ENVIRONMENTAL RESEARCH
HEALTH

PURPOSE-LED PUBLISHING™ Part of the ENVIRONMENTAL RESEARCH SERIES

ACCEPTED MANUSCRIPT • OPEN ACCESS

Relationships between exposure to air pollution and demographic attributes exhibit between-city heterogeneities

To cite this article before publication: Tomas Liska *et al* 2026 *Environ. Res.: Health* in press https://doi.org/10.1088/2752-5309/ae8ff8

Relationships between exposure to air pollution and demographic attributes exhibit between-city heterogeneities

Tomáš Liška[1,2,*], Mathew R Heal[2], Chun Lin[2,5], Massimo Vieno[1], Edward J Carnell[1], Samuel J Tomlinson[3], Miranda Loh[4], Stefan Reis[1,2]

[1] *UK Centre for Ecology & Hydrology, Bush Estate, Penicuik EH26 0QB, United Kingdom*
[2] *School of Chemistry, University of Edinburgh, Joseph Black Building, David Brewster Road, Edinburgh EH9 3FJ, United Kingdom*
[3] *UK Centre for Ecology & Hydrology, Lancaster Environment Centre, Lancaster LA1 4AP, United Kingdom*
[4] *Institute of Occupational Medicine, Research Avenue North, Riccarton, Edinburgh EH14 4AP, United Kingdom*
[5] *Now at: Usher Institute, Usher Building, University of Edinburgh, 5-7 Little France Road, Edinburgh BioQuarter – Gate 3, Edinburgh EH16 4UX, United Kingdom*

[*] Corresponding author: tomasliska@ceh.ac.uk

Keywords: air quality, air pollution exposure differentials, environmental justice, workplace-residential mobility, Scotland

Abstract

Differentials in exposure to air pollution across population sub-groups is a source of environmental health inequality. An important question is the generalisability of the trends between air pollution exposure and demographic attributes across different populations: comparisons are often confounded by different study methodologies. A key challenge is that individual-level demographic data are not usually available. In this study, we apply identical methods to a single cohort of 56,734 individuals to compare trends between exposures to ambient NO_2, $PM_{2.5}$ and O_3 and sex, age, ethnicity, and socioeconomic status (SES) in the cities of Glasgow and Edinburgh, UK. We also use individual-level information on place of work or study (where that applies) to derive more realistic estimates of exposures than studies using exposures at place of residence only. We find that whilst some broad trends in exposure-demographic relationships are similar between Glasgow and Edinburgh – for example that younger adults, those of lower SES and of non-White ethnicity are, on average, exposed to higher concentrations of NO_2 and $PM_{2.5}$ (and to lower concentrations of O_3) – our results also confirm heterogeneities in these relationships between the two cities. Importantly, we show that this geographical specificity extends to between-city geographical distributions of places of work and study as well; for example, males and females have equal exposures to air pollutants in each city based on residence location only, but have different patterns of exposure in the two cities when place of work is included. The heterogeneities we observe presumably arise from the particular way in which the urban fabric of a given city develops over time. The policy message is that it is not appropriate to assume geographically transferable relationships between air pollution exposure and SES, ethnicity, age and sex, even when the population demographic profiles are broadly similar.

1. Introduction

A fundamental aspect of social justice considerations of the harm caused by air pollution is quantification of the exposure of different subgroups of the population to individual air pollutants (Ganzleben and Kazmierczak, 2020; Stephens and Church, 2017). The three ambient air pollutants with greatest impacts on morbidity and mortality are nitrogen dioxide (NO_2), particulate matter of aerodynamic diameter <2.5 µm ($PM_{2.5}$) and ozone (O_3) (Brauer et al., 2024; Forastiere et al., 2024; Kasdagli et al., 2024; Orellano et al., 2024). Many studies have identified differences in exposure to these pollutants across different demographics such as age, ethnicity and measures of socio-economic status (SES) (e.g. Abed Al Ahad et al., 2023; Brook et al., 2023; Di et al., 2017; Gadene et al., 2024; Jbaily et al., 2022; Liu et al., 2021; Samoli et al., 2019; van den Brekel et al., 2024). The existence of such demographic differentials in exposure is of direct policy and public health relevance because they will lead to demographic differentials in morbidity burdens and premature mortality associated with a wide range of diseases, including respiratory, cardiovascular, neurological and diabetes. The differential health outcomes may be exacerbated by the existence of demographic differentials in other relevant factors such as underlying susceptibility to disease and access to health care (RCP, 2016).

However, closer inspection of the literature reveals air pollutant-demographic relationships to be complex and sometimes contradictory, particularly when comparing between different countries, cities and studies (e.g. Fecht et al., 2015; Hajat et al., 2015; Moreno-Jiménez et al., 2016; Padilla et al., 2014; Pye et al., 2006; Temam et al., 2017). The generalisability of trends in the relationships between air pollution exposure and demographic attributes across different populations therefore remains unclear. Consequently, our aim here is to compare these relationships between two cities with similar population demographics, using identical datasets and methods.

A difficulty in this area of research is that it requires individual-level demographic data which are frequently not available. For this study, we not only had access to the sex, age, ethnic group, and SES of individual members of a cohort (the latter variable at coarser granularity) but also to individual-level information on their place of work or study, where applicable, in addition to their place of residence. In earlier work (Liška et al., 2024), we examined the effects of taking into account the exposure to ambient pollution at the place of work or study on the relationships between exposures to $PM_{2.5}$, NO_2 and O_3 and sex, age, ethnicity, and SES, compared with using only residential location to estimate exposure; the latter is usually the only estimate of exposure available. Our analyses were applied to those living across the whole of the 'Central Belt' of Scotland and did not investigate geographical variations in the demographic differentials. However, our cohort includes residents in the two largest cities in Scotland – Glasgow and Edinburgh – enabling us directly to compare the air pollution versus demographic relationships in these two cities. Thus, a key feature of our study is that it eliminates any potential for findings on exposure-demographic relationships to be modified by differences in methodologies, as may be the case when comparing relationships between cities reported in different studies using different approaches. Another key feature is that we can compare the exposure-demographic relationships between Glasgow and Edinburgh using more realistic estimates of exposures that also include time spent at place of work or study.

2. Methods

2.1 Cohort individuals

Our study individuals are participants in the Scottish Longitudinal Study (https://sls.lscs.ac.uk). This is a repeatedly updated cohort consisting of 5.3% of the whole population living in Scotland and which has linkages between each participant's data and their responses to the decadal national population census (Boyle et al., 2009). We used information from the 2011 census, which was the most recent linked data available at the time the data safe-haven was accessed (and was still the case as of early 2026). The number of these census-linked cohort individuals resident in Greater Glasgow and Edinburgh were 37,884 and 18,850, respectively (location map in Supplementary Figure S1). These numbers comprise individuals whose place of work or study were also in one of the two cities or who were economically inactive or not in education, but excludes workers or students who selected the 'No fixed place' option to the place of work/study question on the census form. To adhere to data protection protocols, locations of residence and work/study were available at UK unit postcode level, which contains 15 individual addresses on average. Of the 56,734 cohort individuals in this study, 38.6% were retired, unemployed or otherwise economically inactive and 6.8% gave their place of work or study as their home. Assuming most children under 5 also do not spend significant time out of the home, then 49% of the individuals routinely spent time at a place of work or study different to their home address.

2.2 Demographic data

The individual-level demographic data used in this study were sex, age and ethnicity. Age was grouped into 5-year bins except for the youngest (0–5) and oldest (≥76) age bins. Ethnicity was distributed into 7 groups: White, Asian, African, Caribbean or Black, Arab, Mixed, and Other. Supplementary Table S1 provides a breakdown of the demographic data, which are similar for the two cities. Females comprised 55.1% and 53.8% of the participants in Glasgow and Edinburgh, respectively. Ethnicity was dominated by White (92.4% in Glasgow, 92.7% in Edinburgh) followed by Asian (5.7% in Glasgow, 4.9% in Edinburgh). Age profiles were also similar, for example 31.1% and 32.2% were aged ≤25 in Glasgow and Edinburgh, respectively, and 24.3% and 23.3% were aged ≥61.

Deciles of the Carstairs Index of deprivation (Carstairs and Morris, 1989) were used as the metric of the individual's socio-economic status (SES). The decile is derived from an averaged value of all households in an Output Area – a census geographical unit containing at least 20 households and an average of 114 residents – and is based on social class, overcrowding, male unemployment and car ownership (Brown et al., 2014). Decile 1 is the least deprived and Decile 10 the most deprived.

2.3 Air pollutant exposures

Hourly surface concentrations of $PM_{2.5}$, NO_2 and O_3 were calculated using a UK application of the EMEP MSC-W atmospheric chemistry transport model rv4.17 (https://github.com/metno/emep-ctm/releases/tag/rv4_17) called EMEP4UK (www.emep4uk.ceh.ac.uk). EMEP4UK is driven by meteorology from the Weather and Research Forecasting model (WRF) v3.9.1 (Skamarock et al., 2008). Further details of the model set-up are given in Liška et al. (2024) and its supplementary material. The horizontal resolution of the model over the UK is 0.124□ × 0.124□ (0.8 km × 1.4 km). Output from the EMEP4UK-WRF model is routinely evaluated against measurements and extensively used to simulate air pollutant concentrations for health exposure and policy (e.g. Carnell et al., 2019;

Lin et al., 2017; Macintyre et al., 2023a, b; Purser et al., 2023; Reis et al., 2018; Vieno et al., 2016). For illustration, the annual mean modelled NO_2, O_3 and $PM_{2.5}$ concentrations across central Scotland, which includes Glasgow and Edinburgh, are shown in Figure S2.

Hourly pollutant concentrations at residence, and at place of work or study, were assigned from the model grid in which the address postcode point was located. We calculated an annual mean residential exposure (RE) to each pollutant using residential address only and, for those individuals for whom it was relevant, annual means derived from two combinations of residential and workplace exposures (RWE): an $RWE_{8\text{-}18}$ scenario that assume those working or studying away from home are at their place of work or study between 08:00 and 18:00 Monday to Friday, and at their place of residence at other times; and an RWE_{hw+} scenario that uses a mean of residential and workplace concentrations weighted by the typical number of hours per week worked, which was also part of the census information (albeit with no information on how those hours were distributed). We added one hour for every seven hours worked to allow for breaks. For full-time students, we assumed 30 h per week at their place of study. For part-time students who worked, we assumed their answers to the questions about place of work/study and numbers of hours worked referred to their place of work rather than their place of study. For individuals not working or studying, or working or studying from home, RE, $RWE_{8\text{-}18}$ and RWE_{hw+} were identical. Information was not available to estimate individual's exposures during commuting.

2.4 Data disclosure restrictions

Data analysis was performed with R version 3.5.2. To prevent disclosure, stringent restrictions were placed on our access to and dissemination of the cohort data. Our data requests were extracted and linked with the pollution data by staff at the SLS Development and Support Unit. We may only report a result of an analysis if it is based on at least 10 SLS participants. This limitation on data presentation does not affect the calculated exposures.

3. Results and Discussion

The focus throughout this paper is on the qualitative trends in the pollutant exposures and exposure differentials. The quantitative values of the exposures are not relevant.

Before comparing the trends in demographic-exposure relationships between Glasgow and Edinburgh we compare exposures at the population level as context for discussion of the effects of including place of work or study on the exposure estimates.

3.1. Comparison between Glasgow and Edinburgh population exposures

Table 1 shows that when considering residential address only, the median and interquartile range in annual mean exposure to NO_2 for cohort individuals in Glasgow and Edinburgh are very similar at 13.56 (10.45–15.67) $\mu g\ m^{-3}$ and 13.41 (10.62–14.99) $\mu g\ m^{-3}$, respectively. However, when time spent at place of work/study is taken into account the median exposure of individuals to NO_2 is proportionally much larger compared to the residential-only exposure in Glasgow than is the case in Edinburgh. The median exposures to NO_2 under the $RWE_{8\text{-}18}$ and RWE_{hw+} scenarios are higher than the RE scenario by 3.5% (0.47 $\mu g\ m^{-3}$) and 1.8% (0.24 $\mu g\ m^{-3}$), respectively, in Glasgow, but by only 0.6% (0.08 $\mu g\ m^{-3}$) and 0.5% (0.07 $\mu g\ m^{-3}$), respectively, in Edinburgh. The $RWE_{8\text{-}18}$ scenario for time spent at work/study yields greater change than the RWE_{hw+} scenario since the former assigns 50 h per week to workplace exposure to allow for all time spent away from home, whereas the latter is based only on time spent at work and better represents part-time workers. Both scenarios are plausible narratives for estimating exposures that include time spent at place of work or study.

The greater impact on exposures of populations in Glasgow than in Edinburgh, of including time spent at place of work/study, also applies to exposures to $PM_{2.5}$ and O_3 (Table 1). However, the relative magnitude of changes in exposures are smaller for both $PM_{2.5}$ and O_3 than for NO_2; and, for O_3, the inclusion of place of work/study yields exposures lower than those based on residential location only. For example, the median exposure to $PM_{2.5}$ under the RWE_{8-18} scenario is higher than the RE scenario by 0.4% (0.03 µg m^{-3}) in Glasgow and not higher at all in Edinburgh (compared to comparator increases of 3.7% and 0.6% for RWE_{8-18} exposures to NO_2), whilst the median exposure to O_3 under the RWE_{8-18} scenario is lower than the RE scenario by 0.7% (0.41 µg m^{-3}) in Glasgow and by 0.4% (0.21 µg m^{-3}) in Edinburgh. As is the case for NO_2, differences are smaller between the RWE_{hw+} and RE scenarios than between the RWE_{8-18} and RE scenarios for both $PM_{2.5}$ and O_3, but are still greater in Glasgow than in Edinburgh.

The effect of incorporating time spent at work/study is greatest for NO_2 since this pollutant has greater spatial heterogeneity in concentrations across the cities than $PM_{2.5}$ and O_3. This is because NO_2 concentrations are strongly influenced by within-city emission sources, most notably road traffic, and by its shorter atmospheric lifetime (Reis et al., 2018). Whilst $PM_{2.5}$ also has local primary sources, a substantial proportion of $PM_{2.5}$ comprises a regional background which is the same everywhere in a city (AQEG, 2012). As a consequence, concentrations of NO_2 tend to be relatively much higher in city centres, where people tend to commute to work, compared with the outskirts of the city, than the relative increase in $PM_{2.5}$ in city centres compared with the outskirts. Ozone is entirely a secondary pollutant that also generally has greater spatial homogeneity than NO_2. The reaction between NO emissions and O_3 means that O_3 concentrations tend to be lower in city centres than the outskirts (AQEG, 2021; Hood et al., 2018; Lin et al., 2016) which explains why inclusion of workplace leads to a decrease in population-average exposure to O_3 compared with exposure based on residence only. However, whilst the above are explanations for the broad patterns observed in the exposures to NO_2, $PM_{2.5}$ and O_3, the detail in the differences between the two cities must be driven by city-specific geographical and demographic characteristics. The smaller effect on exposures in Edinburgh of including place of work/study suggests that large centres of employment and education providers in Edinburgh are situated more away from the city centre compared to Glasgow (which local knowledge supports).

As noted above, only 49% of individuals routinely spent time at a place of work/study that is not their residential address, so for those individuals that do, their average increased exposure to NO_2 and $PM_{2.5}$, and averaged decreased exposure to O_3, will be greater than the average increase across all individuals.

Table 1. Summary statistics for the exposures of the cohort individuals in Glasgow and Edinburgh to NO_2, O_3 and $PM_{2.5}$ by exposure scenario. Also shown are the absolute and relative differences in the means and medians between the RWE_{8-18} and RE exposure scenarios and between the RWE_{hw+} and RE exposure scenarios. Units are µg m^{-3}, except where percentages are indicated. Source: Scottish Longitudinal Study.

Pollutant	City	Exposure Scenario[a]	Mean	SD	Median	Q1	Q3	RWE_{xxx} □ RE (means)	RWE_{xxx} □ RE (means) %	RWE_{xxx} □ RE (medians)	RWE_{xxx} □ RE (medians) %
NO_2	Glasgow	RE	13.39	3.95	13.56	10.45	15.67	-	-	-	-
		RWE_{8-18}	13.83	3.83	14.03	10.79	16.31	0.44	3.3	0.47	3.5
		RWE_{hw+}	13.71	3.82	13.80	10.71	16.04	0.32	2.4	0.24	1.8
NO2	Edinburgh	RE	12.71	3.02	13.41	10.62	14.99	-	-	-	-
		RWE_{8-18}	12.90	2.83	13.49	11.02	15.02	0.19	1.5	0.08	0.6
		RWE_{hw+}	12.85	2.84	13.48	10.91	14.97	0.14	1.1	0.07	0.5
O_3	Glasgow	RE	55.72	3.83	55.46	53.20	58.66	-	-	-	-
		RWE_{8-18}	55.37	3.70	55.05	52.88	58.27	-0.35	-0.6	-0.41	-0.7
		RWE_{hw+}	55.44	3.68	55.10	52.94	58.30	-0.28	-0.5	-0.36	-0.6
O3	Edinburgh	RE	58.78	2.87	58.36	56.78	60.46	-	-	-	-
		RWE_{8-18}	58.62	2.69	58.15	56.76	60.14	-0.16	-0.3	-0.21	-0.4
		RWE_{hw+}	58.65	2.68	58.16	56.84	60.15	-0.13	-0.2	-0.20	-0.3
$PM_{2.5}$	Glasgow	RE	8.02	0.44	8.09	7.75	8.32	-	-	-	-
		RWE_{8-18}	8.05	0.41	8.12	7.8	8.34	0.03	0.4	0.03	0.4
		RWE_{hw+}	8.05	0.42	8.11	7.78	8.32	0.03	0.4	0.02	0.2
$PM_{2.5}$	Edinburgh	RE	7.70	0.48	7.75	7.41	8.00	-	-	-	-
		RWE_{8-18}	7.70	0.43	7.75	7.43	7.97	0.00	0.0	0.00	0.0
		RWE_{hw+}	7.70	0.44	7.74	7.43	7.98	0.00	0.0	-0.01	-0.1

[a] RE = annual mean exposure assuming each individual is at their place of residence; RWE_{8-18} = annual mean exposure assuming each individual is at their place of work or study between 08:00 and 18:00 Monday to Friday, otherwise at their place of residence; RWE_{hw+} = annual mean exposure assuming each individual is at their place of work or study for the typical hours per week worked, otherwise at their place of residence. As noted in the main text, 51% of individuals did not have a place of work or study different from their place of residence.

3.2. Comparisons between Glasgow and Edinburgh exposures by demographic attribute

The figures in this section present visualisations of the extent to which trends in exposures with demographic subgroup are or are not similar between Glasgow and Edinburgh. The upper panels in each figure show the medians and interquartile ranges in exposures of each demographic subgroup in each city calculated using residential address only (the RE scenario) and with inclusion of time spent at place at work or study (the RWE scenarios). The lower panels show the % differences between the demographic subgroup median exposures in each of the RE, RWE_{8-18} and RWE_{hw+} scenarios and the overall median exposure of the RE scenario for the given city. We illustrate using median values since the exposure distributions tend to be non-symmetrical; and we show relative differences in exposures because absolute differences are influenced by the different magnitudes of pollutant concentrations in each city. We express all changes in median exposures relative to the residential-only (RE) scenario so as to highlight how inclusion of place of work/study also changes the exposures compared with analyses based only on exposure at place of residence, which is the case for most studies investigating demographic differentials in exposures to air pollutants.

The figures illustrating relationships between exposure to NO_2 or $PM_{2.5}$ and demographics are in the main paper. The equivalent figures for O_3 are in the Supplementary Material since in all cases these are inversions of the relationships with NO_2 exposures; i.e., where NO_2 exposure is higher, O_3 exposure is lower, and vice versa. This is due to the anticorrelation between O_3 and NO_2 concentrations in urban areas described above. The relative magnitudes of the differences in O_3 exposure with demographic sub-group tend to be smaller than the equivalent differentials in NO_2 exposure.

3.2.1. By sex

Figures 1, 2 and S3 show that, as would be predicted, there is no difference between median exposures of males and females in each city to NO_2, $PM_{2.5}$ and O_3, respectively, when basing exposure on place of residence only (the RE scenario). This follows the expectation that males and females are similarly geographically distributed in a city with respect to where they live. However, these figures also show that when place or work or study is included in the exposure estimate then: (1) males and females have different median exposures to the pollutants; and (2) these male and female differences are different in Glasgow and Edinburgh. Thus, while NO_2 exposures for both sexes increase more in Glasgow than in Edinburgh under the RWE scenarios (Fig. 1) (and decrease more in Glasgow than in Edinburgh for exposure to O_3, Fig. S3), the differentials between male and female exposures to both pollutants under these scenarios is larger in Edinburgh than in Glasgow; i.e., females in Edinburgh are, on average, less impacted than males in Edinburgh by their time spent out of home than is the case in Glasgow. For $PM_{2.5}$ (Fig. 2), it turns out that at the spatial resolution of the model exposure values, the median exposures of both sexes in RWE scenarios in Edinburgh are the same (or slightly less) as the median RE exposure.

These male-female differences between Glasgow and Edinburgh when place of work/study is included must reflect different geographical patterns between the two cities in the places of work or study of females compared with males, which in turn must arise from differences in how a city's urban fabric and population develop in time. Changes in exposures at a population level as urban layout changes has been noted before (Kramer and Minet, 2025). Since the precise features of the residential and workplace geographical differences relevant to demographic differentials in exposure are not possible to predict in advance, it is not possible to extrapolate differentials observed in one city to another city. It is also the case that the effect of including place of work/study leads to only small relative changes in exposures between males and females, compared with the magnitude of the changes that inclusion of place of work or study has across the other three demographic subgroups investigated. This means that, as expected, there is less spatial 'clumping' in places of work/study for male versus female than there is across different age groups and socioeconomic deciles.

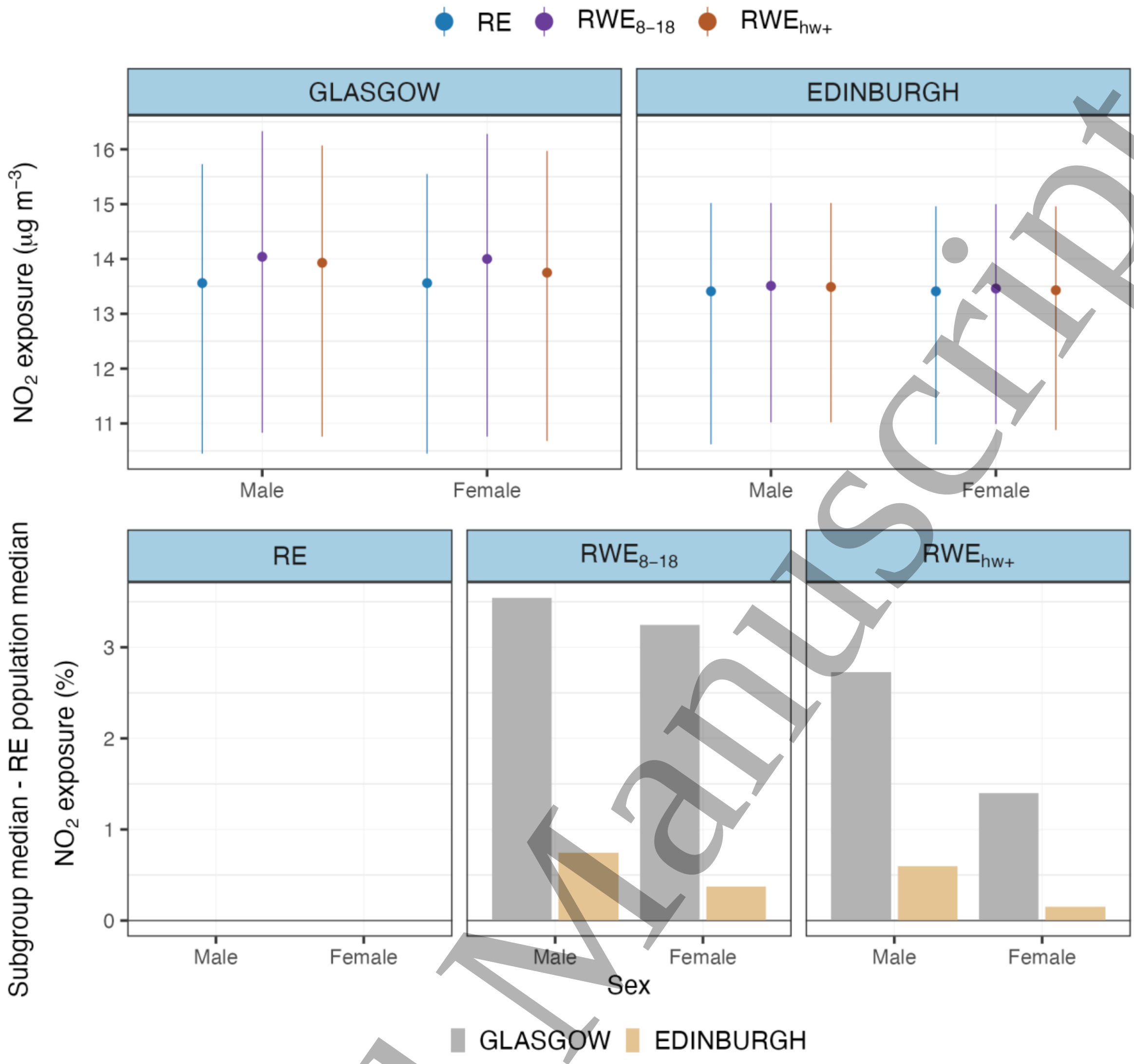

Figure 1. Comparisons between Glasgow and Edinburgh of exposure to NO_2 by sex. Top panel, NO_2 exposure medians (•) and interquartile ranges (|) by sex and exposure scenario; bottom panel, the % differences between male and female median exposures in each of the RE, $RWE_{8\text{-}18}$ and RWE_{hw+} scenarios and the overall median exposure for the RE scenario for that city (13.56 and 13.41 µg m^{-3} for Glasgow and Edinburgh, respectively). The absence of some bars in the lower plots signifies values of 0%, not an absence of data. Source: Scottish Longitudinal Study.

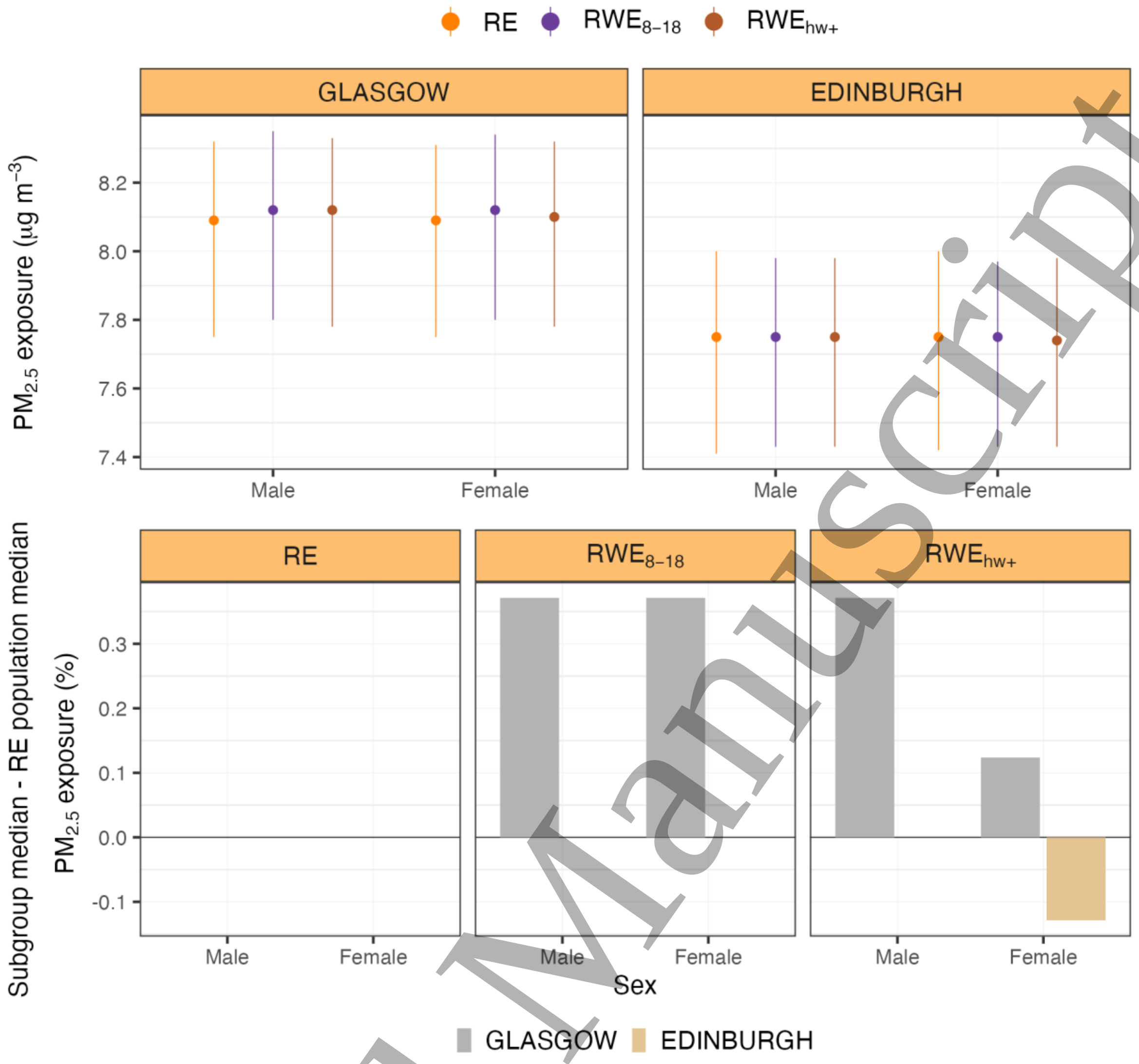

Figure 2. Comparisons between Glasgow and Edinburgh of exposure to $PM_{2.5}$ by sex. Top panel, $PM_{2.5}$ exposure medians (•) and interquartile ranges (|) by sex and exposure scenario; bottom panel, the % differences between male and female median exposures in each of the RE, $RWE_{8\text{-}18}$ and RWE_{hw+} scenarios and the overall median exposure for the RE scenario for that city (8.09 and 7.75 µg m^{-3} for Glasgow and Edinburgh, respectively). The absence of some bars in the lower plots signifies values of 0%, not an absence of data. Source: Scottish Longitudinal Study.

3.2.2. By age

Figures 3, 4 and S4 compare the exposures to NO_2, $PM_{2.5}$ and O_3 in Glasgow and Edinburgh stratified by age group for the three exposure scenarios. Whilst the profiles of exposure to NO_2 and $PM_{2.5}$ by age are broadly similar in Glasgow and Edinburgh – greatest exposures at ages 21–35, lowest exposures at ages 6–10 (Figs. 3 and 4) – there are important differences. Firstly, the range between highest and lowest exposures across age groups is much greater in Glasgow than in Edinburgh. For NO_2, the range spans more than 20% in Glasgow, particularly when place of work/study is also included in the determination of exposure, but less than 10% in Edinburgh. The corresponding ranges for $PM_{2.5}$ are around 3.5% and 2%, respectively. Secondly, when place of work/study is included in the estimates of exposures (the RWE scenarios), the exposures of those in the age range 16-60 in Glasgow are greater than their RE exposures by proportionally much more than is the case for that age range in Edinburgh. (The demographic sub-group exposure patterns for O_3 (Fig. S4) are similar but in the inverse sense to those for NO_2.)

The similarity in the general trend of exposure with age in Glasgow and Edinburgh reflects the general tendency of young adults to live and work in urban centres before relocating to suburbs in later life (Bromley et al., 2007; Thomas et al., 2015). There is also similarity in that the exposures of the youngest (0–16 age range) in both cities is largely unaffected by their exposure at school, which is due to the typically short distance between home and school.

Conversely, there are clearly also different geographical patterns in the locations of places of work for the 16–60 age group relative to their residences that drive the much smaller influence of place of work on exposures for this age range in Edinburgh compared with Glasgow. This observation limits the generalisations that can be made in extrapolating relationships between age and exposure to air pollution across different urban areas.

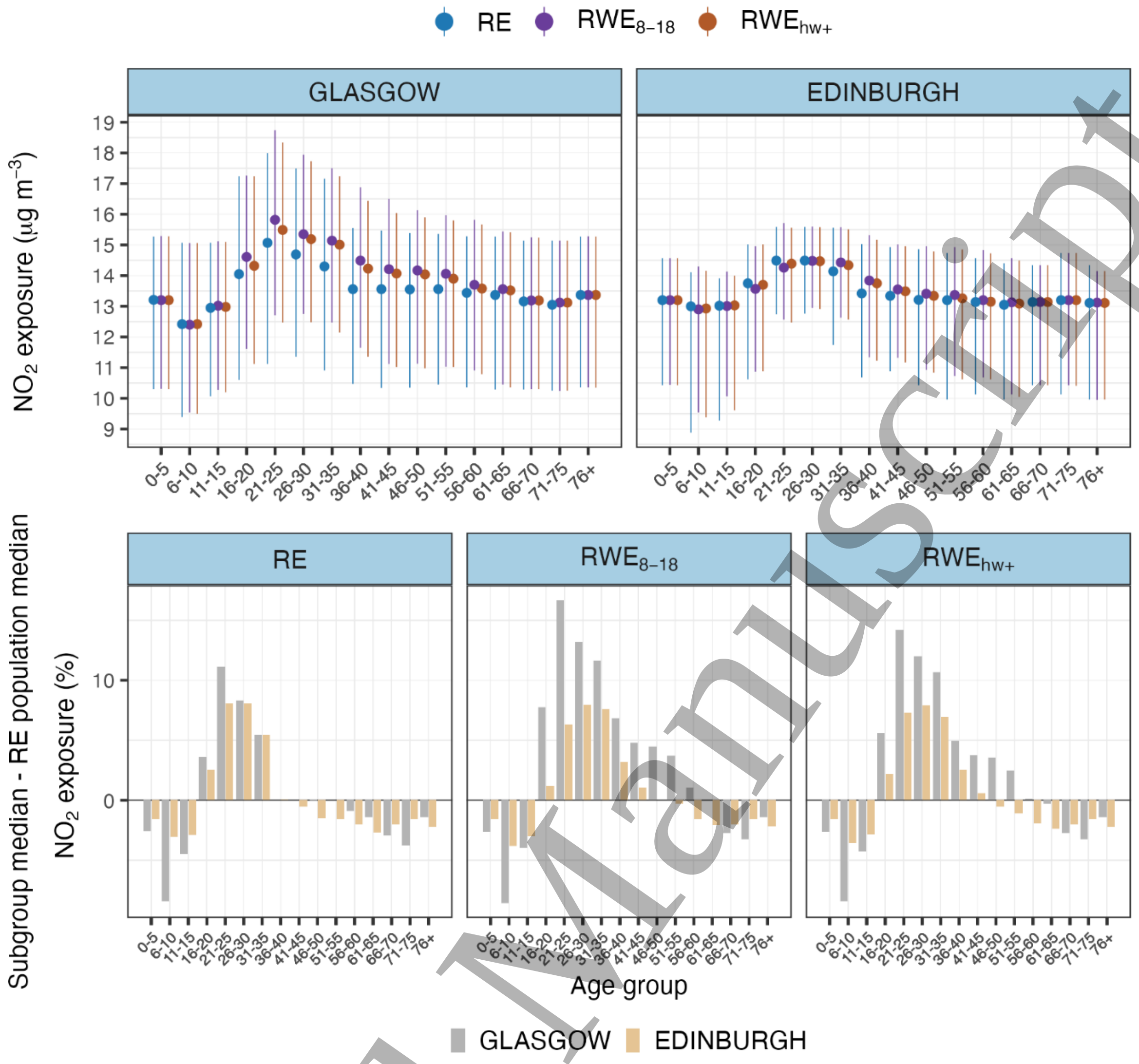

Figure 3. Comparisons between Glasgow and Edinburgh of exposure to NO_2 by age. Top panel, NO_2 exposure medians (•) and interquartile ranges (|) by age group and exposure scenario; bottom panel, the % differences between age group median exposures in each of the RE, RWE_{8-18} and RWE_{hw+} scenarios and the overall median exposure for the RE scenario for that city (13.56 and 13.41 μg m^{-3} for Glasgow and Edinburgh, respectively). Source: Scottish Longitudinal Study.

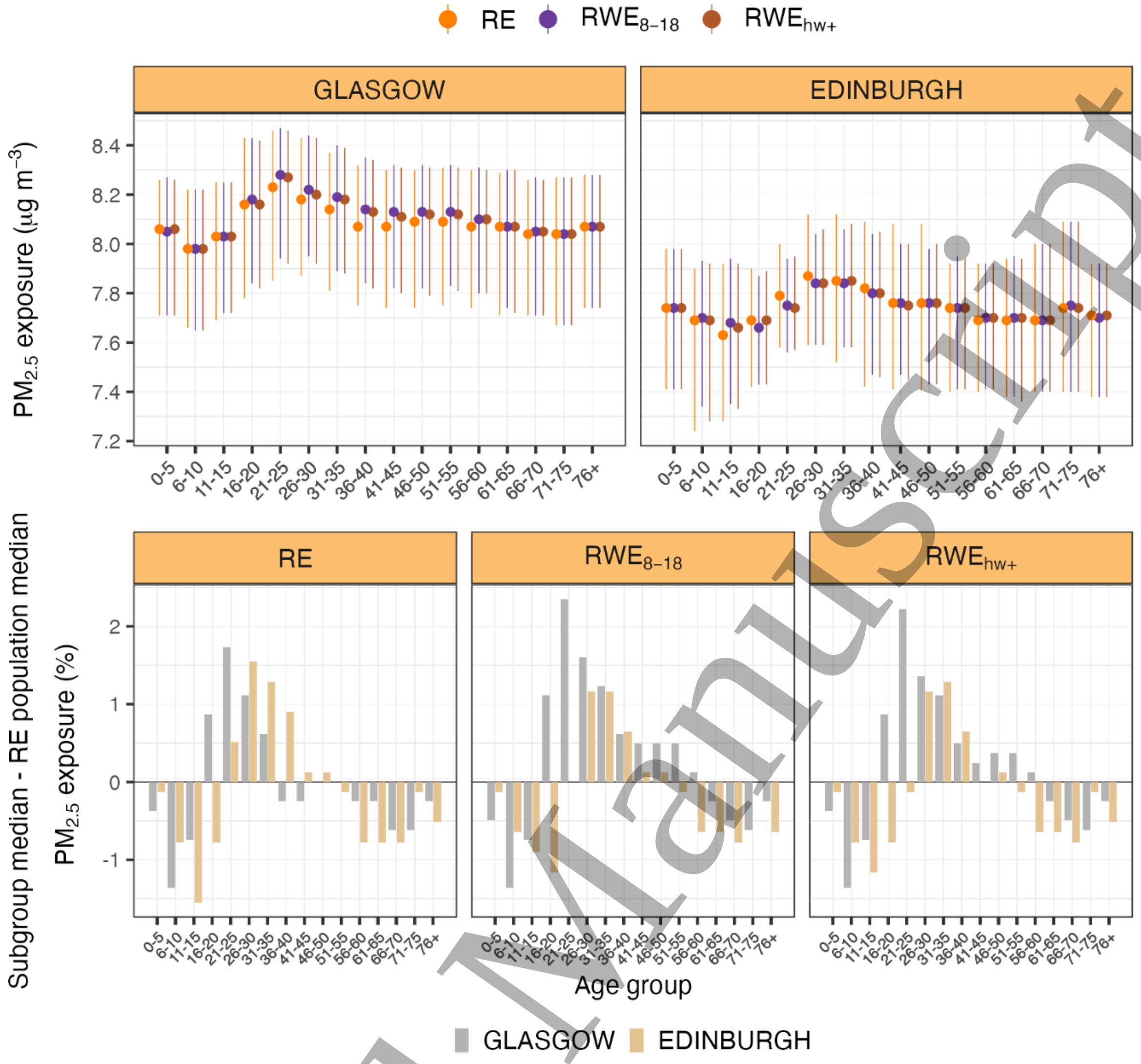

Figure 4. Comparisons between Glasgow and Edinburgh of exposure to $PM_{2.5}$ by age. Top panel, $PM_{2.5}$ exposure medians (•) and interquartile ranges (|) by age group and exposure scenario; bottom panel, the % differences between age group median exposures in each of the RE, $RWE_{8\text{-}18}$ and RWE_{hw+} scenarios and the overall median exposure for the RE scenario for that city (8.09 and 7.75 µg m^{-3} for Glasgow and Edinburgh, respectively). Source: Scottish Longitudinal Study.

3.2.3. By ethnicity

The exposures to NO_2, $PM_{2.5}$ and O_3 in Glasgow and Edinburgh stratified by ethnicity for the three exposure scenarios are shown in Figures 5, 6 and S5, respectively. In Glasgow, all non-white ethnic groups are (on average) exposed to higher concentrations of NO_2 and $PM_{2.5}$ (and to lower concentrations of O_3) than is the white ethnic group, whilst differentials in exposures across ethnic groups in Edinburgh are smaller and of mixed direction. In Glasgow, the non-white ethnic groups experience NO_2 concentrations in the range 11-28% higher than the median exposure across all individuals, and experience $PM_{2.5}$ concentrations in the range 1.1–3.5% higher. In Edinburgh, the higher exposures of some ethnic groups reach only 8% higher (for NO_2) and 1.3% higher (for $PM_{2.5}$) than the median exposures, with individuals in the

Arab ethnic group being exposed to lower than the median exposure. Other studies have also reported lower exposures for minority ethnic groups compared with the majority ethnic group (Al Ahad et al., 2022; Fairburn et al., 2019).

These observations must again reflect different geographical patterns between the two cities in places of residence and of places of work/study for different ethnic groups. This limits the generalisations that can be made in extrapolating relationships between ethnicity and exposure to air pollution across different urban areas, as already highlighted above for both sex and age as demographic attributes. Inconsistency between countries and cities in relationships between air pollution exposure and ethnicity has been highlighted previously (Fairburn et al., 2019; Fecht et al., 2015).

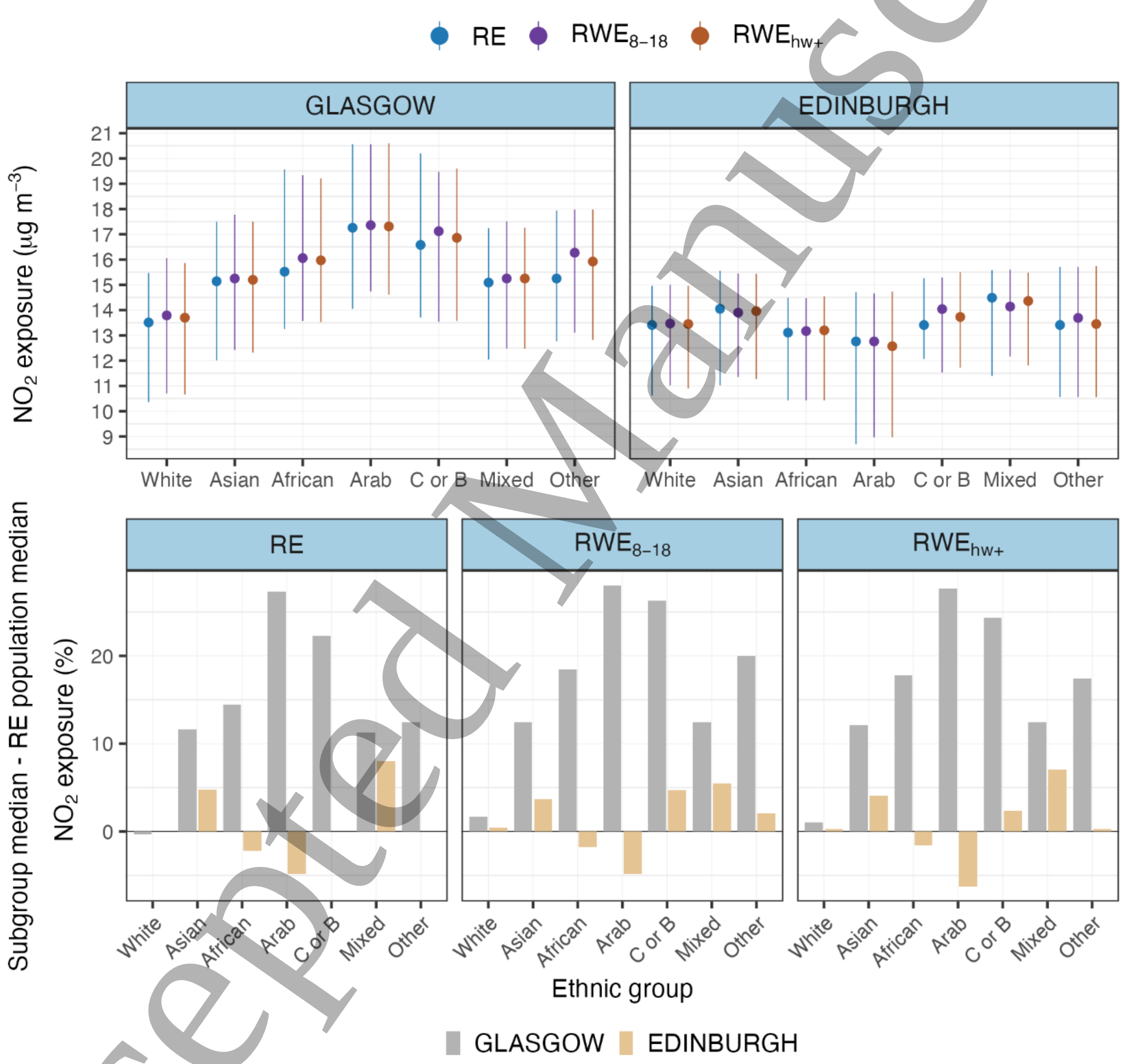

Figure 5. Comparisons between Glasgow and Edinburgh of exposure to NO_2 by ethnicity. Top panel, NO_2 exposure medians (•) and interquartile ranges (|) by ethnicity and exposure scenario; bottom panel, the % differences between ethnic group median exposures in each of the RE, $RWE_{8\text{-}18}$ and RWE_{hw+} scenarios and the overall median exposure for the RE scenario for that city (13.56 and 13.41 μg m^{-3} for Glasgow and Edinburgh, respectively). "C or B" means Caribbean or Black. Source: Scottish Longitudinal Study.

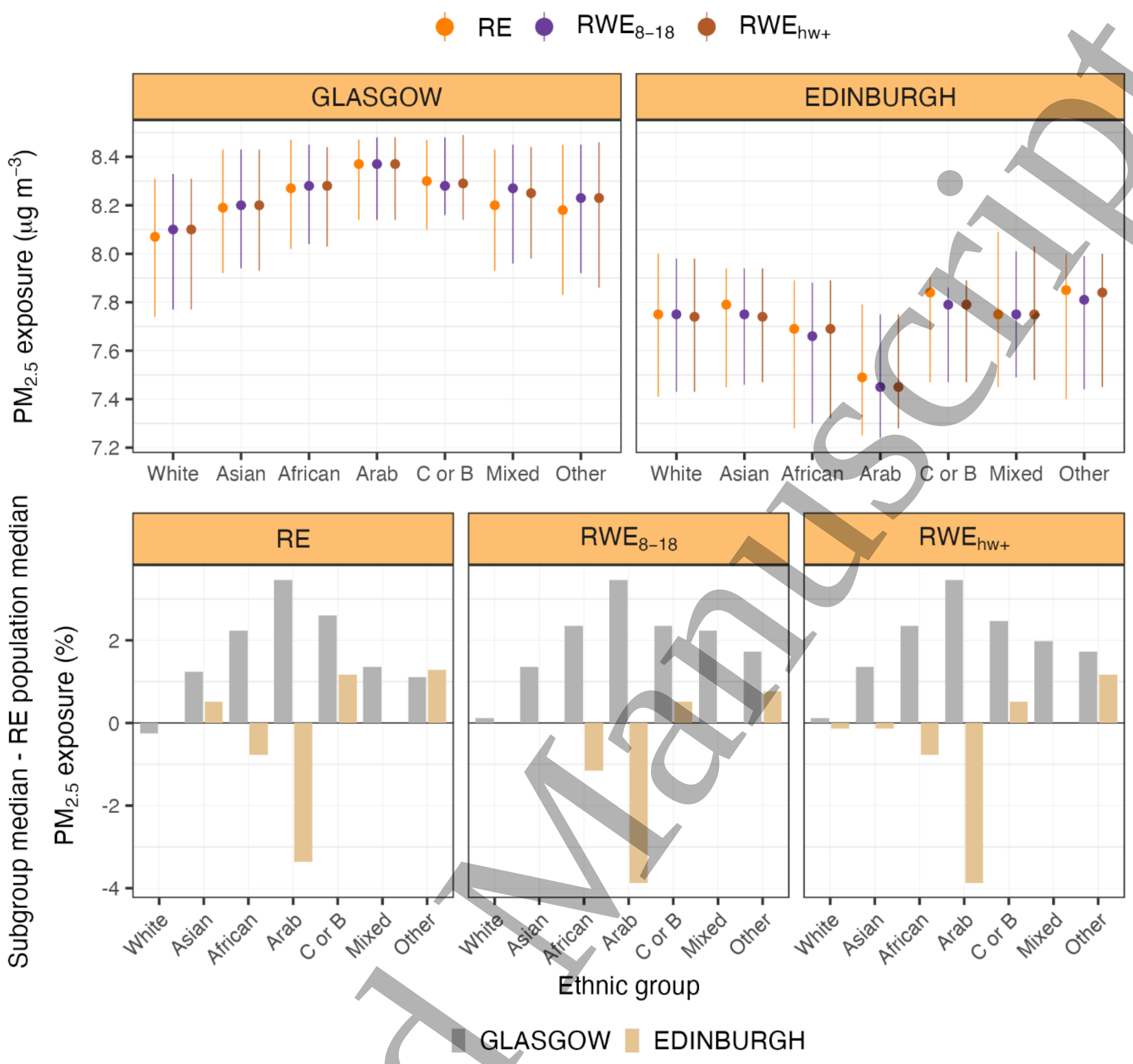

Figure 6. Comparisons between Glasgow and Edinburgh of exposure to $PM_{2.5}$ by ethnicity. Top panel, $PM_{2.5}$ exposure medians (•) and interquartile ranges (|) by ethnicity and exposure scenario; bottom panel, the % differences between ethnic group median exposures in each of the RE, $RWE_{8\text{-}18}$ and RWE_{hw+} scenarios and the overall median exposure for the RE scenario for that city (8.09 and 7.75 µg m^{-3} for Glasgow and Edinburgh, respectively). “C or B” means Caribbean or Black. Source: Scottish Longitudinal Study.

3.2.4. By socioeconomic status (SES)

Figures 7, 8 and S6, respectively compare the exposures to NO_2, $PM_{2.5}$ and O_3 in Glasgow and Edinburgh, for stratification by SES decile. As for the other demographic variables, there are both similarities and differences in exposure relationships between the two cities.

In both cities, the least deprived individuals are (on average) exposed to the lowest concentrations of NO_2 and $PM_{2.5}$ (and to highest concentrations of O_3) and there is a trend of increasing exposure to NO_2 and $PM_{2.5}$ (and decreasing exposure to O_3) as decile of deprivation increases from Decile 1 to 5. In Glasgow, this continues to Decile 10, such that these most deprived individuals in Glasgow are (on average) exposed to ~30% higher NO_2 concentrations (and to ~3.5% higher $PM_{2.5}$ concentrations) than the least deprived. Furthermore, accounting for exposure during time spent at place of work/study reveals that individuals in Deciles 4 to 8 in Glasgow are exposed to higher concentrations of NO_2 and $PM_{2.5}$ than exposures based on residential location only. In stark contrast, in Edinburgh, there is little difference in exposures to NO_2 and $PM_{2.5}$ for individuals in Deciles 3 to 9, and the most-deprived individuals are actually exposed to lower concentrations of NO_2 and $PM_{2.5}$ than all other groups except those in the least deprived Deciles 1 and 2. Another difference between Edinburgh and Glasgow is that inclusion of place of work/study has considerably smaller effect on the pattern of exposure with SES decile in Edinburgh than in Glasgow.

The relationships between exposure to O_3 and SES decile (Fig. S6) are similar to those for NO_2 in each city, but in the inverse sense, because of the anticorrelation between O_3 and NO_2 concentrations in urban areas.

These findings again reflect different geographical patterns between the two cities in the locations of places of residence and of work/study for individuals with differing SES. As for age and ethnicity, a mixed picture in the relationship between residential exposure and SES has been noted before (Briggs et al., 2008; Fecht et al., 2015; Hajat et al., 2015; Temam et al., 2017; Young et al., 2023), including in Scotland (Bailey et al., 2018). In a study in France, Padilla et al. (2014) reported that deprived groups tended to be more localised in the centres of Lille, Marseille and Lyon, where air pollution is greater, yet the centre of Paris tended to be associated with less deprived groups. It is similar case for the comparison here between Glasgow and Edinburgh, respectively.

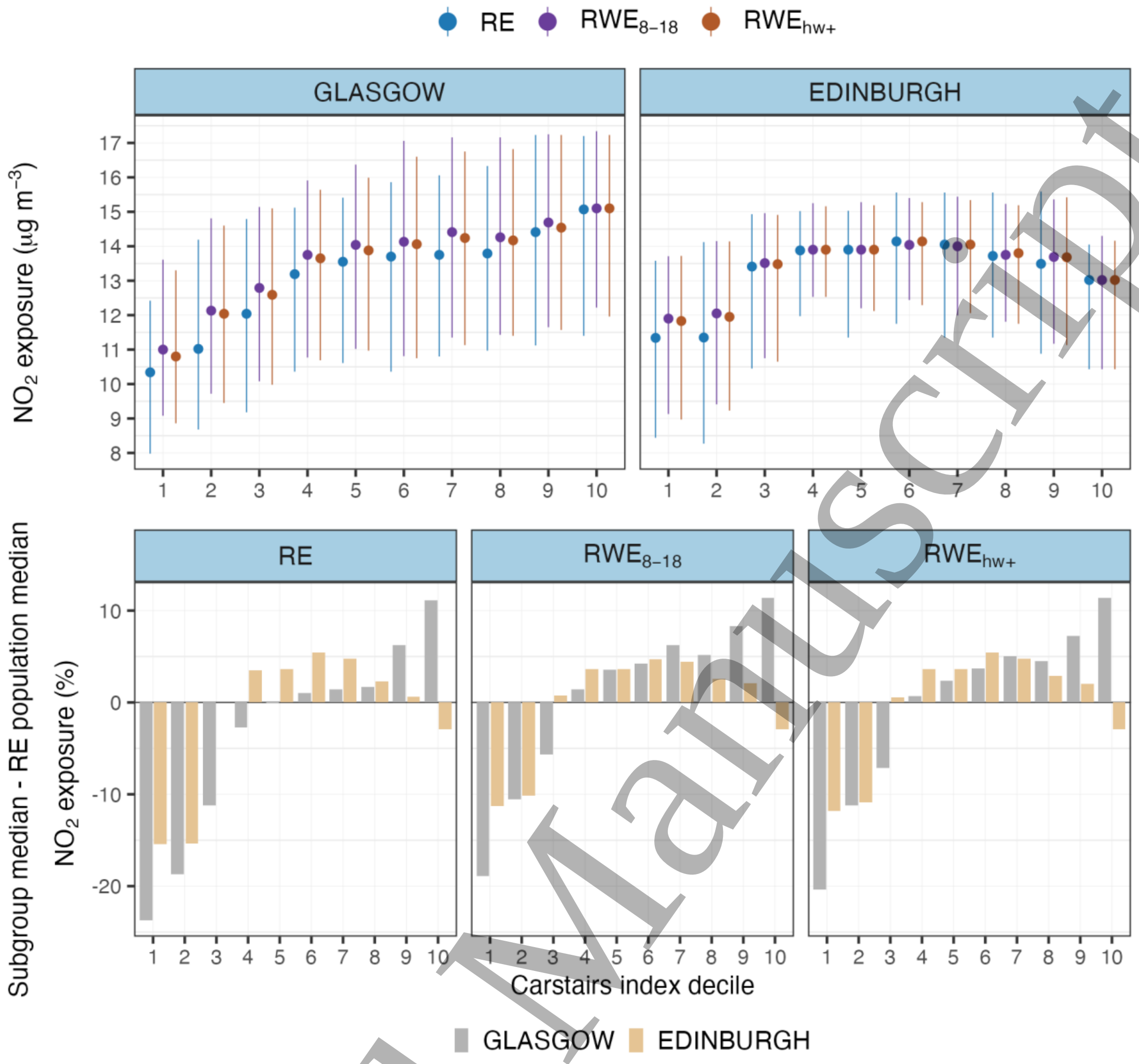

Figure 7. Comparisons between Glasgow and Edinburgh of exposure to NO_2 by socioeconomic status (SES). Top panel, NO_2 exposure medians (•) and interquartile ranges (|) by SES decile and exposure scenario; bottom panel, the % differences between SES decile median exposures in each of the RE, $RWE_{8\text{-}18}$ and RWE_{hw+} scenarios and the overall median exposure for the RE scenario for that city (13.56 and 13.41 μg m^{-3} for Glasgow and Edinburgh, respectively). Decile 1 is least deprived. Source: Scottish Longitudinal Study.

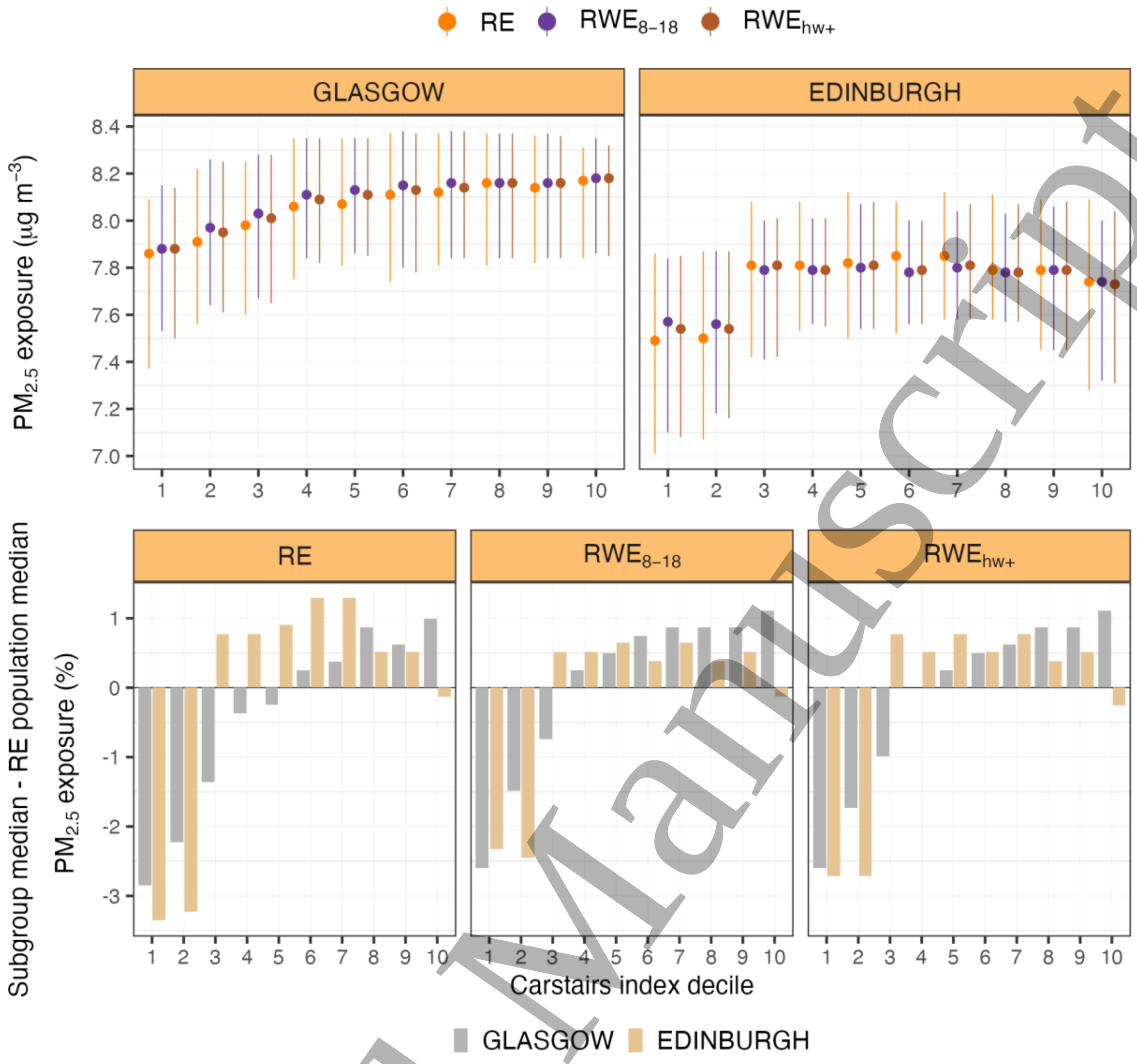

Figure 8. Comparisons between Glasgow and Edinburgh of exposure to $PM_{2.5}$ by socioeconomic status (SES). Top panel, $PM_{2.5}$ exposure medians (•) and interquartile ranges (|) by SES decile and exposure scenario; bottom panel, the % differences between SES decile median exposures in each of the RE, $RWE_{8\text{-}18}$ and RWE_{hw+} scenarios and the overall median exposure for the RE scenario for that city (8.09 and 7.75 µg m^{-3} for Glasgow and Edinburgh, respectively). Decile 1 is least deprived. Source: Scottish Longitudinal Study.

3.3. Limitations

A limitation in our study is that we did not have information to allow estimation of exposures to the air pollutants in other potentially important microenvironments, particularly whilst commuting between home and place of work or study. Whilst some studies report that the contribution of commuting to total exposure (to NO_2) is, on average, small (Shafran-Nathan et al., 2018), and others that it could exceed 10% (de Nazelle et al., 2013), it will certainly be the case that any commuting contribution will vary substantially with individual circumstances (Ragettli et al., 2015). Commuting choices may also be modifiers of relationships between air pollution exposure and demographics, for example the more deprived may be more likely to use buses and the less deprived to use cars (Tonne et al., 2018).

Our estimates of exposure are also limited by the spatial resolution of our simulations. Although the EMEP4UK model we used has very high spatial resolution for an atmospheric chemistry transport model, it is still not able fully to resolve the strongest gradients in air pollutant concentrations close to air pollution sources. This is likely to have resulted in smaller calculated differences in exposure to NO_2 in particular.

A further limitation is that the analyses used data on cohort individuals from 2011, but this was the most recent linkage to Census data available. The Census scheduled for 2021 was delayed for a year because of Covid and linkage to the cohort individuals had not taken place at the time these analyses were undertaken (and were also not available as of early 2026). However, whilst the exact demographic distributions are likely to have changed in that time, it seems plausible that the overall conclusion that details of air pollution-demographic relationships differ between the two cities will stand. The Carstairs Index measure of socioeconomic status is also somewhat dated, but the alternative Scottish Index of Multiple Deprivation was not linked to the SLS cohort individuals. Probably the greatest change relevant to our study to have occurred in the last few years is an increase in residential and hybrid working post Covid compared with pre-Covid. Such a shift would lessen the additional impact on relationships between air pollutant exposure and demographic variables of including place of work on exposure estimates, compared with exposures based on residence only; but would not alter the principal observation, based on residential exposures alone, of between-city differences in pollution-demographic relationships.

4. Conclusions

We have shown that relationships between demographic attributes (sex, age, ethnic group, socioeconomic status) and exposure to NO_2, O_3 and $PM_{2.5}$ air pollution can be city specific, even between two cities in geographic proximity and having broadly similar demographic profiles (Glasgow and Edinburgh in this study). We have demonstrated this using the same datasets and methodologies for the two cities which removes the potential for methodological confounding that may be present in other between-city comparisons. A second distinct advantage of our study design is that it uses individual-level data and is therefore not subject to the modifiable area unit problem. We have also demonstrated that the city specificity in the relationships is additionally complicated by city differentials in the geographical distribution of places of work and study relative to places of residence. These differentials in exposure-demographic relationships must result from the particular history of urban development, employment sectors, population characteristics and other factors that apply to a given city. However, whilst the existence of demographic differentials in exposure is of direct policy relevance because they translate to demographic differentials in burden of disease, we conclude that it is not possible to assume a generic relationship between exposure to air pollution and the categories of a given demographic variable.

Data availability statement

The data cannot be made publicly available because they are owned by a third party and the terms of use prevent public distribution.

Acknowledgments

The help provided by staff of the Longitudinal Studies Centre Scotland (LSCS) is acknowledged. The LSCS is supported by the ESRC/JISC, the Scottish Funding Council, the Chief Scientist's Office and the Scottish Government. The authors alone are responsible for the interpretation of the data. Census output is Crown copyright and supplied by National Records of Scotland. It is re-used under terms of the Open Government Licence.

Funding

This research as funded by Natural Environment Research Council (NERC) grant NE/L002558/1 and a CASE award from the Institute of Occupational Medicine. Development of the EMEP4UK model used in this work was funded in part by NERC grant NE/R016429/1, part of the NERC UK-SCAPE National Capability programme. For the purpose of open access, the authors have applied a creative commons attribution (CC BY) licence to any author accepted manuscript version arising.

Conflict of interests

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Ethical statement

Ethical approval was not required because this study used anonymised data collected as part of the 2011 UK Census. Access was provided through the Scottish Longitudinal Study Development and Support Unit and was subject to its established data-access, confidentiality and governance procedures.

Author contributions

Tomáš Liška: Conceptualization, Methodology, Formal Analysis, Visualization, Writing – Original Draft.
Mathew R Heal: Supervision, Funding Acquisition, Conceptualization, Methodology, Writing – Review & Editing.
Chun Lin: Methodology, Writing – Review & Editing.
Massimo Vieno: Resources, Writing –Review & Editing.
Edward J Carnell: Resources, Writing – Review & Editing.
Samuel J Tomlinson: Resources, Writing – Review & Editing.
Miranda Loh: Funding Acquisition, Writing – Review & Editing.
Stefan Reis: Supervision, Funding Acquisition, Conceptualization, Methodology, Writing – Review & Editing.

ORCID iDs

Tomáš Liška, https://orcid.org/0000-0001-9500-0633
Mathew R Heal, https://orcid.org/0000-0001-5539-7293
Chun Lin, https://orcid.org/0000-0001-5496-8824
Massimo Vieno, https://orcid.org/0000-0001-7741-9377
Edward J Carnell, https://orcid.org/0000-0003-0870-1955
Samuel J Tomlinson, https://orcid.org/0000-0002-3237-7596
Miranda Loh, https://orcid.org/0000-0002-4285-0375

Stefan Reis, https://orcid.org/0000-0003-2428-8320

References

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

Al Ahad, M.A., Demšar, U., Sullivan, F., Kulu, H., 2022. Does Long-Term Air Pollution Exposure Affect Self-Reported Health and Limiting Long Term Illness Disproportionately for Ethnic Minorities in the UK? A Census-Based Individual Level Analysis. Applied Spatial Analysis and Policy 15, 1557-1582. https://doi.org/10.1007/s12061-022-09471-1.

AQEG, 2012. Fine Particulate Matter ($PM_{2.5}$) in the United Kingdom, Report from the Air Quality Expert Group. UK Department for Environment, Food and Rural Affairs, London. http://uk-air.defra.gov.uk/library/reports?report_id=727.

AQEG, 2021. Ozone in the UK – Recent Trends and Future Projections, Report from the Air Quality Expert Group. UK Department for Environment, Food and Rural Affairs, London. https://uk-air.defra.gov.uk/library/reports.php?report_id=1064.

Bailey, N., Dong, G., Minton, J., Pryce, G., 2018. Reconsidering the Relationship between Air Pollution and Deprivation. International Journal of Environmental Research and Public Health 15. https://doi.org/10.3390/ijerph15040629.

Boyle, P.J., Feijten, P., Feng, Z., Hattersley, L., Huang, Z., Nolan, J., Raab, G., 2009. Cohort Profile: The Scottish Longitudinal Study (SLS). International Journal of Epidemiology 38, 385-392. https://doi.org/10.1093/ije/dyn087.

Brauer, M., Roth, G.A., Aravkin, A.Y., Zheng, P., Abate, K.H., Abate, Y.H., . . . Gakidou, E., 2024. Global burden and strength of evidence for 88 risk factors in 204 countries and 811 subnational locations, 1990–2021: a systematic analysis for the Global Burden of Disease Study 2021. The Lancet 403, 2162-2203. https://doi.org/https://doi.org/10.1016/S0140-6736(24)00933-4.

Briggs, D., Abellan, J.J., Fecht, D., 2008. Environmental inequity in England: Small area associations between socio-economic status and environmental pollution. Social Science & Medicine 67, 1612-1629. https://doi.org/https://doi.org/10.1016/j.socscimed.2008.06.040.
Bromley, R.D.F., Tallon, A.R., Roberts, A.J., 2007. New populations in the British city centre: Evidence of social change from the census and household surveys. Geoforum 38, 138-154. https://doi.org/https://doi.org/10.1016/j.geoforum.2006.07.008.

Brook, R., Zhang, H., Sammut, J., 2023. Greater London Authority air quality exposure and inequalites study, https://www.london.gov.uk/sites/default/files/2023-06/Air%20quality%20exposure%20and%20inequalities%20study%20-%20part%20one%20-%20London%20analysis.pdf.

Brown, D., Allik, M., Dundas, R., Leyland, A.H., 2014. Carstairs scores for Scottish postcode sectors, datazones & output areas from the 2011 census, Technical Report. MRC/CSO Social and Public Health Sciences Unit, University of Glasgow, Glasgow (available at: http://eprints.gla.ac.uk/99555/).

Carnell, E.J., Vieno, M., Vardoulakis, S., Beck, R., Heaviside, C., Tomlinson, S.J., Dragosits, U., Heal, M.R., Reis, S., 2019. Modelling public health improvements as a result of air pollution control policies in the UK over four decades - 1970 to 2010. Environmental Research Letters 14, 074001. https://doi.org/10.1088/1748-9326/ab1542.

Carstairs, V., Morris, R., 1989. Deprivation: explaining differences in mortality between Scotland and England and Wales. British Medical Journal 299, 886. https://doi.org/10.1136/bmj.299.6704.886.

de Nazelle, A., Seto, E., Donaire-Gonzalez, D., Mendez, M., Matamala, J., Nieuwenhuijsen, M.J., Jerrett, M., 2013. Improving estimates of air pollution exposure through ubiquitous sensing technologies. Environmental Pollution 176, 92-99.

Di, Q., Wang, Y., Zanobetti, A., Wang, Y., Koutrakis, P., Choirat, C., Dominici, F., Schwartz, J.D., 2017. Air Pollution and Mortality in the Medicare Population. New England Journal of Medicine 376, 2513-2522. https://doi.org/doi:10.1056/NEJMoa1702747.

Fairburn, J., Schüle, S.A., Dreger, S., Karla Hilz, L., Bolte, G., 2019. Social Inequalities in Exposure to Ambient Air Pollution: A Systematic Review in the WHO European Region. International Journal of Environmental Research and Public Health 16, 3127. https://doi.org/10.3390/ijerph16173127.

Fecht, D., Fischer, P., Fortunato, L., Hoek, G., de Hoogh, K., Marra, M., Kruize, H., Vienneau, D., Beelen, R., Hansell, A., 2015. Associations between air pollution and socioeconomic characteristics, ethnicity and age profile of neighbourhoods in England and the Netherlands. Environmental Pollution 198, 201-210. https://doi.org/https://doi.org/10.1016/j.envpol.2014.12.014.

Forastiere, F., Spadaro, J.V., Ancona, C., Jovanovic Andersen, Z., Cozzi, I., Gumy, S., Loncar, D., Mudu, P., Medina, S., Perez Velasco, R., Walton, H., Zhang, J., Krzyzanowski, M., 2024. Choices of morbidity outcomes and concentration–response functions for health risk assessment of long-term exposure to air pollution. Environmental Epidemiology 8, 314. https://doi.org/10.1097/EE9.0000000000000314.

Gadene, L., Leroutier, M., Toneto, R., Upton, B., 2024. Exposure to air pollution in England, 2003-23, The Institute for Fiscal Studies. ISBN 978-1-80103-208-7. https://ifs.org.uk/sites/default/files/2024-12/Exposure-to-air-pollution-in-England-2003-23.pdf.

Ganzleben, C., Kazmierczak, A., 2020. Leaving no one behind – understanding environmental inequality in Europe. Environmental Health 19, 57. https://doi.org/10.1186/s12940-020-00600-2.

Hajat, A., Hsia, C., O'Neill, M.S., 2015. Socioeconomic Disparities and Air Pollution Exposure: a Global Review. Current Environmental Health Reports 2, 440-450. https://doi.org/10.1007/s40572-015-0069-5.

Hood, C., MacKenzie, I., Stocker, J., Johnson, K., Carruthers, D., Vieno, M., Doherty, R., 2018. Air quality simulations for London using a coupled regional-to-local modelling system. Atmospheric Chemistry and Physics 18, 11221-11245. https://doi.org/10.5194/acp-18-11221-2018.

Jbaily, A., Zhou, X., Liu, J., Lee, T.-H., Kamareddine, L., Verguet, S., Dominici, F., 2022. Air pollution exposure disparities across US population and income groups. Nature 601, 228-233. https://doi.org/10.1038/s41586-021-04190-y.

Kasdagli, M.-I., Orellano, P., Pérez Velasco, R., Samoli, E., 2024. Long-Term Exposure to Nitrogen Dioxide and Ozone and Mortality: Update of the WHO Air Quality Guidelines Systematic Review and Meta-Analysis. International Journal of Public Health 69, 1607676. https://doi.org/10.3389/ijph.2024.1607676.

Kramer, A., Minet, L., 2025. Zones of exposure: Urban micro-environments of air pollution and residential intensification. Sustainable Cities and Society 127, 106404. https://doi.org/https://doi.org/10.1016/j.scs.2025.106404.

Lin, C., Feng, X., Heal, M.R., 2016. Temporal persistence of intra-urban spatial contrasts in ambient NO_2, O_3 and Ox in Edinburgh, UK. Atmospheric Pollution Research 7, 734-741. https://doi.org/10.1016/j.apr.2016.03.008.

Lin, C., Heal, M.R., Vieno, M., MacKenzie, I.A., Armstrong, B.G., Butland, B.K., Milojevic, A., Chalabi, Z., Atkinson, R.W., Stevenson, D.S., Doherty, R.M., Wilkinson, P., 2017. Spatiotemporal evaluation of EMEP4UK-WRF v4.3 atmospheric chemistry transport simulations of health-related metrics for NO_2, O_3, PM_{10} and $PM_{2.5}$ for 2001-2010. Geoscientific Model Development 10, 1767-1787. https://doi.org/10.5194/gmd-10-1767-2017.

Liška, T., Heal, M.R., Lin, C., Vieno, M., Carnell, E.J., Tomlinson, S.J., Loh, M., Reis, S., 2024. The effect of workplace mobility on air pollution exposure inequality — a case study in the Central Belt of Scotland. Environmental Research: Health 2, 025006. https://doi.org/10.1088/2752-5309/ad3840.

Liu, J., Clark Lara, P., Bechle Matthew, J., Hajat, A., Kim, S.-Y., Robinson Allen, L., Sheppard, L., Szpiro Adam, A., Marshall Julian, D., 2021. Disparities in Air Pollution Exposure in the United States by Race/Ethnicity and Income, 1990–2010. Environmental Health Perspectives 129, 127005. https://doi.org/10.1289/EHP8584.

Macintyre, H.L., Mitsakou, C., Vieno, M., Heal, M.R., Heaviside, C., Exley, K.S., 2023a. Future impacts of O_3 on respiratory hospital admission in the UK from current emissions policies. Environmental International 178, 108046. https://doi.org/10.1016/j.envint.2023.108046.

Macintyre, H.L., Mitsakou, C., Vieno, M., Heal, M.R., Heaviside, C., Exley, K.S., 2023b. Impacts of emissions policies on future UK mortality burdens associated with air pollution. Environmental International 174, 107862. https://doi.org/10.1016/j.envint.2023.107862.

Moreno-Jiménez, A., Cañada-Torrecilla, R., Vidal-Domínguez, M.J., Palacios-García, A., Martínez-Suárez, P., 2016. Assessing environmental justice through potential exposure to air pollution: A socio-spatial analysis in Madrid and Barcelona, Spain. Geoforum 69, 117-131. https://doi.org/https://doi.org/10.1016/j.geoforum.2015.12.008.

Orellano, P., Kasdagli, M.-I., Pérez Velasco, R., Samoli, E., 2024. Long-Term Exposure to Particulate Matter and Mortality: An Update of the WHO Global Air Quality Guidelines Systematic Review and Meta-Analysis. International Journal of Public Health 69, 1607683. https://doi.org/10.3389/ijph.2024.1607683.

Padilla, C.M., Kihal-Talantikite, W., Vieira, V.M., Rossello, P., Nir, G.L., Zmirou-Navier, D., Deguen, S., 2014. Air quality and social deprivation in four French metropolitan areas—A localized spatio-temporal environmental inequality analysis. Environmental Research 134, 315-324. https://doi.org/https://doi.org/10.1016/j.envres.2014.07.017.

Purser, G., Heal, M.R., Carnell, E.J., Bathgate, S., Drewer, J., Morison, J.I.L., Vieno, M., 2023. Simulating impacts on UK air quality from net-zero forest planting scenarios. Atmospheric Chemistry and Physics 23, 13713-13733. https://doi.org/10.5194/acp-23-13713-2023.

Pye, S., King, K., Sturman, J., 2006. Air Quality and Social Deprivation in the UK: an environmental inequalities analysis, Report to Department of Environment, Food and Rural Affairs. AEAT/ENV/R/2170. https://uk-air.defra.gov.uk/library/reports?report_id=424.

Ragettli, M.S., Phuleria, H.C., Tsai, M.Y., Schindler, C., de Nazelle, A., Ducret-Stich, R.E., Ineichen, A., Perez, L., Braun-Fahrlander, C., Probst-Hensch, N., Kunzli, N., 2015. The relevance of commuter and work/school exposure in an epidemiological study on traffic-related air pollution. Journal of Exposure Science and Environmental Epidemiology 25, 474-481.

RCP, 2016. Every breath we take: the lifelong impact of air pollution. Royal College of Physicians. London. 978-1-86016-567-2. https://www.rcplondon.ac.uk/projects/outputs/every-breath-we-take-lifelong-impact-air-pollution.

Reis, S., Liska, T., Vieno, M., Carnell, E.J., Beck, R., Clemens, T., Dragosits, U., Tomlinson, S.J., Leaver, D., Heal, M.R., 2018. The influence of residential and workday population mobility on exposure to air pollution in the UK. Environment International 121, 803-811. https://doi.org/10.1016/j.envint.2018.10.005.

Samoli, E., Stergiopoulou, A., Santana, P., Rodopoulou, S., Mitsakou, C., Dimitroulopoulou, C., Bauwelinck, M., de Hoogh, K., Costa, C., Marí-Dell'Olmo, M., Corman, D., Vardoulakis, S., Katsouyanni, K., 2019. Spatial variability in air pollution exposure in relation to socioeconomic indicators in nine European metropolitan areas: A study on environmental inequality. Environmental Pollution 249, 345-353. https://doi.org/https://doi.org/10.1016/j.envpol.2019.03.050.

Shafran-Nathan, R., Yuval, Broday, D.M., 2018. Impacts of Personal Mobility and Diurnal Concentration Variability on Exposure Misclassification to Ambient Pollutants. Environmental Science & Technology 52, 3520-3526. https://doi.org/10.1021/acs.est.7b05656.

Skamarock, W.C., Klemp, J.B., Dudhia, J., Huang, X., Wang, W., Powers, J., 2008. A Description of the Advanced Research WRF Version 3. NCAR Technical Note NCAR/TN-475+STR. doi:10.5065/D68S4MVH.

Stephens, C., Church, C., 2017. Environmental Justice and Health, in: Quah, S.R. (Ed.), International Encyclopedia of Public Health (Second Edition). Academic Press, Oxford, pp. 499-506. https://doi.org/10.1016/B978-0-12-803678-5.00134-X.

Temam, S., Burte, E., Adam, M., Antó, J.M., Basagaña, X., Bousquet, J., . . . Jacquemin, B., 2017. Socioeconomic position and outdoor nitrogen dioxide (NO2) exposure in Western Europe: A multi-city analysis. Environment International 101, 117-124. https://doi.org/https://doi.org/10.1016/j.envint.2016.12.026.

Thomas, E., Serwicka, I., Swinney, P., 2015. Urban Demographics: Why People Live Where They Do UK Centre for Cities. Available at: www.centreforcities.org/wp-content/uploads/2015/11/15-11-02-Urban-Demographics.pdf.

Tonne, C., Milà, C., Fecht, D., Alvarez, M., Gulliver, J., Smith, J., Beevers, S., Ross Anderson, H., Kelly, F., 2018. Socioeconomic and ethnic inequalities in exposure to air and noise pollution in London. Environment International 115, 170-179. https://doi.org/https://doi.org/10.1016/j.envint.2018.03.023.

van den Brekel, L., Lenters, V., Mackenbach, J.D., Hoek, G., Wagtendonk, A., Lakerveld, J., Grobbee, D.E., Vaartjes, I., 2024. Ethnic and socioeconomic inequalities in air pollution exposure: a cross-sectional analysis of nationwide individual-level data from the Netherlands. The Lancet Planetary Health 8, e18-e29. https://doi.org/10.1016/S2542-5196(23)00258-9.

Vieno, M., Heal, M.R., Williams, M.L., Carnell, E.J., Nemitz, E., Stedman, J.R., Reis, S., 2016. The sensitivities of emissions reductions for the mitigation of UK $PM_{2.5}$. Atmospheric Chemistry and Physics 16, 265-276. https://doi.org/10.5194/acp-16-265-2016.

Young, K., Zhang, H., Thornton, A., King, K., Robinson, S., 2023. Inequalities in air pollution exposure: comparison with other cities, Report for Greater London Authority. https://www.london.gov.uk/sites/default/files/2023-06/Air%20quality%20exposure%20and%20inequalities%20study%20-%20part%20two%20-%20Comparison%20with%20other%20cities.pdf.