.641	0.624	0.659	0.000
Year dummies: 2002				
2003	0.970	0.925	1.017	0.205
2004	0.961	0.917	1.008	0.105
2005	0.948	0.904	0.995	0.029
2006	0.914	0.871	0.959	0.000
2007	0.906	0.863	0.951	0.000
2008	0.904	0.861	0.949	0.000
2009	0.912	0.868	0.957	0.000
2010	0.908	0.864	0.954	0.000
2011	0.895	0.851	0.942	0.000
2012	0.894	0.850	0.941	0.000
2013	0.862	0.819	0.907	0.000
2014	0.871	0.827	0.917	0.000
2015	0.844	0.802	0.889	0.000
2016	0.792	0.752	0.835	0.000
2017	0.754	0.715	0.795	0.000
Ethnicity: White				
Not-White	1.081	1.014	1.153	0.017
Country of birth: Born in Scotland				
Born in rest of UK	0.930	0.890	0.973	0.002
Born outside UK	0.865	0.805	0.929	0.000

Marital Status: Married				
Single never married	0.935	0.898	0.974	0.001
Divorced/separated/widowed	1.146	1.114	1.179	0.000
No response	1.052	0.870	1.272	0.599
Education: Intermediate school qualification				
No qualification	1.159	1.120	1.201	0.000
High school qualification	0.879	0.837	0.922	0.000
Post-school/university qualification	0.828	0.794	0.863	0.000
Still a student	0.784	0.437	1.408	0.416
No response	1.019	0.944	1.100	0.628
Occupation: White collar high skilled				
White collar low skilled	1.041	1.002	1.081	0.038
Blue collar high skilled	1.104	1.056	1.155	0.000
Blue collar low skilled	1.164	1.120	1.209	0.000
NA: students/never worked	1.124	1.048	1.206	0.001
No response	2.499	2.291	2.725	0.000
Place of residence: Large Urban areas				
Other urban areas	0.986	0.957	1.015	0.340
Accessible small towns	0.967	0.924	1.013	0.159
Remote small towns	0.946	0.879	1.017	0.130
Accessible Rural areas	0.906	0.876	0.937	0.000
Remote rural areas	0.931	0.888	0.975	0.002

Table 12: The association of respiratory hospital admissions binary (yes/no) outcome with the socioeconomic and contextual covariates

Covariates	**OR**	**Lower 95% CI**	**Upper 95% CI**	**P-value**
Age	0.915	0.910	0.921	0.000
Age2	1.001	1.001	1.001	0.000
Gender: Male				
Female	0.815	0.784	0.847	0.000
Year dummies: 2002				
2003	1.089	1.018	1.165	0.013
2004	1.132	1.058	1.212	0.000
2005	1.228	1.147	1.313	0.000
2006	1.297	1.212	1.388	0.000
2007	1.430	1.337	1.529	0.000
2008	1.589	1.486	1.699	0.000
2009	1.546	1.445	1.654	0.000
2010	1.537	1.435	1.646	0.000
2011	1.696	1.583	1.817	0.000
2012	1.754	1.637	1.880	0.000

2013	1.862	1.738	1.995	0.000
2014	1.858	1.733	1.992	0.000
2015	2.165	2.021	2.318	0.000
2016	2.271	2.120	2.432	0.000
2017	2.487	2.323	2.663	0.000
Ethnicity: White				
Not-White	1.093	1.002	1.191	0.045
Country of birth: Born in Scotland				
Born in rest of UK	0.783	0.733	0.837	0.000
Born outside UK	0.797	0.721	0.880	0.000
Marital Status: Married				
Single never married	1.025	0.972	1.082	0.362
Divorced/separated/widowed	1.290	1.241	1.342	0.000
No response	1.181	0.923	1.511	0.187
Education: Intermediate school qualification				
No qualification	1.357	1.293	1.423	0.000
High school qualification	0.840	0.788	0.895	0.000
Post-school/university qualification	0.728	0.687	0.770	0.000
Still a student	0.610	0.373	0.998	0.049
No response	0.864	0.786	0.950	0.003
Occupation: White collar high skilled				
White collar low skilled	1.106	1.050	1.166	0.000
Blue collar high skilled	1.280	1.202	1.363	0.000
Blue collar low skilled	1.462	1.386	1.542	0.000
NA: students/never worked	1.613	1.482	1.756	0.000
No response	5.980	5.340	6.696	0.000
Place of residence: Large Urban areas				
Other urban areas	0.956	0.919	0.995	0.027
Accessible small towns	0.867	0.814	0.923	0.000
Remote small towns	0.899	0.816	0.990	0.030
Accessible Rural areas	0.802	0.765	0.841	0.000
Remote rural areas	0.781	0.731	0.835	0.000

Table 13: The association of infectious hospital admissions binary (yes/no) outcome with the socioeconomic and contextual covariates

Covariates	**OR**	**Lower 95% CI**	**Upper 95% CI**	**P-value**
Age	0.959	0.950	0.968	0.000
Age2	1.001	1.001	1.001	0.000
Gender: Male				
Female	1.056	0.998	1.117	0.057
Year dummies: 2002				

2003	0.877	0.750	1.025	0.100
2004	0.975	0.837	1.136	0.743
2005	1.101	0.949	1.278	0.205
2006	1.254	1.084	1.450	0.002
2007	1.266	1.094	1.465	0.002
2008	1.175	1.012	1.364	0.035
2009	1.315	1.136	1.523	0.000
2010	1.378	1.191	1.595	0.000
2011	1.416	1.222	1.642	0.000
2012	1.663	1.441	1.921	0.000
2013	2.372	2.071	2.718	0.000
2014	2.939	2.575	3.354	0.000
2015	3.023	2.649	3.450	0.000
2016	3.086	2.703	3.523	0.000
2017	3.402	2.983	3.880	0.000
Ethnicity: White				
Not-White	1.162	1.031	1.310	0.014
Country of birth: Born in Scotland				
Born in rest of UK	0.901	0.819	0.990	0.030
Born outside UK	1.079	0.944	1.234	0.264
Marital Status: Married				
Single never married	1.134	1.049	1.226	0.002
Divorced/separated/widowed	1.177	1.108	1.251	0.000
No response	1.184	0.815	1.720	0.375
Education: Intermediate school qualification				
No qualification	1.206	1.120	1.298	0.000
High school qualification	0.851	0.771	0.941	0.002
Post-school/university qualification	0.852	0.783	0.928	0.000
Still a student	0.258	0.081	0.825	0.022
No response	0.952	0.816	1.111	0.532
Occupation: White collar high skilled				
White collar low skilled	1.119	1.034	1.211	0.005
Blue collar high skilled	1.183	1.072	1.306	0.001
Blue collar low skilled	1.243	1.144	1.351	0.000
NA: students/never worked	1.500	1.314	1.713	0.000
No response	2.440	2.025	2.941	0.000
Place of residence: Large Urban areas				
Other urban areas	1.008	0.949	1.070	0.803
Accessible small towns	0.916	0.830	1.010	0.079
Remote small towns	0.869	0.744	1.016	0.078
Accessible Rural areas	0.855	0.794	0.920	0.000
Remote rural areas	0.800	0.721	0.888	0.000

Table 14: The association of mental/behavioural disorders hospital admissions binary (yes/no) outcome with the socioeconomic and contextual covariates

Covariates	**OR**	**Lower 95% CI**	**Upper 95% CI**	**P-value**
Age	0.956	0.944	0.968	0.000
Age2	1.001	1.001	1.001	0.000
Gender: Male				
Female	0.641	0.591	0.696	0.000
Year dummies: 2002				
2003	1.011	0.864	1.182	0.894
2004	0.979	0.835	1.147	0.791
2005	0.964	0.821	1.132	0.656
2006	1.030	0.878	1.209	0.718
2007	1.086	0.926	1.274	0.313
2008	1.085	0.923	1.275	0.322
2009	1.171	0.997	1.376	0.054
2010	1.195	1.017	1.405	0.030
2011	1.297	1.101	1.526	0.002
2012	1.370	1.164	1.612	0.000
2013	1.467	1.248	1.725	0.000
2014	1.592	1.357	1.869	0.000
2015	1.593	1.355	1.871	0.000
2016	1.815	1.548	2.127	0.000
2017	1.983	1.694	2.321	0.000
Ethnicity: White				
Not-White	1.152	0.967	1.372	0.113
Country of birth: Born in Scotland				
Born in rest of UK	0.786	0.682	0.907	0.001
Born outside UK	0.685	0.551	0.851	0.001
Marital Status: Married				
Single never married	2.285	2.048	2.548	0.000
Divorced/separated/widowed	2.214	2.033	2.410	0.000
No response	2.944	1.871	4.633	0.000
Education: Intermediate school qualification				
No qualification	1.312	1.180	1.458	0.000
High school qualification	0.972	0.846	1.117	0.689
Post-school/university qualification	0.809	0.712	0.919	0.001
Still a student	0.299	0.068	1.319	0.111
No response	0.952	0.780	1.162	0.627
Occupation: White collar high skilled				
White collar low skilled	1.303	1.155	1.470	0.000
Blue collar high skilled	1.475	1.283	1.696	0.000
Blue collar low skilled	1.612	1.428	1.819	0.000

NA: students/never worked	2.295	1.923	2.738	0.000
No response	5.425	4.291	6.859	0.000
Place of residence: Large Urban areas				
Other urban areas	0.895	0.822	0.975	0.011
Accessible small towns	0.812	0.705	0.936	0.004
Remote small towns	1.255	1.041	1.514	0.017
Accessible Rural areas	0.721	0.649	0.800	0.000
Remote rural areas	1.122	0.984	1.279	0.087

Table 15: The association of other-causes hospital admissions binary (yes/no) outcome with the socioeconomic and contextual covariates

Covariates	**OR**	**Lower 95% CI**	**Upper 95% CI**	**P-value**
Age	0.981	0.979	0.983	0.000
Age2	1.000	1.000	1.000	0.000
Gender: Male				
Female	1.094	1.079	1.110	0.000
Year dummies: 2002				
2003	0.988	0.967	1.009	0.262
2004	1.006	0.985	1.028	0.561
2005	1.027	1.005	1.049	0.016
2006	1.052	1.030	1.075	0.000
2007	1.076	1.054	1.100	0.000
2008	1.127	1.103	1.151	0.000
2009	1.159	1.135	1.185	0.000
2010	1.138	1.113	1.163	0.000
2011	1.157	1.132	1.183	0.000
2012	1.186	1.160	1.212	0.000
2013	1.170	1.145	1.197	0.000
2014	1.179	1.153	1.206	0.000
2015	1.185	1.158	1.212	0.000
2016	1.145	1.119	1.172	0.000
2017	1.091	1.066	1.116	0.000
Ethnicity: White				
Not-White	1.036	1.001	1.072	0.043
Country of birth: Born in Scotland				
Born in rest of UK	0.888	0.868	0.909	0.000
Born outside UK	0.832	0.802	0.862	0.000
Marital Status: Married				
Single never married	0.953	0.936	0.970	0.000
Divorced/separated/widowed	1.105	1.089	1.122	0.000
No response	1.238	1.111	1.379	0.000

Education: Intermediate school qualification				
No qualification	1.140	1.121	1.159	0.000
High school qualification	0.873	0.856	0.891	0.000
Post-school/university qualification	0.863	0.847	0.879	0.000
Still a student	0.663	0.569	0.772	0.000
No response	0.917	0.883	0.953	0.000
Occupation: White collar high skilled				
White collar low skilled	1.071	1.053	1.089	0.000
Blue collar high skilled	1.104	1.080	1.128	0.000
Blue collar low skilled	1.157	1.136	1.178	0.000
NA: students/never worked	1.177	1.140	1.215	0.000
No response	2.029	1.929	2.134	0.000
Place of residence: Large Urban areas				
Other urban areas	0.981	0.967	0.995	0.010
Accessible small towns	0.942	0.921	0.964	0.000
Remote small towns	1.029	0.994	1.066	0.104
Accessible Rural areas	0.913	0.898	0.928	0.000
Remote rural areas	1.002	0.979	1.025	0.873

Supplementary Tables 10 to 15 describe the association of all-cause and cause-specific hospital admissions binary (yes/no) outcome with the socioeconomic and contextual covariates. The calculated ORs and 95%CIs are the author's own calculations based on the Scottish Longitudinal Study (SLS) data (*Scottish Longitudinal Study*, Accessed 08 November 2021).

Similar to the results with the hospital admission treated as a count outcome, lower odd ratios were observed for all-cause, cardiovascular, respiratory, infectious, mental/behavioural disorders, and other-causes hospital admissions binary (yes/no) outcome among females (except for all-cause, infectious and other-causes hospital admissions), people born in rest of UK or outside UK compared to Scottish-born, single never married compared to married (except for infectious and mental hospital admissions), people who have high school or post-school/university education compared to people who have intermediate school education, and people who live in towns or rural areas compared to those living in large urban areas.

In contrast, higher odd ratios were observed for all-cause, cardiovascular, respiratory, infectious, mental/behavioural disorders, and other-causes hospital admissions binary (yes/no) outcome among not-white compared to white ethnicity, divorced/separated/widowed compared to married, people with no educational qualification compared to people with intermediate school education, and people who work in white collar low skilled, blue collar high skilled, and blue collar low skilled jobs compared to people working in white collar high skilled jobs.

Citation:

Scottish Longitudinal Study. (Accessed 08 November 2021). https://sls.lscs.ac.uk/

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Title: Long-term exposure to ambient air pollution and the hospital admission burden in Scotland: A 16-year prospective population cohort study

Mary Abed Al Ahad, PhD[1]; Urška Demšar, PhD[1]; Frank Sullivan, FRSE, FRCP, FRCGP[2]; Hill Kulu, PhD[1]

[1] School of Geography and Sustainable Development, University of St Andrews, Scotland, United Kingdom.

[2] School of Medicine, University of St Andrews, Scotland, United Kingdom.

Correspondence should be addressed to
Mary Abed Al Ahad
School of Geography and Sustainable Development,
University of St Andrews,
Scotland, United Kingdom
Email: maaa1@st-andrews.ac.uk

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Ethical considerations: This paper is part of a PhD project (ID=2019006) that was granted ethical approval on the 14th of May 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.

Conflict of Interest: The authors declare that they have no conflict of interest.

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Transparency declaration: The corresponding author affirms that this manuscript is an honest, accurate, and transparent account of the study being reported; that no important aspects of the study have been omitted; and that any discrepancies from the study as planned (and, if relevant, registered) have been explained.

Data availability statement: Data underlying this study is confidential and is not publicly available due to ethical and legal restrictions. We are using the "Scottish Longitudinal Study" dataset which contains linked census, vital events, and education data for a five per cent sample of the population of Scotland. These data are protected by a copyright license and only available for licensed researchers in the UK following a detailed application and security checks. Researchers must also pass a Safe Researcher Training which equip them with the needed knowledge and information to analyse data in safe settings. Further information on how to access the SLS data are available on the following web page: https://sls.lscs.ac.uk/

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.

The guarantor of the study is Mary Abed Al Ahad and she accepts full responsibility for the finished work and/or the conduct of the study, had access to the data, and controlled the decision to publish.

Title: Long-term exposure to ambient air pollution and the hospital admission burden in Scotland: A 16-year prospective population cohort study

Abstract

Objectives: Air pollution is considered a major threat for global health and is associated with various health outcomes. Previous research on long-term exposure to ambient air pollution and health places more emphasis on mortality rather than hospital admission outcomes and is characterised with heterogeneities in the size of effect estimates between studies and less focus on mental/behavioural or infectious diseases outcomes. In this study, we investigate the association between long-term exposure to ambient air pollution and all-cause and cause-specific hospital admissions.

Design: This is a prospective cohort study.

Setting: Individual-level data from the "*Scottish Longitudinal Study (SLS)*" are linked to yearly concentrations of four pollutants (NO_2, SO_2, PM_{10}, $PM_{2.5}$) at 1 Km^2 spatial resolution using the individual's residential postcode for each year between 2002 and 2017.

Participants: The study includes 202,237 adult individuals aged 17 and older.

Outcome measures: The associations between air pollution and all-cause, cardiovascular, respiratory, infectious, mental/behavioural disorders, and other-causes hospital admissions are examined using multilevel mixed-effects negative binomial regression.

Results: Higher exposure to NO_2, PM_{10}, and $PM_{2.5}$ is associated with higher incidence of all-cause, cardiovascular, respiratory, and infectious hospital admissions before adjusting for the area of residence and in fully adjusted models when considering cumulative exposure across time. In fully adjusted models, the incidence rate for respiratory hospital admissions increased by 4.2% (95%CI=2.1%-6.3%) and 1.2% (95%CI=0.8%-1.7%) per 1 $\mu g/m^3$ increase in $PM_{2.5}$ and NO_2 pollutants, respectively. SO_2 was mainly associated with respiratory hospital admissions (IRR=1.016; 95%CI=1.004-1.027) and NO_2 was related to higher incidence of mental/behavioural disorders hospital admissions (IRR=1.021; 95%CI=1.011-1.031). Average cumulative exposure to air pollution showed stronger positive associations with higher rates of hospital admissions.

Conclusion: This study supports an association between long-term (16-years) exposure to ambient air pollution and increased all-cause and cause-specific hospital admissions for both physical and mental/behavioural illnesses. The results suggest that interventions on air pollution through stricter environmental regulations could help ease the hospital-care burden in Scotland in the long-term.

Keywords: Air pollution, hospital admissions, long-term, cardio-respiratory, mental disorders, Scottish Longitudinal Study.

Strengths and limitations of this study

- This study utilises 16 years (2002-2017) of administrative prospective cohort individual-level data from Scotland and links it to high-resolution 1 km^2 air pollution data at the residential postcode to investigate the association between long-term exposure to air pollution and all-cause and cause-specific hospital admissions, focusing on admissions related to physical illness such as cardiovascular, respiratory, and infectious diseases as well as on mental and behavioural disorders.
- This study attempted to develop previous research by contributing to the existing evidence on air pollution and health through the examination of multiple air pollutants (i.e., NO_2, SO_2, PM_{10}, and $PM_{2.5}$) in relation to multiple hospital admission outcomes over prolonged period of time.
- The limitations of this study included following individuals for 16 years starting the year of 2002; thus, bias may result from earlier life-time exposures to air pollution.
- The assessment of air pollution exposure was done at the place of residence. However, individuals are exposed to air pollution not only at the place of residence, but also at the workplace, during daily outdoor activities, and through commuting patterns.
- We could not account for some important lifestyle covariates (e.g., smoking, alcohol consumption, and exercise) due to the unavailability of this information in administrative data.

1. Introduction

Air pollution is considered by the World Health Organisation as one of the largest environmental health risks in the 21st century [1]. Air pollution results in poor health and in increased hospital admissions, mortality, and doctor visits, mostly for cardiovascular, respiratory, and cancer diseases [2-8]. For example, in Italy, long-term exposure to NO_2 (nitrogen dioxide) and $PM_{2.5}$ (particulate-matter diameter ≤2.5 μm) was associated with increased hospital admissions for circulatory diseases, myocardial infarction, lung cancer, kidney cancer, and lower-respiratory tract infections [9]. Results from the "Effects of Low-Level Air Pollution: A Study in Europe (ELAPSE)" project have shown elevated asthma, chronic obstructive pulmonary disease (COPD), and stroke incidence with higher long-term exposure to NO_2, $PM_{2.5}$, and black carbon pollutants [10-12], and elevated lung cancer incidence with higher exposure to $PM_{2.5}$ [13]. Similarly, the Danish "Health Effects of Air Pollution Components, Noise and Socioeconomic Status (HERMES)" project found an association between long-term exposure to $PM_{2.5}$ and higher risks of stroke and myocardial infarction [14-16], and between NO_2 pollutant and higher diabetes risk [17]. A similar association was also shown with short-term exposures to PM_{10} (particulate-matter diameter ≤10 μm) and $PM_{2.5}$ pollutants and increased respiratory hospital admissions in Poland [18].

Although the association between long-term exposure to air pollution and health is well-documented, most research is focused on mortality outcomes [4 7 19-32]. This is because of the ease of access to mortality databases, the less strict ethical considerations, and the straightforward analysis of mortality that occurs only once in the individual's life [2].

Studies that investigate the association between long-term air pollution and health outcomes other than mortality often estimate a combined risk of mortality with the other health indicators such as hospital admissions or doctoral prescriptions and focus only on analysing the first hospital admission [12 14 16]. Besides, variations in the magnitude of effect estimates among studies have been identified in numerous systematic literature reviews and meta-analyses [2 33-36]. These discrepancies may be attributed to differences in the assessment of air pollution exposure, such as residential versus combined residential and workplace assessments, high versus low spatial resolution, baseline versus annual assessments, or temporal resolution including hourly, daily, weekly, monthly, or yearly measurements. Other contributing factors include variations in exposure levels, outcome measurements, study locations, population characteristics (e.g., age, sex, socioeconomic status), and study designs (e.g., cohort, cross-sectional, case-crossover, case-control, and ecological) and methodologies (e.g., survival analysis, multilevel mixed effects modelling, structural equation modelling, and difference in differences approach) [35 36]. The differences in estimates also underscore the necessity for further research to obtain more conclusive evidence regarding the association between air pollution and health.

Additionally, over the past decade, the majority of literature has concentrated on investigating the health implications of NO_2, PM_{10}, and $PM_{2.5}$ exposure, while other pollutants such as sulphur dioxide (SO_2) were less studied [2 23 35]. This lack of emphasis on SO_2 may be attributed to a substantial decrease in its emissions, driven by the diminished use of coal in the energy sector and the desulfurization efforts in cars and power plants in developed nations [37]. Consequently, SO_2 has become a lower priority compared to other pollutants. Nonetheless, investigating the link between prolonged exposure to SO_2 and health outcomes, such as hospital admissions, remains crucial as even at reduced levels, SO_2 can still pose harm to human health [37].

Finally, despite the literature availability on air pollution in relation to cardiovascular and respiratory diseases [2 3], other health complications such as mental/behavioural disorders have not been thoroughly studied [38 39]. A recent study has also found an association between short-term exposure to $PM_{2.5}$ and hospital admissions for rarely studied infectious diseases such as sepsis, kidney failure, urinary tract and skin infections [40]. This suggests the need for more studies that investigate the association between air pollution and less studied health outcomes such as infectious diseases and mental/behavioural disorders.

Taken collectively, this study examines the association between long-term exposure to air pollution and all-cause and cause-specific hospital admissions. We distinguish between hospital admissions related to cardiovascular, respiratory, infectious, mental/behavioural disorders, and other illnesses. In examining these associations, we will be relying on administrative longitudinal individual-level data from a large Scottish cohort that will be linked to yearly 1 km^2 air pollution data using the individuals' residential postcodes for each year between 2002 and 2017. Our study attempts to develop previous research by contributing to the existing evidence on air pollution and health through the examination of multiple air pollutants (i.e., NO_2, SO_2, PM_{10}, and $PM_{2.5}$) in relation to multiple hospital admission outcomes over time.

2. Methods

2.1. Design, sample, and structure

We used individual-level longitudinal prospective-cohort data from the Scottish Longitudinal Study (SLS). This is a representative dataset on 5% of the Scottish population which includes information from linked censuses (2001 and 2011 in the case of our study) on individuals' socio-demographics, vital events records on marriages, births, and mortality (up to 2013), and migration and residential histories at the postcode level [7]. To supplement SLS mortality data after 2013 through 2017, data on the individuals' year and month of death were obtained from Public Health Scotland (PHS) via Electronic Data Research and Innovation Service (eDRIS) [7].

For this study, we followed 202,237 individuals aged 17^+ with a total of 2,810,414 person-years between 2002 and 2017. Basic demographic information regarding gender, ethnicity, country of birth, marital status, education, and occupation were based on the 2001 and 2011 censuses. The usage of information from two censuses was essential as some of the demographic characteristics (e.g., marital status, education and occupation) can change over time. Additionally, we only considered individuals aged 17 and over because the mechanisms by which air pollution impacts health may differ between adults and children. Future research would benefit from assessing the impacts of air pollution on health among children.

Initially, information was sought for all identified individuals in the SLS aged 16 and above during the 2001 census (totalling 205,732 individuals). However, 36 individuals were excluded due to the absence of gender data, and 1,127 individuals (constituting 0.55%) were excluded due to missing postcode history. We also dropped 2001 observations (n=204,569) due to missing data on deaths that occurred prior to the census date (April 2001), which made 2001 death rate incomparable to the death rates at later years [7]. The SLS cohort structure and the possibilities of entering and exiting the study between 2002 and 2017 are illustrated in a Lexis-diagram (Figure 1).

2.2. Variables

2.2.1. Hospital admissions

The month, year, and main underlying cause of hospital admissions were obtained from PHS and linked to SLS data by eDRIS using the individual's unique identification number. We then calculated the yearly count of all-cause and cause-specific hospital admissions for each SLS individual. Individuals who did not go to the hospital in a certain year were given a count of zero. The International Statistical Classification of Diseases, 10th Revision (ICD-10) codes of the main underlying cause of hospital admission were used to determine the cause-specific outcomes (Supplementary material Table 1) as follows: cardiovascular (I00-I99), respiratory (J00-J99), infectious (A00-B99), and mental/behavioural disorders (F00-F99). It should be noted that the infectious categorisation does not include respiratory viral infections covered within the respiratory categorisation of J00-J99.

2.2.2. Air pollution

Annual air pollution data encompassing all sources, including road traffic and industrial/combustion processes for NO_2, SO_2, PM_{10}, and $PM_{2.5}$, was acquired from the "Department for Environment Food and Rural Affairs (DEFRA)" [41]. These data consist of raster representations indicating the average annual concentrations of pollutants measured in $\mu g/m^3$. Air dispersion models were utilized to estimate these concentrations at a spatial resolution of 1 Km^2 on the UK National Grid [41]. These data were in turn linked to postcodes in Scotland obtained from the National Records of Scotland that fell within the 1 Km^2 raster cells for each year between 2002 and 2017. Figure 2 describes the concentrations of NO_2, SO_2, PM_{10}, and $PM_{2.5}$ pollutants in 2017 across the residential postcodes in Scotland. In a second step, we linked the data file of matched annual air pollution concentrations with postcodes with the data file of SLS residential postcode histories. Where individuals changed residential postcodes during a certain year, the postcode with the lengthiest monthly duration within that year was the one used [7].

2.2.3. Study covariates

The association between air pollution and hospital admissions is influenced by several factors: (1) socioeconomic (e.g. age, gender, income, education, occupation, ethnicity, country of birth, economic activity) [2 8 42]; (2) individual-lifestyle (e.g. pre-existing diseases, smoking, alcohol consumption, exercise, obesity) [8 43]; (3) contextual (e.g. neighbourhood, deprivation, rural-urban classifications)[43 44]; and (4) environmental (e.g. season, temperature, humidity, rainfall, wind)[45].

Accordingly, the following individual-level baseline socioeconomic covariates collected at the 2001 and 2011 censuses were included in our study: age, squared age (age^2; to account for possible non-linear age effects), gender, ethnicity, country of birth, marital status, education, and occupation (Supplementary material Table 2). We additionally included a yearly-varying place of residence variable that classifies the individuals' residential postcodes into six rural-urban categories, based on the data-zone where the postcode is located. Calendar year dummies were also included for each year between 2002 and 2017 to control for the time trend.

2.3.Analysis

All-cause and cause-specific hospital admission counts, socioeconomic and place of residence covariates were described using frequencies, percentages, means, variances and standard deviations (SD). The mean and correlation between the four pollutants were also calculated. Given the high correlations between NO_2, PM_{10}, and $PM_{2.5}$ (Pearson's coefficient ≥ 0.7), the association of the four pollutants with all-cause and cause-specific hospital admissions was assessed in separate models. SO_2 showed weak correlations (Pearson's coefficient <0.5) with the other pollutants, which enabled us to assess in a sensitivity analysis the association between NO_2, PM_{10}, and $PM_{2.5}$ and hospital admissions in two-pollutant models adjusting for SO_2.

We used multilevel mixed-effects negative binomial regression with a random intercept for individuals to study the association between air pollution and all-cause and cause-specific (cardiovascular, respiratory, infectious, mental/behavioural disorders, and other-causes) hospital admissions. The negative binomial model was used because around 85% of annual individual observations did not include an admission into a hospital (a skewed distribution with a high number of zeros). Therefore, the variance of the count of hospital admissions is greater than the mean (Table 1), and the overdispersion parameter (α) for all hospital admission outcomes is greater than zero (Supplementary material Tables 4-9). This makes the negative binomial regression that can account for overdispersion in hospital admission counts more appropriate than Poisson regression[46]. In a sensitivity analysis, we treated the hospital admission outcomes as binary variables (0=Not admitted to hospital; 1=Admitted to hospital) and used multilevel mixed-effects logistic regression for analysis.

Three stepwise models were developed: Model 1 included the air pollution independent variable and controlled for age, age^2, gender and calendar year dummies; Model 2 controlled additionally for ethnicity, country of birth, marital status, education, and occupation; and Model 3 included the place of residence covariate.

The association of all-cause and cause-specific hospital admissions with the socioeconomic and place of residence covariates is shown in Supplementary material Tables 4-15. Results of the multilevel negative binomial regression are presented as incidence rate ratios (IRRs) with 95% confidence intervals (CIs) per 1 $\mu g/m^3$ increase in pollutants and visualised in coefficient plots. Statistical significance is at a p-value of less than 0.05. Statistical analysis was conducted in STATA$_{16}$. Coefficient plots using ggplot package were performed in R Studio. Spatial pre-processing was conducted in ArcGIS-Pro software.

The equation for the calculation of the IRRs is as follows:

$$IRR_{ti} = e^{\beta_0 + U_{0i} + \beta 1 \text{overall pollutant concentration}_{ti} + \beta n \text{Covariates}_{ti} + \varepsilon_{ti}}$$

Where *IRRti* is the incident rate ratio for the hospital admission outcome for individuals *i* at year *t* ; *β1* is the air pollution coefficient, *βn* represents coefficients of the other study covariates and *β0* is the fixed intercept; U_{0i} is level 2 random intercept of individuals; ε_{ti} are the model residuals.

2.3.1. Additional analysis

To assess the impact of cumulative air pollution (CAP) exposure from year to year and across the different places of residence between 2002 and 2017, we repeated models 1 to 3 replacing the yearly air pollution variable with average CAP exposure. Following the methods of Bentayeb et al. (2015) [47], the CAP variable was calculated as the average of cumulative yearly exposure before censoring or death. Thus, for every individual, we computed the mean pollutant concentration from the baseline year (2002) to each year of follow-up (e.g., exposure in 2004 was calculated as the average of annual concentrations from 2002 to 2004; in 2005, from 2002 to 2005, etc).

2.4. Ethics

On May 14th, 2020, ethical clearance was obtained from the Ethics Committee of the University of St Andrews. Approval for accessing SLS data was granted by the SLS board, and access to linked data from PHS was authorized through the application to the Public Benefit and Privacy Panel for Health and Social Care (HSC-PBPP). Consent was not deemed necessary for this study as it relied on secondary data analysis. The tasks of data cleaning, management, and analysis were conducted within the secure settings of the SLS. Final outputs were cleared following a thorough screening protocol. Information classified as potentially disclosive such as full dates of birth, death and hospital admissions were not given for analysis. Instead, the researcher had access to the month and year of those events.

2.5. Patient and public involvement

The research conducted was carried out on the SLS quantitative data. A summary of the main findings of this study was shared with the SLS team and published on their website. Individuals in the SLS dataset are anonymised, and therefore it is impossible to share the data directly with each individual participant. Patients were not involved within the direct creation or carrying out of the research study. Instead, we had access to the month and year of mortality and hospital admissions records of each anonymised individual within the SLS dataset.

3. Results

3.1. Hospital admissions description

Around 15% of person-years involved an admission into a hospital. The mean of all-cause hospital admissions was 0.3 (variance=1.6; SD=1.3) with 8.6% of yearly individual observations including one hospital admission, 2.9% including two admissions, and 3.5% including 3 or more admissions. The mean of cardiovascular, respiratory, infectious, mental/behavioural disorders, and other-causes hospital admission count was 0.04 (variance=0.14; SD=0.37), 0.03 (variance=0.1; SD=0.32), 0.005 (variance=0.01; SD=0.1), 0.003 (variance=0.01; SD=0.1), and 0.26 (variance=1.18; SD=1.1), respectively (Table 1).

3.2.Study covariates description

Most individuals were females (53% versus 47% for males), belonged to white ethnicity (~95%), were born in Scotland (~87%), were married (~55%), had a post-school/university education (24% in 2002-2010; 34% in 2011-2017), worked in white collar high skilled (27% in 2002-2010; 33% in 2011-2017) or white collar low skilled (25% in 2002-2010; 29% in 2011-2017) jobs, and lived in large urban (35%) areas (Table 2).

3.3.Air pollution description

Fluctuations in air pollutant levels were observed across the years 2002 to 2017, with higher concentrations recorded in the initial three years (2002-2004) compared to subsequent years (Supplementary material Figure 1). Over the period from 2002 to 2017, the mean concentrations ± SD of NO_2, SO_2, PM_{10}, and $PM_{2.5}$ pollutants were 11.9 ± 6.4 , 1.9 ± 1.5, 11.3 ± 2.1, and 7.2 ± 1.6 μg/m^3, respectively (Supplementary material Table 3). The average annual mean concentrations for NO_2, PM_{10}, and $PM_{2.5}$ pollutants are lower than the 2005 WHO guidelines of 40 μg/m^3 for NO_2, 20 μg/m^3 for PM_{10}, and 10 μg/m^3 for $PM_{2.5}$, however, the concentrations of NO_2 and $PM_{2.5}$ are higher than the most recent 2021 WHO guidelines of 10 μg/m^3 for NO_2, and 5 μg/m^3 for $PM_{2.5}$ [48].

Significant correlations (Pearson's coefficient ≥ 0.7) were observed among NO_2, PM_{10}, and $PM_{2.5}$ (Supplementary material Table 3), potentially attributed to the atmospheric chemical reactions involving these pollutants [19].

3.4.The association of air pollution with hospital admissions

Results revealed higher incidence rate ratios for cardiovascular (except for model 3), respiratory, and infectious hospital admissions with increasing concentrations of NO_2, PM_{10} (except for model 3) and $PM_{2.5}$ pollutants. After adjusting for socioeconomic variables and place of residence (model 3), the incidence rate for respiratory hospital admissions increased by 4.2% (95%CI=2.1%-6.3%) and 1.2% (95%CI=0.8%-1.7%) per 1 μg/m^3 increase in $PM_{2.5}$ and NO_2, respectively. Higher exposure to SO_2 was associated with higher rates of respiratory hospital admissions only in models 1 and 2. Hospital admissions for mental/behavioural disorders were associated with higher exposure to NO_2 (IRR=1.021; 95%CI=1.011-1.031). Contrary to our expectations, higher exposure to SO_2 was associated with lower incidence rates for all-cause, mental/behavioural disorders, and other-causes hospital admissions in models 2 and 3 (Figure 3).

In a sensitivity analysis considering hospital admissions as binary (yes/no) outcomes, we observed similar results whereby a higher exposure to NO_2, PM_{10}, and $PM_{2.5}$ pollutants was associated with higher odds of cardiovascular, respiratory, and infectious hospital admissions. An exception was the absence of an association between NO_2 and $PM_{2.5}$ pollutants and all-cause hospital admission treated as a binary (yes/no) outcome (Supplementary material Figure 3). Similar results were observed in two-pollutant models, which include SO_2 and one of the other three pollutants in the same model (Supplementary material Figures 2 and 4).

3.4.1. Average CAP results

Stronger positive associations were noticed in the analysis of average CAP effect on hospital admissions compared to the analysis of yearly air pollution effects. Higher average CAP concentrations for NO_2, PM_{10}, and $PM_{2.5}$ pollutants were associated with higher incidence rate ratios for all-cause, cardiovascular, respiratory, infectious, mental/behavioural disorders, and other-causes hospital admissions. Cumulative exposure to SO_2 was associated with higher rates of respiratory hospital admissions in all three models. The incidence rate for respiratory hospital admissions increased by 12.6% (95%CI=9.9%-15.5%), 6.8% (95%CI=5.1%-8.5%), 2.8% (95%CI=1.1%-4.6%), and 2.1% (95%CI=1.7%-2.6%) per 1 $\mu g/m^3$ increase in average cumulative exposure to $PM_{2.5}$, PM_{10}, SO_2 and NO_2 pollutants, respectively. Higher cumulative exposure to SO_2 is not associated anymore with a lower incidence of mental/behavioural disorders hospital admissions (Figure 4). Similar results were noted when hospital admissions were treated as binary (yes/no) outcomes (Supplementary material Figure 5). This shows that long-term average cumulative exposure to air pollution has a greater effect on both physical and mental health outcomes, resulting in higher rates of hospital admissions.

4. Discussion

This study used a large and representative census-based individual-level cohort data linked to 1 km^2 resolution air pollution at the postcode level between 2002 and 2017. Analysis supported an association between long-term exposure to NO_2, SO_2, PM_{10} and $PM_{2.5}$ pollutants and higher rates of all-cause, cardiovascular, respiratory, infectious, mental/behavioural disorders, and other-causes hospital admissions. The direction of these positive associations is concordant with previous studies investigating the long-term effects of different air pollutants on all-cause [8 49 50], cardiovascular [9 12 16 49], respiratory [9-11 50], and mental/behavioural disorders [51] hospital admissions.

Given the differences in population size, study location, air pollution exposure assessment and level, outcomes measurement, and methodology, we cannot compare directly the magnitude of our estimates to the estimates from other studies. Rather, we can conclude that our findings are in line with what previous literature has suggested with some noted heterogenieties. For example, Yazdi et al. (2021) found that with every 1 $\mu g/m^3$ increase in $PM_{2.5}$ and NO_2 pollutants, the risk of stroke hospital admission increases by 0.0091% and 0.00059%, respectively [49]. Gandini et al. (2018) found higher hazard ratios of 1.05/1.05, 1.03/1.02, 1.15/1.14, 1.18/1.20, 1.24/1.20, 1.06/1.06, and 1.10/1.05 for circulatory system diseases, respiratory system diseases, stroke, lung cancer, kidney cancer, all cancers excluding lung cancer, and Lower Respiratory Tract Infections (LRTI) first-ever hospital admissions with every 10 μg/m^3 higher exposure to $PM_{2.5}$/NO_2 pollutants [9]. Similarly, Liu et al. (2021) found 1.17 and 1.11 higher hazard ratios of COPD first-ever hospital admission with every 5 μg/m^3 and 10 μg/m^3 higher exposure to $PM_{2.5}$ and NO_2 pollutants, respectively [11].

Some of these heterogenities might be due to residual confounding from unobserved factors. For example, our models adjusted only for socio-demographic and economic factors of individuals (e.g., age, squared age, gender, education, marital status, ethnicity, country of birth, and occupation), as well as for the time trend (i.e., year dummies) and place of residence (i.e., rural-urban area classifications). However, lifestyle covariates at the individual level, such as smoking, exercise, alcohol consumption, or body mass index, which could influence the relationship between air pollution and hospital admissions, were not considered due to their unavailability in the SLS register-based data. Accounting for these lifestyle covariates could result in a slight adjustment of association estimates, typically within the range of a 1–2% increase or decrease, depending on the specific outcome, as indicated by other studies [4 6 25 52-54]. Similarly, our models did not incorporate environmental factors at the place of residence, such as noise pollution or the absence of green spaces. However, the impact on association magnitudes is anticipated to be minimal, with estimates showing an attenuation of 0-3% increase or decrease, as documented in previous studies [17 54 55]. The adjustment of our models for the individual-level socioeconomic and rural-urban covariates might also absorb some of the residual confounding due to the interconnections between the individuals' socioeconomic circumstances, their lifestyle, and their surrounding environment. Additionally, our models were not adjusted for weather factors such as temperature, humidity, rainfall, or wind, which might impact the association between air pollution and hospital admissions. Nevertheless, the air pollution data used in this study are modelled yearly data using air dispersion models and meteorological factors such as temperature and wind are accounted for within the modelling framework [41].

As for the positive association between long-term exposure to NO_2, PM_{10}, and $PM_{2.5}$ and infectious hospital admissions, the literature on this outcome is scarce. Yet, one study examining the association between short-term exposure to $PM_{2.5}$ air pollution and hospital admissions for infectious diseases such as sepsis, urinary tract and skin infections corroborate our findings [40].

Our study showed that yearly exposures to different air pollutants can be associated with different hospital admission outcomes. For example, NO_2 was associated with all hospital admission outcomes, SO_2 was related to respiratory hospital admissions, while PM_{10} and $PM_{2.5}$ were associated with respiratory and infectious hospital admissions. This could be related to the mechnisims of action of specific pollutants in producing toxic effects. Gaseous pollutants (e.g., NO_2 and SO_2) are irritants of the respiratory system that can penetrate deep in the lungs inducing respiratory irritation, mucus production, coughing, wheezing, bronchoconstriction, airways inflammation, bronchospasm and pulmonary-edema [2 56 57]. Long-term exposure to NO_2 is also related to the weakening of the immune system and to cardiovscular problems such as ventricle hypertrophy [56]. Additionally, NO_2 exposure can trigger neuronal injury and neurological disorders through the formation of Reactive Oxygen Species (ROS) and free radicals [58 59].

Despite the harmful effect of gaseous air pollutants (e.g., NO_2 and SO_2) on health, particulate-matter especially particles with smaller diameters (e.g. $PM_{2.5}$) have the greatest effect as shown in our study and particularly on respiratory health. Particulate matter can penetrate deeply into the respiratory system through air breathing reaching alveoli and blood stream. This will initiate the oxidative stress mechanism and the production of ROS affecting various systems in the human body including the respiratory, cardiovascular, immune, and neural systems [2 56 57].

We also observed elevated estimates for average cumulative compared to yearly air pollution exposures in relation to hospital admissions, particularly in relation to mental and behavioural disorders admissions. Whilst yearly exposure to SO_2 showed an unexpected negative association with mental/behavioural disorders hospital admissions, which could be attributed to the small variation in the yearly concentrations of SO_2 across time (Supplementary material Figure 1) or to the residual confounding from unobserved factors, average cumulative exposure to SO_2 did not show this association. Higher exposure to cumulative PM_{10} and $PM_{2.5}$ pollutants was also associated with a higher incidence of mental/behavioural disorders hospital admissions, while this association was not observed for yearly PM_{10} and $PM_{2.5}$ exposures. This shows that the average accumulation of air pollution exposures across time and through different places of residence has a greater effect on health, especially for mental and behavioural complications that take time to show-up.

Finally, adjusting our analysis for the place of residence (model 3), reduced the magnitude of associations between hospital admission outcomes and all the four pollutants. This 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 illness. For example, air pollution emission sources are more abundant in urban areas and factors that can absorb the air pollution emissions (e.g., green spaces) are less available. Confirming to this, Figure 2 shows higher concentrations of traffic-related (i.e., NO_2) and industrial (i.e., SO_2) air pollution in the urban Central Belt of Scotland and in large cities. Figure 2 also shows high concentrations of PM_{10} and $PM_{2.5}$ in major cities and along the east coast because particulate-matter pollution originates from both traffic and industrial sources and can travel for long distances based on the wind direction and other metereological and topological factors [60-62].

Despite the strengths of this study, it has some limitations. First, individuals were followed for 16 years (2002-2017); thus, bias may result from previous life-time exposures to air pollution at different residences. As shown in our analysis, average CAP exposure across the 16 years of study period had a greater effect on hospital admission rates compared to yearly exposures, particularly for mental/behavioural disorders.

Second, the individuals' exposure to ambient air pollution was assessed at a yearly rather than monthly or daily basis which did not allow for seasonal variations, and the residential postcode was used as a proxy for the individual's exposure to air pollution. This does not necessarily equate to the true personal exposure, which can happen indoors, at the workplace, during daily outdoor activities, and through commuting patterns. Yet, the emergence of real-time GPS data would create an opportunity for future research to analyse real-time exposure to ambient air pollution by knowing the real-time location of individuals.

Finally, we could not account for some important lifestyle covariates (e.g., smoking or exercise) as discussed previously due to the unavailability of this information in the SLS census-based data. However, using administrative data has its advantages including high quality large representative data, less selection bias, and the provision of continuous longitudinal information on residential postcode histories, emigrations and immigrations, and mortality and births vital events. Knowing the exact postcode histories of individuals between 2002 and 2017 as provided in the SLS census-based data was also essential to obtain accurate assessments of individual's residential air pollution exposure.

5. Conclusion

This study supported an association between long-term exposure to air pollution and all-cause and cause-specific hospital admissions. Air pollution was associated with higher rates of hospital admissions for both physical (e.g., respiratory, cardiovascular, and infectious) and mental/behavioural diseases. Policies and interventions on air pollution through stricter environmental regulations, long-term planning, and the shifting toward renewable energy could eventually help ease the hospital-care burden in Scotland in the long-term. Specifically, policies aiming at making the zero-emission zones – small areas where only zero-emission vehicles, pedestrians, and bikes are permitted – more abundant in Scotland, especially in the central belt of Scotland where busy and more polluted cities such as Glasgow and Edinburgh are located, would improve the air quality and in turn lower the hospital-care burden in those cities. For future research, it is also recommended to study the impact of air pollution on health outcomes synergically alongside other environmental issues such as weather fluctuations and climate change.

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Figure 1: Possibilities of entering and exiting the cohort for 8 hypothetical individuals demonstrated in a Lexis-diagram.

Numbers and percentages in the diagram key are the author's own calculations based on the Scottish Longitudinal Study data. The green vertical line represents the starting year of follow-up (2002) after dropping the 2001 observations; Individuals can either be followed-up until the last year of observation which is 2017 where they are censored (e.g., individuals 1 and 6), or can die (e.g., individuals 2, 4, and 5), or can migrate without returning to Scotland during the observation period 2002-2017 (e.g., individual 3), or can migrate and then return to Scotland and thus to our study within the follow-up period (e.g., individuals 7 and 8). In this context, individual 7 is being followed between 2002 and 2005 and then between 2010 and 2017, inclusive. The years spent by individual 7 outside Scotland (2006-2009) due to migration are dropped from the analysis. A similar situation is experienced by individual 8 who was present in 2002 and then was followed from 2012 to 2017 with years spent abroad (2003-2011) due to migration being removed from the analysis. This lexis diagram further reveals that individuals can enter and exit the cohort based on four scenarios. First, individuals can be followed for the whole study period (2002-2017) and then either be censored, migrate, or die in 2017. Second, individuals can exit the cohort before 2017 due to death at any year during the follow-up period (2002-2017). Third, individuals can exit the cohort due to migration out of Scotland, without returning during the follow-up time (2002-2017). Fourth, individuals can exit the cohort due to out migration, but then they re-enter the cohort in later years due to returning to Scotland within the follow-up time (2002-2017). If individuals migrate out of Scotland and then return in the same year, this short-term migration is disregarded because the individual stayed in Scotland for some months of the full calendar year. If an individual comes back to Scotland from a previous year migration and then migrates out again within the same year, the individuals' observation for that year is kept because some months out of the full calendar year have been spent in Scotland.

Figure 2: Four maps illustrating the concentrations of NO_2, SO_2, PM_{10}, and $PM_{2.5}$ 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 [41] and postcode boundaries shapefiles obtained from the National Records of Scotland. Both DEFRA and National Records of Scotland shapefiles are governed under the Open Government Licence v.3.0.

Table 1: Description of hospital admissions (N=2,810,414 observations; Study period=2002-2017)

	Frequency	%	Mean	Variance	SD
All-cause hospital admission			0.33	1.64	1.28
0	2388584	85			
1	241717	8.6			
2	80813	2.9			
3+	99300	3.5			
Cardiovascular hospital admission			0.04	0.14	0.37
0	2753992	98			
1	29432	1.1			
2	13091	0.5			
3+	13899	0.5			
Respiratory hospital admission			0.03	0.10	0.32
0	2773192	98.7			
1	19685	0.7			
2	9538	0.3			
3+	7999	0.3			
Infectious hospital admission			0.005	0.01	0.10
0	2802217	99.7			
1	5174	0.2			
2	1937	0.1			
3+	1086	0.04			
Mental/behavioural disorders hospital admission			0.003	0.01	0.10
0	2804737	99.8			
1	3521	0.1			
2	1263	0.04			
3+	893	0.03			
Other-causes hospital admission			0.26	1.18	1.09
0	2448665	87.1			
1	225980	8.0			
2	66976	2.4			
3+	68793	2.5			

Data source: Author's own calculations based on the Scottish Longitudinal Study data.

Table 2: Description of socioeconomic study covariates (N=2,810,414 observations; Study period=2002-2017)

Census-fixed socioeconomic covariates (N=202,237 individuals)					
		2002-2010		**2011-2017**	
		Frequency	**%**	**Frequency**	**%**
Gender	Male	94859	46.9	80282	46.9
	Female	107314	53.1	90753	53.1
Ethnicity	White	192485	95.2	163571	95.6
	Not-white	9688	4.8	7464	4.4
Ethnicity-3 categories	White	192485	95.2	163571	95.6
	Pakistani/Bangladeshi/Indian	1525	0.8	1323	0.8
	Other ethnicities	8163	4.0	6141	3.6
Country of birth	Born in Scotland	173229	85.7	149018	87.1
	Born in rest of UK	19649	9.7	15340	9.0
	Not born in UK	9295	4.6	6677	3.9
Marital Status	Married	104386	51.6	93867	54.9
	Single never married	58396	28.9	38979	22.8
	Divorced/separated/widowed	38481	19.0	37770	22.1
	No response	910	0.5	419	0.2
Education	No educational qualification	60311	29.8	53223	31.1
	Intermediate school	44854	22.2	36561	21.4
	High school	27844	13.8	20343	11.9
	Post-school/university	48251	23.9	58781	34.4
	Still a student	688	0.3	53	0.0
	No response/not recoded	20225	10.0	2074	1.2
Occupation	White collar high skilled	54299	26.9	55595	32.5
	White collar low skilled	50325	24.9	49202	28.8
	Blue collar high skilled	20530	10.2	20500	12.0
	Blue collar low skilled	46718	23.1	38173	22.3
	Not applicable: students/never worked	25535	12.6	5793	3.4
	No response	4766	2.4	1772	1.0
Total		202173	100	171035	100
Yearly varying covariates (N=2,810,414 observations)					
Age		Mean=52.53	SD=17.57		
		Frequency	**%**		
Place of residence	Large Urban areas	977697	34.8		
	Other urban areas	815048	29.0		
	Accessible small towns	207083	7.4		
	Remote small towns	67776	2.4		
	Accessible Rural areas	528929	18.8		
	Remote rural areas	213881	7.6		

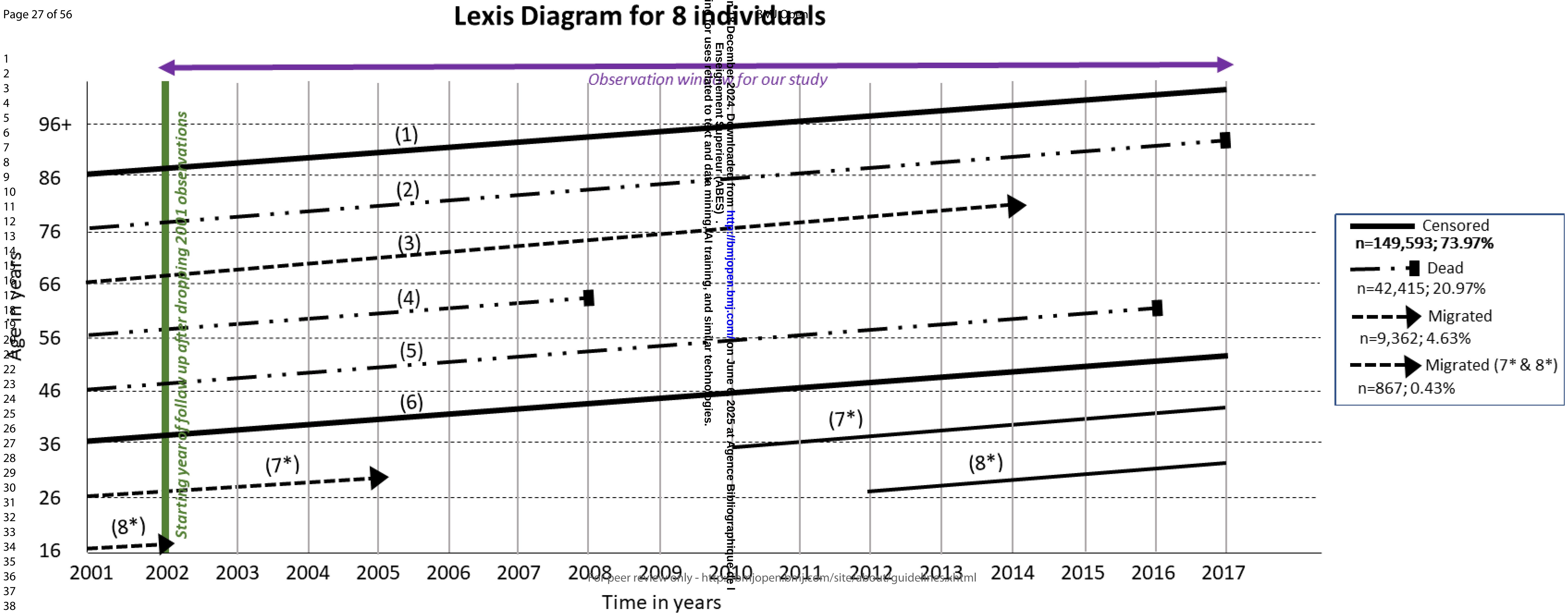
Data source: Author's own calculations based on the Scottish Longitudinal Study data.
Z test to compare the percentages between 2002-2010 and 2011-2017 is equal to 0.0046 with a P-value of 0.996 indicating that there is no significant difference in the percentages between the two study periods.

Figure 3: The association of all-cause and cause-specific hospital admissions with NO_2, SO_2, PM_{10}, and $PM_{2.5}$ air pollutants in separate multilevel mixed-effects negative binomial models (N=202,237 individuals and 2,810,414 observations).

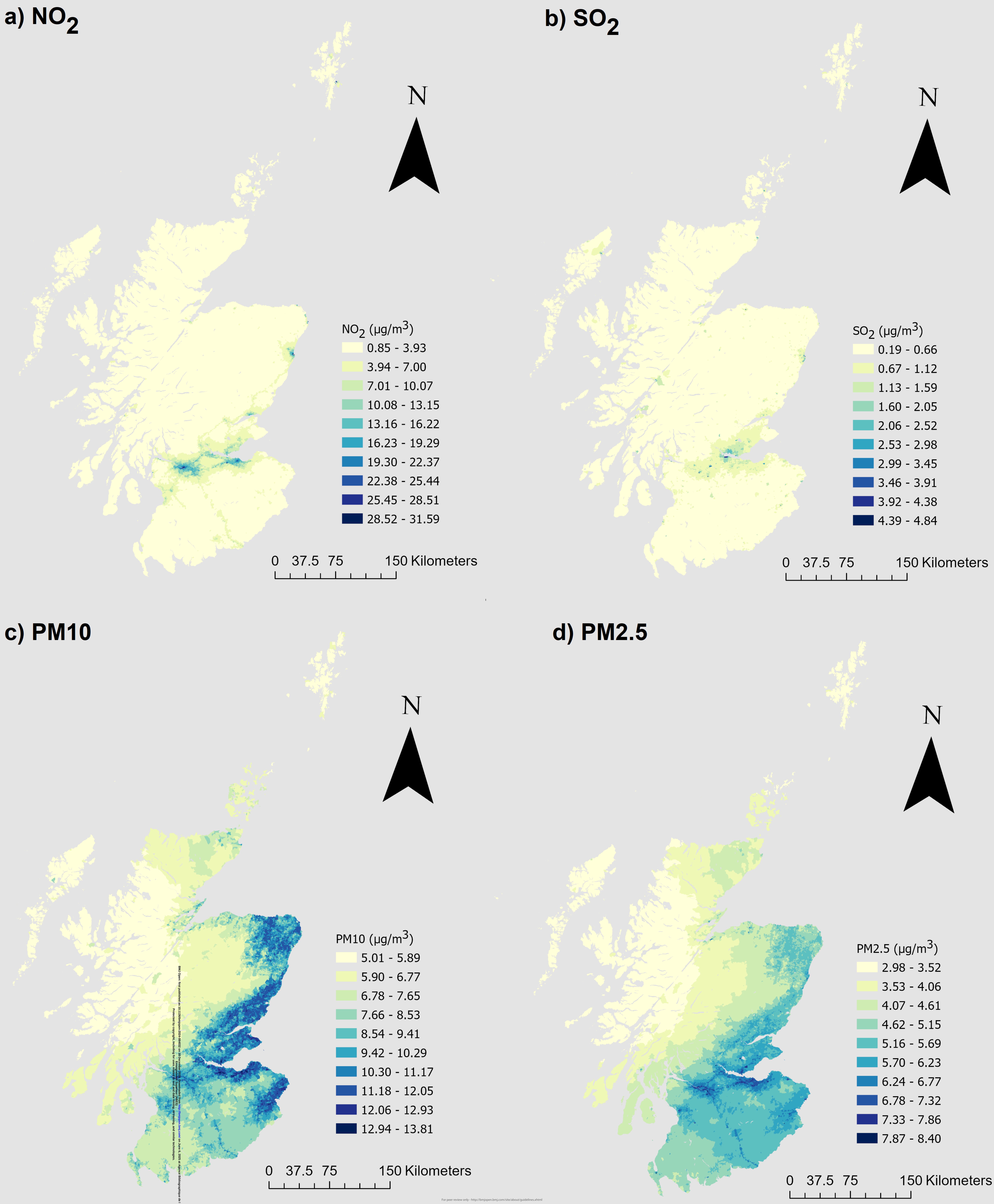
Data source: Author's own calculations based on the Scottish Longitudinal Study data; The dashed line is placed at IRR=1 as a cut-off for statistically insignificant results; Model 1 is adjusted for age, age^2, gender and calendar year dummies; Model 2= Model 1 + ethnicity + country of birth + marital status + education + occupation; Model 3= Model 2 + place of residence.

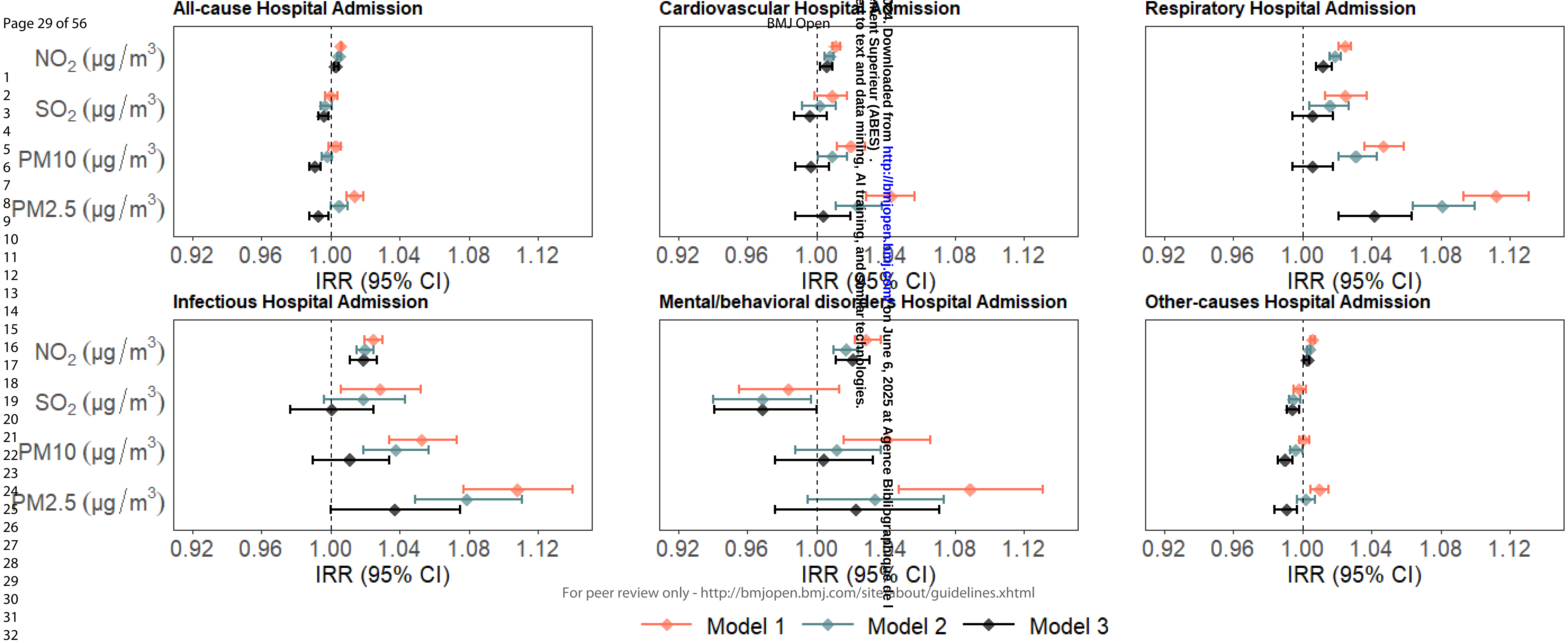
Figure 4: The association of all-cause and cause-specific hospital admissions with average cumulative exposure to NO_2, SO_2, PM10, and PM2.5 air pollutants (N=202,237 individuals and 2,810,414 observations).

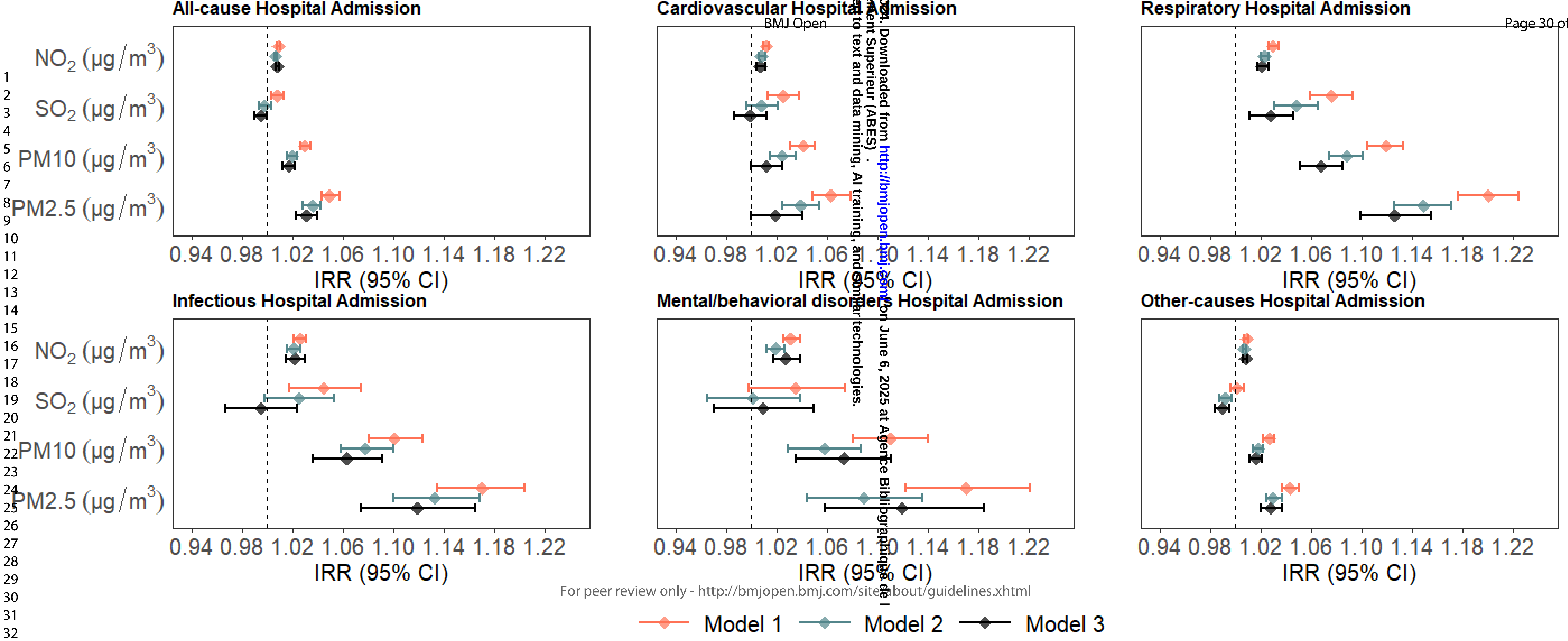
Data source: Author's own calculations based on the Scottish Longitudinal Study data; The dashed line is placed at IRR=1 as a cut-off for statistically insignificant results; Model 1 is adjusted for age, age^2, gender and calendar year dummies; Model 2= Model 1 + ethnicity + country of birth + marital status + education + occupation; Model 3= Model 2 + Place of residence.



Lexis Diagram for 8 individuals
Observation window for our study
Starting year of follow up after dropping 2001 observations
Age in years
96+
86
76
66
56
46
36
26
16
(1)
(2)
(3)
(4)
(5)
(6)
(7*)
(8*)
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
Time in years
Censored
n=149,593; 73.97%
Dead
n=42,415; 20.97%
Migrated
n=9,362; 4.63%
Migrated (7* & 8*)
n=867; 0.43%


a) NO_2
N
NO_2 (µg/m^3)
0.85 - 3.93
3.94 - 7.00
7.01 - 10.07
10.08 - 13.15
13.16 - 16.22
16.23 - 19.29
19.30 - 22.37
22.38 - 25.44
25.45 - 28.51
28.52 - 31.59
0 37.5 75 150 Kilometers
b) SO_2
N
SO_2 (µg/m^3)
0.19 - 0.66
0.67 - 1.12
1.13 - 1.59
1.60 - 2.05
2.06 - 2.52
2.53 - 2.98
2.99 - 3.45
3.46 - 3.91
3.92 - 4.38
4.39 - 4.84
0 37.5 75 150 Kilometers
c) PM10
N
PM10 (µg/m^3)
5.01 - 5.89
5.90 - 6.77
6.78 - 7.65
7.66 - 8.53
8.54 - 9.41
9.42 - 10.29
10.30 - 11.17
11.18 - 12.05
12.06 - 12.93
12.94 - 13.81
0 37.5 75 150 Kilometers
d) PM2.5
N
PM2.5 (µg/m^3)
2.98 - 3.52
3.53 - 4.06
4.07 - 4.61
4.62 - 5.15
5.16 - 5.69
5.70 - 6.23
6.24 - 6.77
6.78 - 7.32
7.33 - 7.86
7.87 - 8.40
0 37.5 75 150 Kilometers


All-cause Hospital Admission
Cardiovascular Hospital Admission
Respiratory Hospital Admission
Infectious Hospital Admission
Mental/behavioral disorders Hospital Admission
Other-causes Hospital Admission
NO2 (μg/m3)
SO2 (μg/m3)
PM10 (μg/m3)
PM2.5 (μg/m3)
0.92 0.96 1.00 1.04 1.08 1.12
IRR (95% CI)
Model 1
Model 2
Model 3


All-cause Hospital Admission
Cardiovascular Hospital Admission
Respiratory Hospital Admission
Infectious Hospital Admission
Mental/behavioral disorders Hospital Admission
Other-causes Hospital Admission
NO2 (μg/m3)
SO2 (μg/m3)
PM10 (μg/m3)
PM2.5 (μg/m3)
0.94 0.98 1.02 1.06 1.10 1.14 1.18 1.22
IRR (95% CI)
Model 1
Model 2
Model 3

Supplemental Material

Contents

ICD-10 codes for classification of the main cause of hospital admissions

Table 1: Classification of the cause-specific hospital admission outcomes based on the ICD-10 codes of the main underlying cause of hospital admission

Cause-specific hospital admission outcomes	ICD-10 codes of the main underlying cause of hospital admission
Cardiovascular	I00-I99
Respiratory	J00-J99
Infectious	A00-B99
Mental and behavioural disorders including dementia, mental retardation, schizophrenia, schizotypal, delusional disorders, mood disorders, neurotic, stress-related and somatoform disorders, and mental and behavioural disorders due to psychoactive substance use and alcohol	F00-F99
Other causes hospital admission	All other causes of hospital admission excluding cardiovascular, respiratory, infectious, and mental/behavioural disorders causes

ICD-10 codes are accessed from the WHO. (2016). International Statistical Classification of Diseases and Related Health Problems 10th Revision. https://icd.who.int/browse10/2016/en

Socioeconomic and contextual covariates description

Table 2: Description of the socioeconomic and contextual covariates included in the study

Covariates	Description
Age	Age was calculated using the individuals' month and year of birth as per the below equation. For example, if an individual is born in June (month=06) 1982, he/she will be given the age of 19.5 at the beginning of the year 2002 and will age by one year with each additional year of follow-up. $$Age_i = Year_{2002-2017} - (M\ birth_i \times (1 \div 12) + Y\ birth_i)$$ Where Age_i is the individual's age; $Year_{2002-2017}$ is the year of follow-up ranging between 2002 and 2017; $M\ birth_i$ is the month of birth for individual i; and $Y\ birth_i$ is the year of birth for individual i.
Age^2	We also considered the possible non-linear effect of individuals' age and introduced a square term of age as an additional covariate following the approach of other researchers (Liu et al., 2021; Pereira Gray et al., 2017).
Gender	1=male; 2=female
Ethnicity	1=White; 2=Not-white
Country of birth	1=born in Scotland; 2=born in rest of UK; 3=born outside UK
Marital status	1=married; 2=single never married; 3=divorced/separated/widowed; 4=No response
Education	1=No educational qualification; 0=Intermediate school [reference category]; 2=High school qualification; 3=Post-school/university; 4=Still a student; 5=Not recoded/No response
Occupation	1=White collar high skilled: Managers, professionals, Associate professionals; 2=White collar low skilled: Administrative, service, care and shop sales; 3=Blue collar high skilled: Skilled trades occupations; 4=Blue collar low skilled: Process, Plant, Machine operatives and elementary occupations; 5=Not applicable: students/never worked; 6=No response
Place of residence	1=Large Urban areas: Settlements of 125,000 people and over; 2=other urban areas: Settlements of 10,000 to 124,999 people; 3=Accessible small towns: Settlements of 3,000 to 9,999 people, and within 30 minute drive time of a Settlement of 10,000 or more; 4=Remote small towns: Settlements of 3,000 to 9,999 people, and with drive time of over 30 minutes to a Settlement of 10,000 or more; 5=Accessible Rural areas: Areas with a population of less than 3,000 people, and within 30 minute drive time of a Settlement of 10,000 or more; and 6=Remote rural areas: Areas with a population of less than 3,000 people, and with drive time of over 30 minutes to a Settlement of 10,000 or more (Scottish-Government, 2021).

Citations:

Liu, Y., Zhu, K., Li, R.-L., Song, Y., & Zhang, Z.-J. (2021). Air Pollution Impairs Subjective Happiness by Damaging Their Health. *International journal of environmental research and public health*, *18*(19), 10319. https://doi.org/10.3390/ijerph181910319

Pereira Gray, D., Henley, W., Chenore, T., Sidaway-Lee, K., & Evans, P. (2017). What is the relationship between age and deprivation in influencing emergency hospital admissions? A model using data from a defined, comprehensive, all-age cohort in East Devon, UK. *BMJ Open*, *7*(2), e014045. https://doi.org/10.1136/bmjopen-2016-014045

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

Description of air pollution

Figure 1: The average exposure to NO_2, SO_2, PM10, and PM2.5 air pollutants from the year of 2002 to 2017

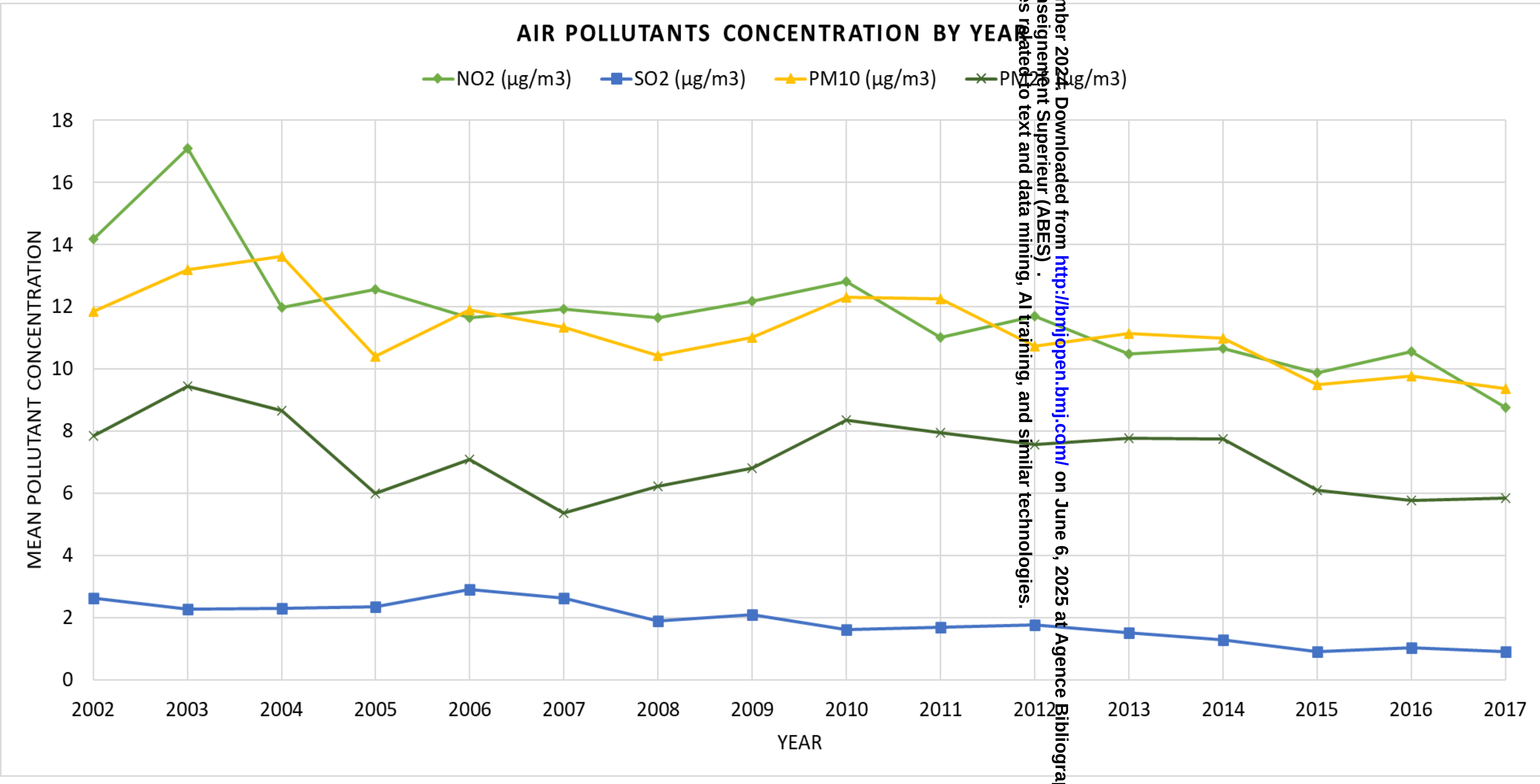


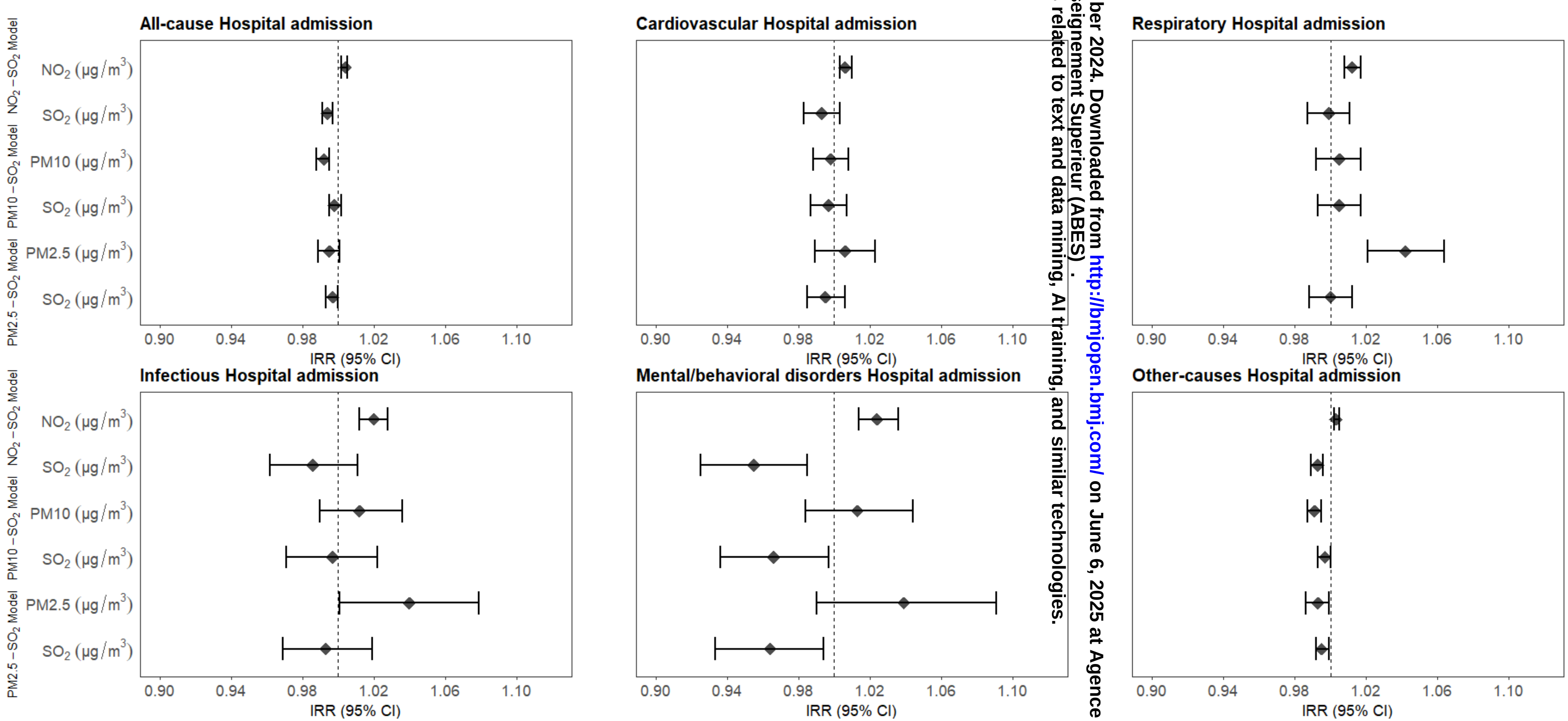
Table 3: Description of air pollution.

	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.

The association between air pollution and hospital admissions in two-pollutant models

Figure 2: The association of all-cause and cause-specific hospital admissions with NO_2, SO_2, PM10, and PM2.5 air pollutants in two-pollutant models (N=202,237 individuals and 2,810,414 observations).



Data source: Author's own calculations based on the Scottish Longitudinal Study data; The dashed line is placed at IRR=1 as a cut-off for statistically insignificant results; The two-pollutant models which include SO_2 + one of the other three pollutants are adjusted for age, age^2, gender, calendar year dummies, ethnicity, country of birth, marital status, education, occupation, and place of residence.

The association between hospital admissions and the socioeconomic and contextual covariates

Table 4: The association of all-cause hospital admissions with the socioeconomic and contextual covariates

Covariates	IRR	Lower 95% CI	Upper 95% CI	P-value
Age	0.970	0.968	0.972	0.000
Age2	1.001	1.001	1.001	0.000
Gender: Male				
Female	0.996	0.981	1.010	0.571
Year dummies: 2002				
2003	0.981	0.961	1.000	0.053
2004	0.998	0.978	1.018	0.812
2005	1.017	0.997	1.038	0.096
2006	1.040	1.020	1.061	0.000
2007	1.088	1.066	1.110	0.000
2008	1.129	1.106	1.152	0.000
2009	1.156	1.132	1.179	0.000
2010	1.160	1.137	1.184	0.000
2011	1.173	1.150	1.198	0.000
2012	1.214	1.189	1.239	0.000
2013	1.246	1.221	1.272	0.000
2014	1.274	1.247	1.301	0.000
2015	1.318	1.291	1.346	0.000
2016	1.346	1.318	1.375	0.000
2017	1.345	1.317	1.374	0.000
Ethnicity: White				
Not-White	1.047	1.011	1.084	0.011
Country of birth: Born in Scotland				
Born in rest of UK	0.865	0.845	0.886	0.000
Born outside UK	0.805	0.775	0.836	0.000
Marital Status: Married				
Single never married	0.970	0.953	0.988	0.001
Divorced/separated/widowed	1.127	1.110	1.143	0.000
No response	1.204	1.078	1.344	0.001
Education: Intermediate school qualification				
No qualification	1.157	1.138	1.176	0.000
High school qualification	0.877	0.860	0.894	0.000
Post-school/university qualification	0.845	0.830	0.860	0.000
Still a student	0.641	0.551	0.745	0.000
No response	0.845	0.814	0.877	0.000

Occupation: White collar high skilled				
White collar low skilled	1.069	1.052	1.087	0.000
Blue collar high skilled	1.117	1.093	1.141	0.000
Blue collar low skilled	1.178	1.157	1.199	0.000
NA: students/never worked	1.157	1.121	1.194	0.000
No response	2.699	2.566	2.840	0.000
Place of residence: Large Urban areas				
Other urban areas	0.973	0.959	0.987	0.000
Accessible small towns	0.932	0.911	0.952	0.000
Remote small towns	0.963	0.931	0.997	0.034
Accessible Rural areas	0.903	0.889	0.918	0.000
Remote rural areas	0.966	0.944	0.989	0.004
Overdispersion parameter (α)	2.49	2.48	2.51	

Table 5: The association of cardiovascular hospital admissions with the socioeconomic and contextual covariates

Covariates	**IRR**	**Lower 95% CI**	**Upper 95% CI**	**P-value**
Age	1.083	1.076	1.090	0.000
Age2	1.000	1.000	1.000	0.949
Gender: Male				
Female	0.560	0.541	0.579	0.000
Year dummies: 2002				
2003	0.943	0.887	1.002	0.059
2004	0.925	0.869	0.984	0.013
2005	0.901	0.847	0.959	0.001
2006	0.852	0.800	0.907	0.000
2007	0.858	0.806	0.914	0.000
2008	0.872	0.818	0.928	0.000
2009	0.902	0.847	0.960	0.001
2010	0.883	0.829	0.941	0.000
2011	0.885	0.830	0.943	0.000
2012	0.884	0.829	0.943	0.000
2013	0.885	0.829	0.943	0.000
2014	0.895	0.839	0.955	0.001
2015	0.874	0.820	0.933	0.000
2016	0.849	0.796	0.907	0.000
2017	0.833	0.779	0.890	0.000
Ethnicity: White				
Not-White	1.100	1.016	1.191	0.019
Country of birth: Born in Scotland				
Born in rest of UK	0.906	0.858	0.957	0.000
Born outside UK	0.844	0.773	0.921	0.000
Marital Status: Married				

Single never married	0.938	0.893	0.984	0.009
Divorced/separated/widowed	1.192	1.151	1.235	0.000
No response	1.026	0.803	1.310	0.840
Education: Intermediate school qualification				
No qualification	1.227	1.176	1.280	0.000
High school qualification	0.870	0.822	0.921	0.000
Post-school/university qualification	0.787	0.749	0.827	0.000
Still a student	0.716	0.373	1.373	0.314
No response	0.982	0.892	1.081	0.713
Occupation: White collar high skilled				
White collar low skilled	1.050	1.004	1.099	0.035
Blue collar high skilled	1.143	1.082	1.206	0.000
Blue collar low skilled	1.217	1.162	1.275	0.000
NA: students/never worked	1.177	1.079	1.283	0.000
No response	3.059	2.733	3.424	0.000
Place of residence: Large Urban areas				
Other urban areas	0.973	0.938	1.009	0.145
Accessible small towns	0.939	0.887	0.993	0.029
Remote small towns	0.917	0.838	1.003	0.058
Accessible Rural areas	0.884	0.848	0.922	0.000
Remote rural areas	0.894	0.844	0.947	0.000
Overdispersion parameter (α)	12.79	12.55	13.03	

Table 6: The association of respiratory hospital admissions with the socioeconomic and contextual covariates

Covariates	**IRR**	**Lower 95% CI**	**Upper 95% CI**	**P-value**
Age	0.898	0.891	0.904	0.000
Age2	1.001	1.001	1.002	0.000
Gender: Male				
Female	0.786	0.751	0.822	0.000
Year dummies: 2002				
2003	1.056	0.976	1.142	0.174
2004	1.091	1.008	1.181	0.031
2005	1.180	1.091	1.277	0.000
2006	1.255	1.160	1.357	0.000
2007	1.410	1.305	1.524	0.000
2008	1.582	1.464	1.709	0.000
2009	1.519	1.404	1.642	0.000
2010	1.541	1.425	1.667	0.000
2011	1.736	1.604	1.879	0.000
2012	1.867	1.725	2.020	0.000
2013	2.045	1.890	2.212	0.000

2014	2.129	1.967	2.304	0.000
2015	2.592	2.397	2.802	0.000
2016	2.849	2.635	3.081	0.000
2017	3.223	2.981	3.484	0.000
Ethnicity: White				
Not-White	1.112	1.004	1.232	0.043
Country of birth: Born in Scotland				
Born in rest of UK	0.748	0.692	0.809	0.000
Born outside UK	0.752	0.668	0.845	0.000
Marital Status: Married				
Single never married	1.043	0.980	1.110	0.185
Divorced/separated/widowed	1.353	1.293	1.416	0.000
No response	1.235	0.921	1.655	0.158
Education: Intermediate school qualification				
No qualification	1.416	1.341	1.496	0.000
High school qualification	0.815	0.758	0.877	0.000
Post-school/university qualification	0.693	0.650	0.740	0.000
Still a student	0.559	0.316	0.989	0.046
No response	0.766	0.685	0.856	0.000
Occupation: White collar high skilled				
White collar low skilled	1.132	1.066	1.202	0.000
Blue collar high skilled	1.317	1.224	1.416	0.000
Blue collar low skilled	1.552	1.460	1.651	0.000
NA: students/never worked	1.789	1.622	1.974	0.000
No response	8.220	7.187	9.402	0.000
Place of residence: Large Urban areas				
Other urban areas	0.922	0.881	0.966	0.001
Accessible small towns	0.833	0.774	0.895	0.000
Remote small towns	0.854	0.763	0.956	0.006
Accessible Rural areas	0.760	0.720	0.802	0.000
Remote rural areas	0.714	0.661	0.771	0.000
Overdispersion parameter (α)	7.07	6.89	7.26	

Table 7: The association of infectious hospital admissions with the socioeconomic and contextual covariates

Covariates	**IRR**	**Lower 95% CI**	**Upper 95% CI**	**P-value**
Age	0.938	0.926	0.949	0.000
Age2	1.001	1.001	1.001	0.000
Gender: Male				
Female	1.057	0.987	1.132	0.111
Year dummies: 2002				
2003	0.871	0.723	1.049	0.145

2004	0.993	0.827	1.192	0.937
2005	1.115	0.931	1.335	0.236
2006	1.262	1.057	1.507	0.010
2007	1.342	1.125	1.601	0.001
2008	1.185	0.990	1.419	0.065
2009	1.384	1.159	1.653	0.000
2010	1.504	1.261	1.794	0.000
2011	1.543	1.291	1.844	0.000
2012	1.849	1.552	2.202	0.000
2013	2.996	2.535	3.541	0.000
2014	3.848	3.267	4.533	0.000
2015	4.033	3.424	4.749	0.000
2016	4.315	3.664	5.082	0.000
2017	4.862	4.131	5.724	0.000
Ethnicity: White				
Not-White	1.212	1.044	1.408	0.012
Country of birth: Born in Scotland				
Born in rest of UK	0.896	0.799	1.004	0.059
Born outside UK	1.121	0.951	1.322	0.174
Marital Status: Married				
Single never married	1.169	1.064	1.284	0.001
Divorced/separated/widowed	1.228	1.139	1.325	0.000
No response	1.206	0.750	1.939	0.439
Education: Intermediate school qualification				
No qualification	1.268	1.158	1.387	0.000
High school qualification	0.844	0.751	0.950	0.005
Post-school/university qualification	0.826	0.746	0.915	0.000
Still a student	0.184	0.050	0.679	0.011
No response	0.876	0.721	1.065	0.184
Occupation: White collar high skilled				
White collar low skilled	1.144	1.040	1.259	0.006
Blue collar high skilled	1.239	1.099	1.397	0.000
Blue collar low skilled	1.313	1.187	1.453	0.000
NA: students/never worked	1.579	1.339	1.861	0.000
No response	3.122	2.468	3.950	0.000
Place of residence: Large Urban areas				
Other urban areas	0.995	0.923	1.071	0.885
Accessible small towns	0.861	0.763	0.973	0.016
Remote small towns	0.770	0.632	0.937	0.009
Accessible Rural areas	0.808	0.738	0.884	0.000
Remote rural areas	0.729	0.642	0.828	0.000
Overdispersion parameter (α)	40.81	37.36	44.58	

Table 8: The association of mental/behavioural disorders hospital admissions with the socioeconomic and contextual covariates

Covariates	IRR	Lower 95% CI	Upper 95% CI	P-value
Age	0.939	0.925	0.954	0.000
Age2	1.001	1.001	1.001	0.000
Gender: Male				
Female	0.578	0.524	0.638	0.000
Year dummies: 2002				
2003	0.994	0.819	1.207	0.954
2004	0.921	0.756	1.121	0.410
2005	0.941	0.771	1.147	0.545
2006	0.990	0.813	1.206	0.923
2007	1.072	0.881	1.305	0.485
2008	1.045	0.858	1.274	0.662
2009	1.149	0.944	1.399	0.166
2010	1.269	1.043	1.545	0.017
2011	1.387	1.137	1.692	0.001
2012	1.538	1.263	1.873	0.000
2013	1.655	1.360	2.014	0.000
2014	1.799	1.479	2.188	0.000
2015	1.904	1.567	2.314	0.000
2016	2.456	2.028	2.974	0.000
2017	2.763	2.284	3.343	0.000
Ethnicity: White				
Not-White	1.218	0.985	1.507	0.068
Country of birth: Born in Scotland				
Born in rest of UK	0.740	0.623	0.880	0.001
Born outside UK	0.619	0.476	0.806	0.000
Marital Status: Married				
Single never married	2.723	2.382	3.113	0.000
Divorced/separated/widowed	2.676	2.410	2.972	0.000
No response	3.874	2.211	6.788	0.000
Education: Intermediate school qualification				
No qualification	1.412	1.241	1.607	0.000
High school qualification	0.958	0.810	1.134	0.620
Post-school/university qualification	0.758	0.650	0.884	0.000
Still a student	0.313	0.069	1.423	0.133
No response	0.875	0.684	1.119	0.288
Occupation: White collar high skilled				
White collar low skilled	1.341	1.161	1.548	0.000
Blue collar high skilled	1.563	1.320	1.851	0.000
Blue collar low skilled	1.723	1.488	1.994	0.000

NA: students/never worked	2.676	2.152	3.326	0.000
No response	7.897	5.914	10.545	0.000
Place of residence: Large Urban areas				
Other urban areas	0.862	0.777	0.956	0.005
Accessible small towns	0.743	0.625	0.882	0.001
Remote small towns	1.233	0.975	1.558	0.080
Accessible Rural areas	0.672	0.592	0.762	0.000
Remote rural areas	1.081	0.920	1.271	0.345
Overdispersion parameter (α)	13.25	12.30	14.26	

Table 9: The association of other-causes hospital admissions with the socioeconomic and contextual covariates

Covariates	**IRR**	**Lower 95% CI**	**Upper 95% CI**	**P-value**
Age	0.978	0.976	0.980	0.000
Age2	1.001	1.001	1.001	0.000
Gender: Male				
Female	1.078	1.062	1.094	0.000
Year dummies: 2002				
2003	0.976	0.956	0.997	0.027
2004	0.995	0.974	1.016	0.632
2005	1.017	0.995	1.039	0.123
2006	1.046	1.024	1.068	0.000
2007	1.092	1.068	1.115	0.000
2008	1.135	1.111	1.160	0.000
2009	1.164	1.139	1.189	0.000
2010	1.166	1.141	1.191	0.000
2011	1.174	1.148	1.200	0.000
2012	1.215	1.188	1.242	0.000
2013	1.237	1.210	1.265	0.000
2014	1.258	1.231	1.287	0.000
2015	1.289	1.261	1.318	0.000
2016	1.300	1.271	1.330	0.000
2017	1.278	1.249	1.308	0.000
Ethnicity: White				
Not-White	1.039	1.002	1.077	0.040
Country of birth: Born in Scotland				
Born in rest of UK	0.876	0.854	0.897	0.000
Born outside UK	0.815	0.784	0.847	0.000
Marital Status: Married				
Single never married	0.971	0.953	0.990	0.003
Divorced/separated/widowed	1.109	1.092	1.126	0.000
No response	1.234	1.100	1.384	0.000

Education: Intermediate school qualification				
No qualification	1.139	1.119	1.158	0.000
High school qualification	0.877	0.859	0.895	0.000
Post-school/university qualification	0.857	0.841	0.873	0.000
Still a student	0.661	0.565	0.773	0.000
No response	0.848	0.815	0.882	0.000
Occupation: White collar high skilled				
White collar low skilled	1.067	1.049	1.085	0.000
Blue collar high skilled	1.103	1.078	1.128	0.000
Blue collar low skilled	1.156	1.135	1.178	0.000
NA: students/never worked	1.152	1.114	1.191	0.000
No response	2.343	2.222	2.471	0.000
Place of residence: Large Urban areas				
Other urban areas	0.971	0.957	0.986	0.000
Accessible small towns	0.931	0.910	0.952	0.000
Remote small towns	0.980	0.946	1.016	0.283
Accessible Rural areas	0.906	0.891	0.921	0.000
Remote rural areas	0.982	0.958	1.005	0.130
Overdispersion parameter (α)	2.57	2.55	2.59	

Supplementary Tables 4 to 9 describe the association of all-cause and cause-specific hospital admissions with the socioeconomic and contextual covariates. The calculated IRRs and 95%CIs are the author's own calculations based on the Scottish Longitudinal Study (SLS) data (*Scottish Longitudinal Study*, Accessed 08 November 2021).

Lower incidence rate ratios were observed for all-cause, cardiovascular, respiratory, infectious, mental/behavioural disorders, and other-causes hospital admissions among females (except for all-cause, infectious and other-causes hospital admissions), people born in rest of UK or outside UK compared to Scottish-born, single never married compared to married (except for infectious and mental hospital admissions), people who have high school or post-school/university education compared to people who have intermediate school education, and people who live in towns or rural areas compared to those living in large urban areas.

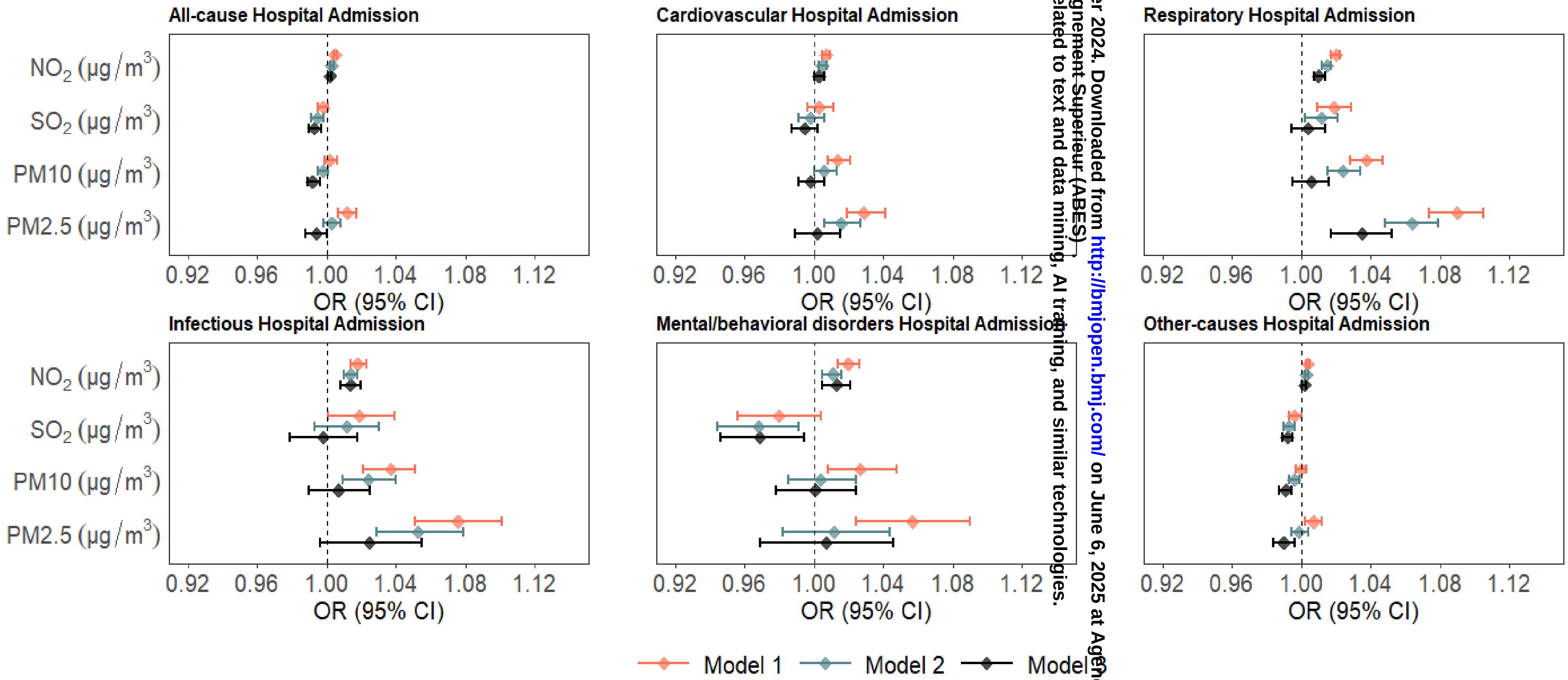
In contrast, higher incidence rate ratios were observed for all-cause, cardiovascular, respiratory, infectious, mental/behavioural disorders, and other-causes hospital admissions among not-white compared to white ethnicity, divorced/separated/widowed compared to married, people with no educational qualification compared to people with intermediate school education, and people who work in white collar low skilled, blue collar high skilled, and blue collar low skilled jobs compared to people working in white collar high skilled jobs.

Citation:

Scottish Longitudinal Study. (Accessed 08 November 2021). https://sls.lscs.ac.uk/

The association between air pollution and hospital admissions binary (yes/no) outcome

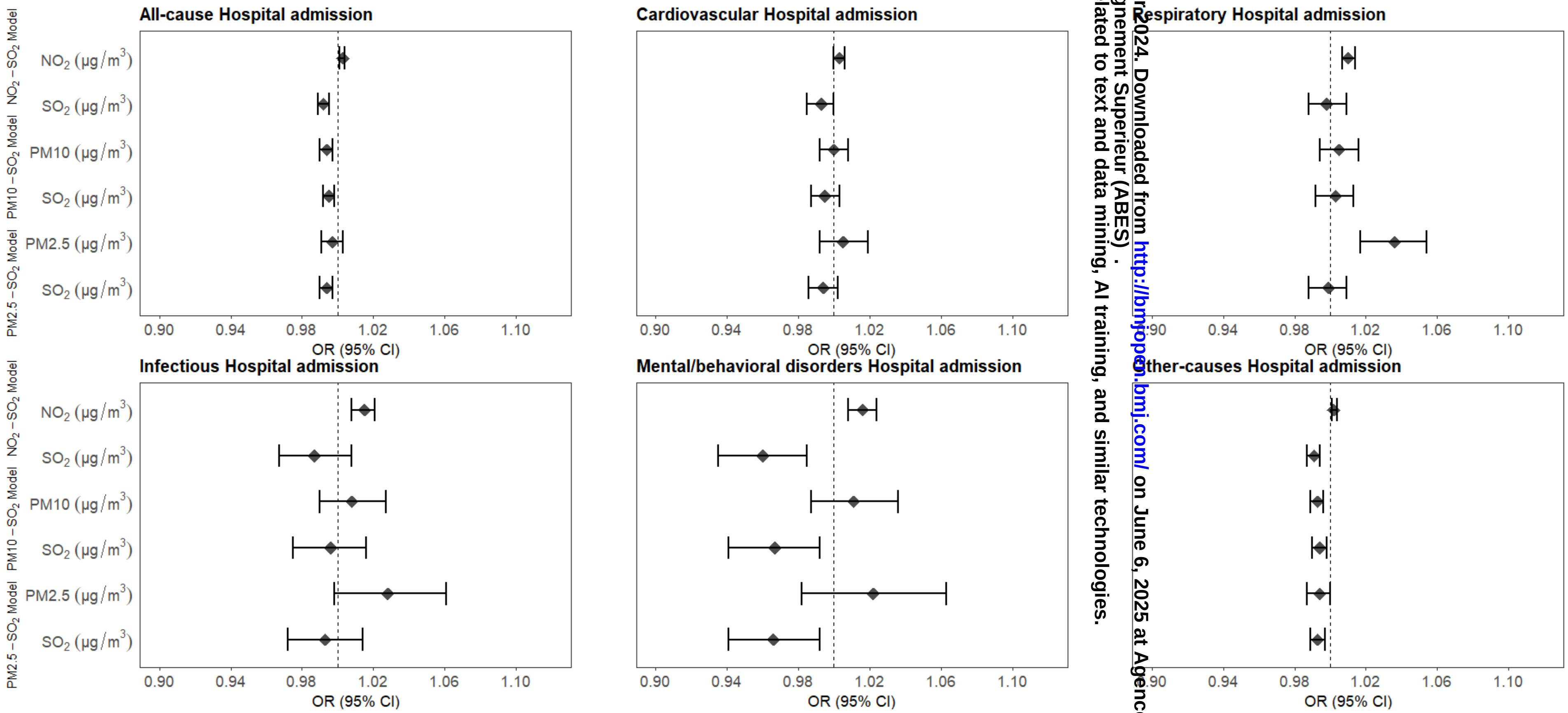
Figure 3: The association of all-cause and cause-specific hospital admissions binary (yes/no) outcome with NO_2, SO_2, PM10, and PM2.5 air pollutants in separate multilevel mixed-effects logistic models (N=202,237 individuals and 2,810,414 observations).



Data source: Author's own calculations based on the Scottish Longitudinal Study data; The dashed line is placed at OR=1 as a cut-off for statistically insignificant results; Model 1 is adjusted for age, age^2, gender and calendar year dummies; Model 2= Model 1 + ethnicity + country of birth + marital status + education + occupation; Model 3= Model 2 + Place of residence.

The association between air pollution and hospital admissions binary (yes/no) outcome in two-pollutant models

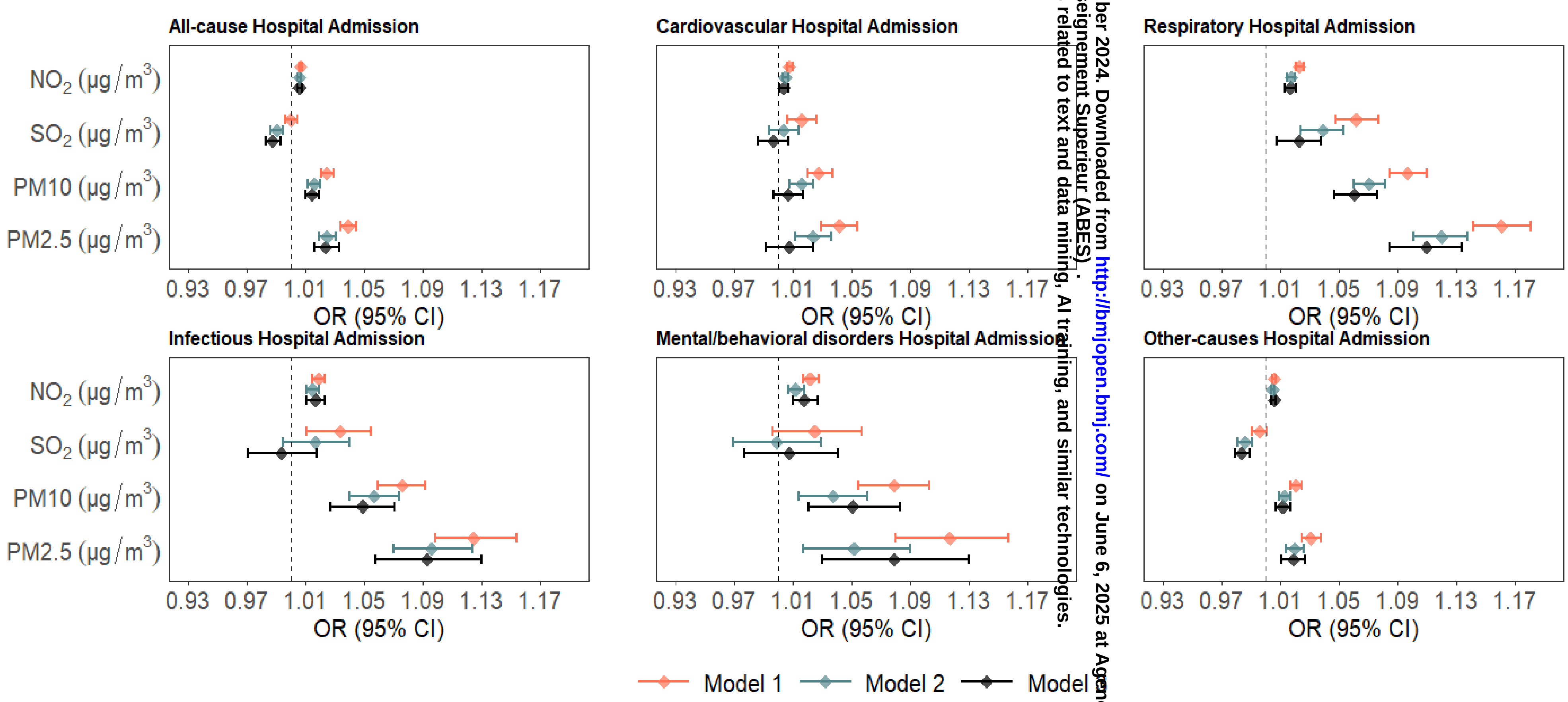
Figure 4: The association of all-cause and cause-specific hospital admissions binary (yes/no) outcome with NO_2, SO_2, PM10, and PM2.5 air pollutants in two-pollutant models (N=202,237 individuals and 2,810,414 observations).



Data source: Author's own calculations based on the Scottish Longitudinal Study data; The dashed line is placed at OR=1 as a cut-off for statistically insignificant results; The two-pollutant models which include SO_2 + one of the other three pollutants are adjusted for age, age2, gender, calendar year dummies, ethnicity, country of birth, marital status, education, occupation, and Place of residence.

The association between cumulative air pollution (CAP) exposure and hospital admissions binary (yes/no) outcome

Figure 5: The association of all-cause and cause-specific hospital admissions binary (yes/no) outcome with average CAP exposure to NO_2, SO_2, PM10, and PM2.5 air pollutants in separate multilevel mixed-effects logistic models (N=202,237 individuals and 2,810,414 observations).



Data source: Author's own calculations based on the Scottish Longitudinal Study data; The dashed line is placed at OR=1 as a cut-off for statistically insignificant results; Model 1 is adjusted for age, age^2, gender and calendar year dummies; Model 2= Model 1 + ethnicity + country of birth + marital status + education + occupation; Model 3= Model 2 + Place of residence.

The association between hospital admissions binary (yes/no) outcome and the socioeconomic and contextual covariates

Table 10: The association of all-cause hospital admissions binary (yes/no) outcome with the socioeconomic and contextual covariates

Covariates	OR	Lower 95% CI	Upper 95% CI	P-value
Age	0.970	0.968	0.972	0.000
Age2	1.001	1.001	1.001	0.000
Gender: Male				
Female	1.033	1.019	1.047	0.000
Year dummies: 2002				
2003	0.991	0.971	1.011	0.360
2004	1.009	0.989	1.030	0.389
2005	1.031	1.010	1.052	0.003
2006	1.052	1.031	1.074	0.000
2007	1.079	1.057	1.101	0.000
2008	1.124	1.101	1.147	0.000
2009	1.148	1.125	1.172	0.000
2010	1.132	1.109	1.156	0.000
2011	1.154	1.129	1.178	0.000
2012	1.185	1.160	1.210	0.000
2013	1.168	1.143	1.193	0.000
2014	1.180	1.155	1.206	0.000
2015	1.197	1.171	1.223	0.000
2016	1.162	1.136	1.187	0.000
2017	1.124	1.099	1.149	0.000
Ethnicity: White				
Not-White	1.043	1.009	1.079	0.014
Country of birth: Born in Scotland				
Born in rest of UK	0.878	0.858	0.898	0.000
Born outside UK	0.824	0.795	0.854	0.000
Marital Status: Married				
Single never married	0.948	0.931	0.965	0.000
Divorced/separated/widowed	1.123	1.107	1.139	0.000
No response	1.207	1.085	1.343	0.001
Education: Intermediate school qualification				
No qualification	1.158	1.139	1.177	0.000
High school qualification	0.873	0.856	0.890	0.000
Post-school/university qualification	0.854	0.839	0.869	0.000
Still a student	0.641	0.553	0.744	0.000

No response	0.924	0.891	0.959	0.000
Occupation: White collar high skilled				
White collar low skilled	1.072	1.055	1.090	0.000
Blue collar high skilled	1.119	1.096	1.143	0.000
Blue collar low skilled	1.174	1.153	1.195	0.000
NA: students/never worked	1.182	1.146	1.220	0.000
No response	2.362	2.247	2.482	0.000
Place of residence: Large Urban areas				
Other urban areas	0.982	0.968	0.996	0.010
Accessible small towns	0.941	0.921	0.962	0.000
Remote small towns	1.015	0.981	1.050	0.401
Accessible Rural areas	0.907	0.893	0.921	0.000
Remote rural areas	0.989	0.966	1.011	0.318

Table 11: The association of cardiovascular hospital admissions binary (yes/no) outcome with the socioeconomic and contextual covariates

Covariates	**OR**	**Lower 95% CI**	**Upper 95% CI**	**P-value**
Age	1.070	1.064	1.075	0.000
Age2	1.000	1.000	1.000	0.196
Gender: Male				
Female	0.641	0.624	0.659	0.000
Year dummies: 2002				
2003	0.970	0.925	1.017	0.205
2004	0.961	0.917	1.008	0.105
2005	0.948	0.904	0.995	0.029
2006	0.914	0.871	0.959	0.000
2007	0.906	0.863	0.951	0.000
2008	0.904	0.861	0.949	0.000
2009	0.912	0.868	0.957	0.000
2010	0.908	0.864	0.954	0.000
2011	0.895	0.851	0.942	0.000
2012	0.894	0.850	0.941	0.000
2013	0.862	0.819	0.907	0.000
2014	0.871	0.827	0.917	0.000
2015	0.844	0.802	0.889	0.000
2016	0.792	0.752	0.835	0.000
2017	0.754	0.715	0.795	0.000
Ethnicity: White				
Not-White	1.081	1.014	1.153	0.017
Country of birth: Born in Scotland				
Born in rest of UK	0.930	0.890	0.973	0.002
Born outside UK	0.865	0.805	0.929	0.000

Marital Status: Married				
Single never married	0.935	0.898	0.974	0.001
Divorced/separated/widowed	1.146	1.114	1.179	0.000
No response	1.052	0.870	1.272	0.599
Education: Intermediate school qualification				
No qualification	1.159	1.120	1.201	0.000
High school qualification	0.879	0.837	0.922	0.000
Post-school/university qualification	0.828	0.794	0.863	0.000
Still a student	0.784	0.437	1.408	0.416
No response	1.019	0.944	1.100	0.628
Occupation: White collar high skilled				
White collar low skilled	1.041	1.002	1.081	0.038
Blue collar high skilled	1.104	1.056	1.155	0.000
Blue collar low skilled	1.164	1.120	1.209	0.000
NA: students/never worked	1.124	1.048	1.206	0.001
No response	2.499	2.291	2.725	0.000
Place of residence: Large Urban areas				
Other urban areas	0.986	0.957	1.015	0.340
Accessible small towns	0.967	0.924	1.013	0.159
Remote small towns	0.946	0.879	1.017	0.130
Accessible Rural areas	0.906	0.876	0.937	0.000
Remote rural areas	0.931	0.888	0.975	0.002

Table 12: The association of respiratory hospital admissions binary (yes/no) outcome with the socioeconomic and contextual covariates

Covariates	OR	Lower 95% CI	Upper 95% CI	P-value
Age	0.915	0.910	0.921	0.000
Age2	1.001	1.001	1.001	0.000
Gender: Male				
Female	0.815	0.784	0.847	0.000
Year dummies: 2002				
2003	1.089	1.018	1.165	0.013
2004	1.132	1.058	1.212	0.000
2005	1.228	1.147	1.313	0.000
2006	1.297	1.212	1.388	0.000
2007	1.430	1.337	1.529	0.000
2008	1.589	1.486	1.699	0.000
2009	1.546	1.445	1.654	0.000
2010	1.537	1.435	1.646	0.000
2011	1.696	1.583	1.817	0.000
2012	1.754	1.637	1.880	0.000

2013	1.862	1.738	1.995	0.000
2014	1.858	1.733	1.992	0.000
2015	2.165	2.021	2.318	0.000
2016	2.271	2.120	2.432	0.000
2017	2.487	2.323	2.663	0.000
Ethnicity: White				
Not-White	1.093	1.002	1.191	0.045
Country of birth: Born in Scotland				
Born in rest of UK	0.783	0.733	0.837	0.000
Born outside UK	0.797	0.721	0.880	0.000
Marital Status: Married				
Single never married	1.025	0.972	1.082	0.362
Divorced/separated/widowed	1.290	1.241	1.342	0.000
No response	1.181	0.923	1.511	0.187
Education: Intermediate school qualification				
No qualification	1.357	1.293	1.423	0.000
High school qualification	0.840	0.788	0.895	0.000
Post-school/university qualification	0.728	0.687	0.770	0.000
Still a student	0.610	0.373	0.998	0.049
No response	0.864	0.786	0.950	0.003
Occupation: White collar high skilled				
White collar low skilled	1.106	1.050	1.166	0.000
Blue collar high skilled	1.280	1.202	1.363	0.000
Blue collar low skilled	1.462	1.386	1.542	0.000
NA: students/never worked	1.613	1.482	1.756	0.000
No response	5.980	5.340	6.696	0.000
Place of residence: Large Urban areas				
Other urban areas	0.956	0.919	0.995	0.027
Accessible small towns	0.867	0.814	0.923	0.000
Remote small towns	0.899	0.816	0.990	0.030
Accessible Rural areas	0.802	0.765	0.841	0.000
Remote rural areas	0.781	0.731	0.835	0.000

Table 13: The association of infectious hospital admissions binary (yes/no) outcome with the socioeconomic and contextual covariates

Covariates	**OR**	**Lower 95% CI**	**Upper 95% CI**	**P-value**
Age	0.959	0.950	0.968	0.000
Age2	1.001	1.001	1.001	0.000
Gender: Male				
Female	1.056	0.998	1.117	0.057
Year dummies: 2002				

2003	0.877	0.750	1.025	0.100
2004	0.975	0.837	1.136	0.743
2005	1.101	0.949	1.278	0.205
2006	1.254	1.084	1.450	0.002
2007	1.266	1.094	1.465	0.002
2008	1.175	1.012	1.364	0.035
2009	1.315	1.136	1.523	0.000
2010	1.378	1.191	1.595	0.000
2011	1.416	1.222	1.642	0.000
2012	1.663	1.441	1.921	0.000
2013	2.372	2.071	2.718	0.000
2014	2.939	2.575	3.354	0.000
2015	3.023	2.649	3.450	0.000
2016	3.086	2.703	3.523	0.000
2017	3.402	2.983	3.880	0.000
Ethnicity: White				
Not-White	1.162	1.031	1.310	0.014
Country of birth: Born in Scotland				
Born in rest of UK	0.901	0.819	0.990	0.030
Born outside UK	1.079	0.944	1.234	0.264
Marital Status: Married				
Single never married	1.134	1.049	1.226	0.002
Divorced/separated/widowed	1.177	1.108	1.251	0.000
No response	1.184	0.815	1.720	0.375
Education: Intermediate school qualification				
No qualification	1.206	1.120	1.298	0.000
High school qualification	0.851	0.771	0.941	0.002
Post-school/university qualification	0.852	0.783	0.928	0.000
Still a student	0.258	0.081	0.825	0.022
No response	0.952	0.816	1.111	0.532
Occupation: White collar high skilled				
White collar low skilled	1.119	1.034	1.211	0.005
Blue collar high skilled	1.183	1.072	1.306	0.001
Blue collar low skilled	1.243	1.144	1.351	0.000
NA: students/never worked	1.500	1.314	1.713	0.000
No response	2.440	2.025	2.941	0.000
Place of residence: Large Urban areas				
Other urban areas	1.008	0.949	1.070	0.803
Accessible small towns	0.916	0.830	1.010	0.079
Remote small towns	0.869	0.744	1.016	0.078
Accessible Rural areas	0.855	0.794	0.920	0.000
Remote rural areas	0.800	0.721	0.888	0.000

Table 14: The association of mental/behavioural disorders hospital admissions binary (yes/no) outcome with the socioeconomic and contextual covariates

Covariates	OR	Lower 95% CI	Upper 95% CI	P-value
Age	0.956	0.944	0.968	0.000
Age2	1.001	1.001	1.001	0.000
Gender: Male				
Female	0.641	0.591	0.696	0.000
Year dummies: 2002				
2003	1.011	0.864	1.182	0.894
2004	0.979	0.835	1.147	0.791
2005	0.964	0.821	1.132	0.656
2006	1.030	0.878	1.209	0.718
2007	1.086	0.926	1.274	0.313
2008	1.085	0.923	1.275	0.322
2009	1.171	0.997	1.376	0.054
2010	1.195	1.017	1.405	0.030
2011	1.297	1.101	1.526	0.002
2012	1.370	1.164	1.612	0.000
2013	1.467	1.248	1.725	0.000
2014	1.592	1.357	1.869	0.000
2015	1.593	1.355	1.871	0.000
2016	1.815	1.548	2.127	0.000
2017	1.983	1.694	2.321	0.000
Ethnicity: White				
Not-White	1.152	0.967	1.372	0.113
Country of birth: Born in Scotland				
Born in rest of UK	0.786	0.682	0.907	0.001
Born outside UK	0.685	0.551	0.851	0.001
Marital Status: Married				
Single never married	2.285	2.048	2.548	0.000
Divorced/separated/widowed	2.214	2.033	2.410	0.000
No response	2.944	1.871	4.633	0.000
Education: Intermediate school qualification				
No qualification	1.312	1.180	1.458	0.000
High school qualification	0.972	0.846	1.117	0.689
Post-school/university qualification	0.809	0.712	0.919	0.001
Still a student	0.299	0.068	1.319	0.111
No response	0.952	0.780	1.162	0.627
Occupation: White collar high skilled				
White collar low skilled	1.303	1.155	1.470	0.000
Blue collar high skilled	1.475	1.283	1.696	0.000
Blue collar low skilled	1.612	1.428	1.819	0.000

NA: students/never worked	2.295	1.923	2.738	0.000
No response	5.425	4.291	6.859	0.000
Place of residence: Large Urban areas				
Other urban areas	0.895	0.822	0.975	0.011
Accessible small towns	0.812	0.705	0.936	0.004
Remote small towns	1.255	1.041	1.514	0.017
Accessible Rural areas	0.721	0.649	0.800	0.000
Remote rural areas	1.122	0.984	1.279	0.087

Table 15: The association of other-causes hospital admissions binary (yes/no) outcome with the socioeconomic and contextual covariates

Covariates	**OR**	**Lower 95% CI**	**Upper 95% CI**	**P-value**
Age	0.981	0.979	0.983	0.000
Age2	1.000	1.000	1.000	0.000
Gender: Male				
Female	1.094	1.079	1.110	0.000
Year dummies: 2002				
2003	0.988	0.967	1.009	0.262
2004	1.006	0.985	1.028	0.561
2005	1.027	1.005	1.049	0.016
2006	1.052	1.030	1.075	0.000
2007	1.076	1.054	1.100	0.000
2008	1.127	1.103	1.151	0.000
2009	1.159	1.135	1.185	0.000
2010	1.138	1.113	1.163	0.000
2011	1.157	1.132	1.183	0.000
2012	1.186	1.160	1.212	0.000
2013	1.170	1.145	1.197	0.000
2014	1.179	1.153	1.206	0.000
2015	1.185	1.158	1.212	0.000
2016	1.145	1.119	1.172	0.000
2017	1.091	1.066	1.116	0.000
Ethnicity: White				
Not-White	1.036	1.001	1.072	0.043
Country of birth: Born in Scotland				
Born in rest of UK	0.888	0.868	0.909	0.000
Born outside UK	0.832	0.802	0.862	0.000
Marital Status: Married				
Single never married	0.953	0.936	0.970	0.000
Divorced/separated/widowed	1.105	1.089	1.122	0.000
No response	1.238	1.111	1.379	0.000

Education: Intermediate school qualification				
No qualification	1.140	1.121	1.159	0.000
High school qualification	0.873	0.856	0.891	0.000
Post-school/university qualification	0.863	0.847	0.879	0.000
Still a student	0.663	0.569	0.772	0.000
No response	0.917	0.883	0.953	0.000
Occupation: White collar high skilled				
White collar low skilled	1.071	1.053	1.089	0.000
Blue collar high skilled	1.104	1.080	1.128	0.000
Blue collar low skilled	1.157	1.136	1.178	0.000
NA: students/never worked	1.177	1.140	1.215	0.000
No response	2.029	1.929	2.134	0.000
Place of residence: Large Urban areas				
Other urban areas	0.981	0.967	0.995	0.010
Accessible small towns	0.942	0.921	0.964	0.000
Remote small towns	1.029	0.994	1.066	0.104
Accessible Rural areas	0.913	0.898	0.928	0.000
Remote rural areas	1.002	0.979	1.025	0.873

Supplementary Tables 10 to 15 describe the association of all-cause and cause-specific hospital admissions binary (yes/no) outcome with the socioeconomic and contextual covariates. The calculated ORs and 95%CIs are the author's own calculations based on the Scottish Longitudinal Study (SLS) data (*Scottish Longitudinal Study*, Accessed 08 November 2021).

Similar to the results with the hospital admission treated as a count outcome, lower odd ratios were observed for all-cause, cardiovascular, respiratory, infectious, mental/behavioural disorders, and other-causes hospital admissions binary (yes/no) outcome among females (except for all-cause, infectious and other-causes hospital admissions), people born in rest of UK or outside UK compared to Scottish-born, single never married compared to married (except for infectious and mental hospital admissions), people who have high school or post-school/university education compared to people who have intermediate school education, and people who live in towns or rural areas compared to those living in large urban areas.

In contrast, higher odd ratios were observed for all-cause, cardiovascular, respiratory, infectious, mental/behavioural disorders, and other-causes hospital admissions binary (yes/no) outcome among not-white compared to white ethnicity, divorced/separated/widowed compared to married, people with no educational qualification compared to people with intermediate school education, and people who work in white collar low skilled, blue collar high skilled, and blue collar low skilled jobs compared to people working in white collar high skilled jobs.

Citation:

Scottish Longitudinal Study. (Accessed 08 November 2021). https://sls.lscs.ac.uk/