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PAPER

The effect of workplace mobility on air pollution exposure inequality—a case study in the Central Belt of Scotland

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Abstract

A large number of epidemiological studies have identified air pollution as a major risk to human health. Exposures to the pollutants $PM_{2.5}$, NO_2 and O_3 cause cardiovascular and respiratory diseases, cancer and premature mortality. Whilst previous studies have reported demographic inequalities in exposure, with the most deprived and susceptible often being disproportionately exposed to the highest pollutant concentrations, the vast majority of these studies have quantified exposure based only on individuals' place of residence. Here we use anonymised personal data from UK Census 2011, and hourly modelled air pollution concentrations at 0.8 km $\times$ 1.4 km spatial resolution in the Central Belt of Scotland, to investigate how inclusion of time spent at place of work or study affects demographic inequalities in exposure. We split the population by sex, ethnic group, age and socio-economic status. Exposure gradients are observed across all demographic characteristics. Air pollution exposures of males are more affected by workplace exposures than females. The White ethnic group has the lowest exposures to NO_2 and $PM_{2.5}$, and highest to O_3. Exposures to NO_2 and $PM_{2.5}$ tend to peak between the ages of 21 and 30, but those aged 31–50 tend to be most impacted by the inclusion of time spent at workplace in the exposure assessment. People in the two least deprived deciles consistently have the lowest residential-only and combined residential-workplace exposure to NO_2 and $PM_{2.5}$, but experience the highest increase in exposure when including workplace. Overall, including workplace exposure results in relatively small change in median exposure but attenuates some of the exposure inequalities associated with ethnicity and socioeconomic status observed in exposure assessments based only on place of residence.

1. Introduction

Numerous studies have shown that spatial variability of air pollution leads to differential exposure at both individual and community levels, resulting in environmental inequality between various population strata (e.g. Mitchell and Dorling 2003, Bell and Ebisu 2012, Hajat *et al* 2015, Moreno-Jiménez *et al* 2016, Barnes *et al* 2019, Jbaily *et al* 2022, Abed Al Ahad *et al* 2023). In contrast to the USA, where research into environmental inequality began and predominantly focused on links with ethnicity (Bolte *et al* 2011), in Europe the emphasis has largely been on the relationship between air quality and level of deprivation. The relationship between socio-economic status (SES) and air pollution exposure is not simple. It has been shown to vary between investigated areas (Padilla *et al* 2014, Temam *et al* 2017), study types (individual vs ecological) (Temam *et al* 2017), metrics of SES (Samoli *et al* 2019) and pollutants (Milojevic *et al* 2017). However, the most deprived neighbourhoods are often exposed to the highest concentrations of nitrogen oxides and particulate matter (Fairburn *et al* 2019). Few studies in Europe have explored relationships with other demographic characteristics such as age and ethnicity. Most of those investigating ethnicity suggest air pollution exposure is higher in ethnic minority and immigrant groups than for other ethnicities, but results vary by ethnic groups (Padilla *et al* 2014, Fecht *et al* 2015, Moreno-Jiménez *et al* 2016, Tonne *et al* 2018). Studies of exposures of the very young and the very old also show mixed results depending on the study area (Mitchell and Dorling 2003, Cesaroni *et al* 2010, Fecht *et al* 2015, Moreno-Jiménez *et al* 2016, Barnes *et al* 2019).

Higher levels of exposure to air pollution in socially disadvantaged and vulnerable communities contravene the concept of environmental justice, which aims for environmental benefits and burdens to be equitably shared within the population regardless of individuals' social characteristics. Worse still, higher exposures to air pollution by vulnerable and low SES communities may exacerbate some adverse health outcomes that already disproportionally occur in such communities (Bolte *et al* 2011, Brunt *et al* 2017).

Nearly all studies that have investigated differential exposure to air pollution relied on the assumption that residential exposure is a satisfactory proxy of personal exposure across the communities. Whilst this may be true for some subgroups such as the very young and very old, those of school and working ages may spend a substantial proportion of their time away from home. Several studies (Ragettli *et al* 2015, Reis *et al* 2018) show that, at the population scale, accounting for a place of work or study in quantifying overall exposure results only in relatively small changes in exposure to nitrogen dioxide (NO_2), ozone (O_3) and $PM_{2.5}$ (particulate matter of diameter <2.5 μm) when compared to residential exposure only. However, the effect on some individuals can be substantially larger than the population average (Reis *et al* 2018), particularly for those whose residence and place of work are situated in contrasting built-up environments (suburban or rural vs inner urban). Such differences may affect the inequalities observed using residential exposure only.

In this study we investigate for a cohort population how the inclusion of exposure to ambient air at the place of work or study affects exposure inequalities compared with an assessment based on residential exposure only. Firstly, we explored the impact of exposure to ambient NO_2, O_3 and $PM_{2.5}$ at the place of work or study on the overall exposure of the study population as a whole. Secondly, we stratified the study population by sex, age, ethnicity and SES and examined the impact of the combined residential + workplace exposure on exposure inequality across each of these population characteristics. We selected the 'Central Belt' region of Scotland as the study area. Whilst previous studies have demonstrated the existence of environmental inequality in Scotland related to SES (Fairburn *et al* 2005, Morrison *et al* 2014), other social characteristics have not been examined and data from Census 2011 indicates that ethnic diversity in Scotland is rapidly increasing.

2. Methods

2.1. Study area and population

Our population all resided in the 'Central Belt' of Scotland. This name refers to the central region of Scotland encompassing the two largest cities of Glasgow in the west and Edinburgh in the east, and the surrounding commuter belt. There are however no strictly defined boundaries of the region. In this study, the area shown in figure 1 was used which extends from Inverclyde in the west to western parts of East Lothian in the east. To the north it includes the city of Stirling, Clackmannanshire and south-western parts of Fife, and to the south it extends to the southern boundary of East Renfrewshire. The study area covers $\sim$4000 km^2 and had approximately 2.9 million residents in 2011, corresponding to 56% of the Scottish population at the time.

The population data we used were anonymised personal data based on responses in the UK Census in March 2011 by the participants of the Scottish Longitudinal Study (SLS) (https://sls.lscs.ac.uk) (Boyle *et al* 2009). From the full SLS participants dataset we selected those participants whose place of residence and place of work or study were within the Central Belt, or whose place of residence was within the Central Belt but who were either economically inactive or not in education. We then excluded workers or students who selected the 'No fixed place' option to the workplace/place of study address question in the Census form. Participants reporting place of work as a depot were included.

The locations of SLS participants' places of residence and work or study were available at the unit postcode level (see text below regarding data access restriction) which, on average, is shared by 15–100 individual addresses. We selected postcodes whose point coordinates were within the study area at the time of the census (https://borders.ukdataservice.ac.uk/pds.html).

The SLS has linked census data (from 1991 onwards) to other vital events, migration and school census data for a 5.3% representative sample of the Scottish population (Boyle *et al* 2009). The extracted personal data included SLS participants' age, ethnicity and data related to economic activity. Additionally, we obtained the Carstairs deprivation score decile (Carstairs and Morris 1989) to represent each member's SES. The Carstairs Index is an unweighted score calculated from four variables derived from the Census—no car

Figure 1. The extent of the Central Belt study area (light pink colour). The study area includes Scotland's two largest urban areas: Greater Glasgow and Edinburgh. Contains OS Data © Crown copyright and database right (2023). Contains NRS data © Crown copyright and database right (2023).

ownership, male unemployment, overcrowding and low social class. Unlike all the other personal data, which were extracted at an individual level, the Carstairs Index decile was an averaged value of all households within an Output Area—a Census geographical unit created by gathering postcodes together and containing at least 20 households and an average of 114 residents (Brown *et al* 2014).

The number of SLS participants living in the study area during the Census who fulfilled the inclusion criteria is 124 659. The demographic characteristics of the Central Belt SLS sample are presented in the Supplementary Material. Just over 45 000 (36.3%) of the Central Belt SLS participants over the age of 16 are economically inactive and approximately 7500 (6.1%) of those working or studying do so at their home address. This, together with most children under the age of 5 also staying at home only, results in only 64 452 (51.7%) of the Central Belt SLS participants working or studying in a different place from their home address.

2.2. Air pollution data

We used hourly air pollution data from EMEP4UK model version rv4.17. This is an Eulerian atmospheric chemistry transport model that has been widely used to simulate air quality over the UK (e.g. Vieno *et al* 2014, 2016, Lin *et al* 2017, Nemitz *et al* 2020, Macintyre *et al* 2023). Version rv4.17 version has a horizontal spatial resolution of $\sim$0.124° $\times$ $\sim$0.124° which is equivalent to $\sim$0.8 km $\times$ $\sim$1.4 km in the study area. The temporal resolution of output is 1 hour. The model is driven by hourly meteorology provided by the Weather Research Forecast (WRF) model version 3.9.1 and the modelled year is 2015. Further details of the model set-up are provided in the Supplementary Material. Modelled annual mean surface NO_2, O_3 and $PM_{2.5}$ concentrations for the model grids where postcode coordinates are located are shown in figure 2.

2.3. Exposure analysis

For the exposure analysis we assigned to each postcode point within the study area the hourly NO_2, O_3 and $PM_{2.5}$ concentrations of the EMEP4UK grid in which it was located. We compared exposure to these pollutants that included exposure both at the workplace address and the residence address with exposure at the residence address only. We considered two combined residential—workplace exposure scenarios; in the $RWE_{8\text{-}18}$ scenario workers and students are at their place of work/study between 08:00 and 18:00 Monday to Friday whereas the RWE_{hw+} scenario is a weighted mean of residential and workplace ambient concentrations weighted by the number of typical hours per week worked. The number of typical hours per week were also obtained from the Census; however, there was no information in the Census on how those hours were distributed over the week. For part-time students we assumed their answers to the place of work/study and typical hours per week questions in the Census referred to their place of work (rather than their place of study) and we used the number of hours per week worked in the analysis. Since there was no information on how many hours per week full-time students typically spent at their place of study we set it to 30 h per week for all full-time students. We also assumed that all of the typical hours per week worked were spent at the workplace address provided. For every seven hours worked we added an additional hour to the

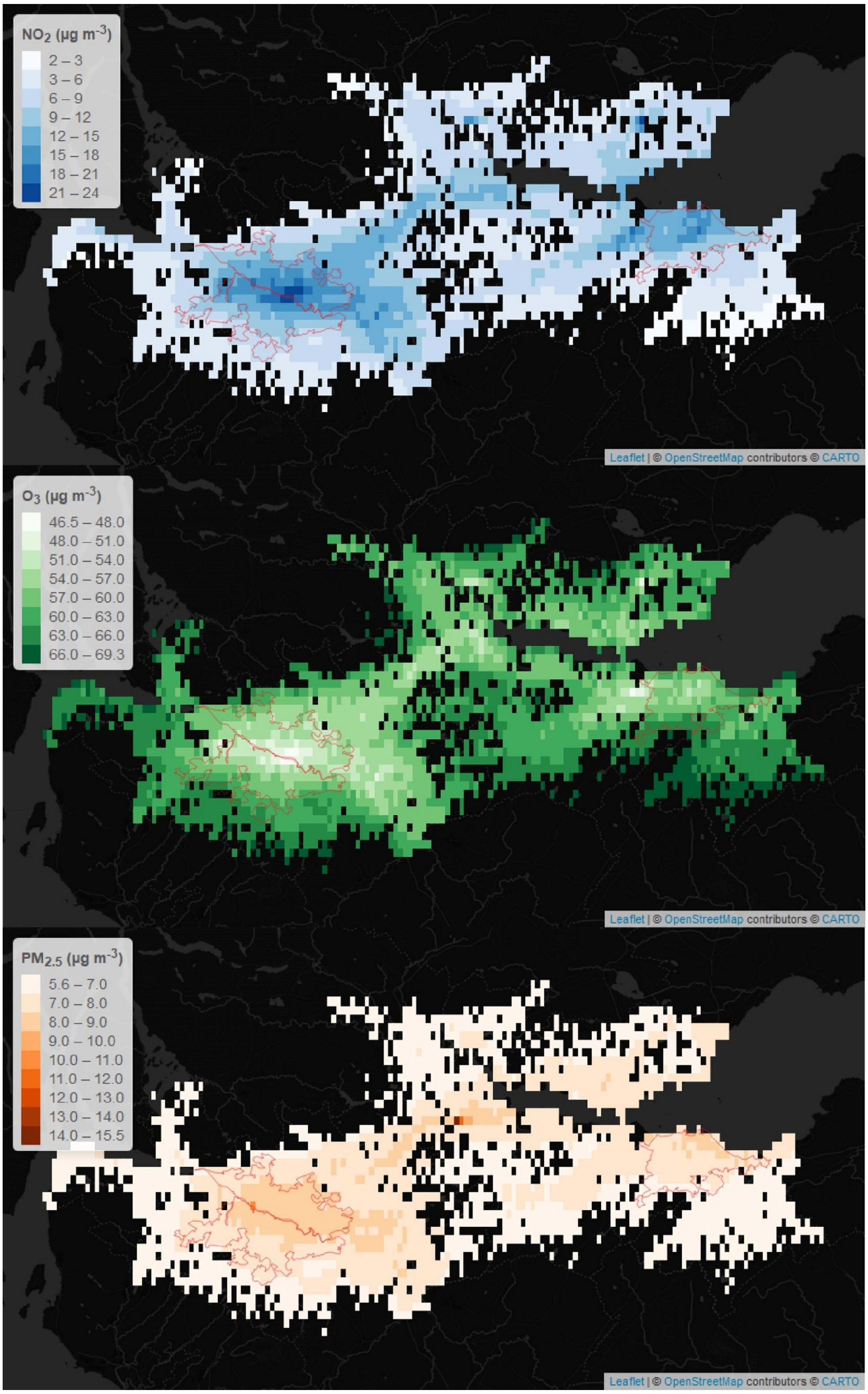

Figure 2. Modelled annual mean NO_2, O_3 and $PM_{2.5}$ concentrations in the study area. Only the grid cells containing postcode locations are shown. Contains OS Data © Crown copyright and database right (2023).

total hours worked to allow for breaks. For example, a person whose typical hours per week worked were between 35 and 41 inclusive was assigned an additional 5 h at the workplace for the exposure calculation.

We used the exposure scenarios to estimate exposure of the total population as well as population sub-groups based on age, ethnic group and Carstairs index decile. We grouped the age variable into 5 year wide bins except for the youngest (0–5 years inclusive) and oldest (76 years and over) age groups. We grouped the ethnicity variable based on the main groupings in the Census form to White, Asian, African, Caribbean or Black, Arab, Mixed, and Other ethnic groups. We then calculated the descriptive statistics of exposures for each group and exposure scenario. Data analysis was performed with R language version 3.5.2.

2.4. Data access and dissemination restrictions

Due to the high sensitivity of the population data used in this study, several restrictions were placed on access and dissemination of the data in order to prevent disclosure. The requested population data were extracted and linked with the pollution data by staff at the SLS Development and Support Unit. We never had access to the SLS participants' home or workplace postcode unit data.

We are only able to report a result of the analysis if the result datum is shared by at least 10 SLS participants. As a consequence, we cannot report exposure extremes, and exposure distribution bins in figures may have varying widths in order to ensure at least 10 SLS participants in each bin. However, the limitations on data presentation do not affect the calculated exposures.

3. Results

3.1. Population exposure

The descriptive statistics of the residential-only exposure (RE) and combined residential-workplace exposure (RWE) scenarios for the three pollutants are presented in table 1. We also show the absolute and relative differences in means and medians between each RWE scenario and the baseline RE scenario. In general, the $RWE_{8\text{-}18}$ scenario has a larger impact on annual mean exposures than the RWE_{hw+} scenario. As expected from the modelled pollution concentrations in the study area (figure 2), the largest changes in the mean population exposures (3.0%) are observed for NO_2.

The relatively modest changes in the mean participant population exposures when including exposure at place of work/study compared to the baseline scenario are explained by the largely overlapping distributions of personal REs and RWEs. These are shown for NO_2, O_3 and $PM_{2.5}$ in the left-hand panels of figures 3–5, respectively, in which distribution overlaps are shown in grey shading. As noted above, almost 50% of the SLS participants either do not work or study, or do so at their home, and therefore their personal exposure change is zero. Furthermore, a large proportion of the remaining individuals who commute for work or study away from home experience only a tiny change in their personal exposure. This is demonstrated in the right-hand panels of figures 3–5 which show the distributions of the change in exposure for the commuters between the RWE and RE scenarios. In the case of exposures to NO_2, the magnitude of exposure change, whether positive or negative, is $\leqslant 0.1\ \mu g\ m^{-3}$ for approximately 16.0% ($RWE_{8\text{-}18}$) and 21.6% (RWE_{hw+}) of the commuters in the study area. For O_3, the magnitude of exposure change is $\leqslant 0.1\ \mu g\ m^{-3}$ for approximately 16.8% ($RWE_{8\text{-}18}$) and 19.3% (RWE_{hw+}) of the commuters in the study area. For exposure to $PM_{2.5}$, 52.8% ($RWE_{8\text{-}18}$) and 66.5% (RWE_{hw+}) of commuters experience a change in exposure of $\leqslant 0.1\ \mu g\ m^{-3}$.

Even though RWE–RE exposure differences are close to zero for the majority of the studied population, the inclusion of place of work/study leads to some large differences in personal exposure for a small number of individuals. At the extremes of the $RWE_{8\text{-}18}$–RE distributions, 29 participants experience an increase in $PM_{2.5}$ exposure $\geqslant 3.90\ \mu g\ m^{-3}$ and 17 participants experience an increase in NO_2 exposure $\geqslant 6.30\ \mu g\ m^{-3}$. When scaled up those numbers translate into approximately 550 and 320 Central Belt residents whose $PM_{2.5}$ and NO_2 exposures change by those amounts. Conversely, 10 and 16 participants have $PM_{2.5}$ and NO_2 $RWE_{8\text{-}18}$–RE exposure differences decreasing by more than 3.90 $\mu g\ m^{-3}$ and 4.70 $\mu g\ m^{-3}$, respectively. These numbers scale up to approximately 190 and 300 individuals across the Central Belt.

3.2. Population subgroup exposure

The top panels in figures 6–9 show NO_2 exposure means, medians and interquartile ranges for each exposure scenario and for the participant population categorised by sex, ethnic group, age and socioeconomic status. These panels indicate that the exposure distributions tend to be skewed. As a result, we show differences in median exposure between RWE and RE rather than differences in mean exposure in the bottom panels of figures 6–9. The corresponding figures for O_3 and $PM_{2.5}$ are presented in the Supplementary Material.

Figure 6 shows that both sexes have the same median RE to NO_2 (10.6 $\mu g\ m^{-3}$), but that males tend to have marginally higher median RWEs than females. This difference is more pronounced in the RWE scenario based on hours worked, as illustrated in the lower panel of differences between RWE and RE. Median $RWE_{8\text{-}18}$–RE differences for males and females are 0.41 and 0.37 $\mu g\ m^{-3}$, respectively, whilst median RWE_{hw+}–RE differences for males and females are 0.38 and 0.26 $\mu g\ m^{-3}$. The pattern in exposure is reversed for O_3 (figure S1) and the magnitude of the differences between the two RWEs and RE are smaller ($<0.20\ \mu g\ m^{-3}$) than for NO_2. The exposures to $PM_{2.5}$ (figure S2) are the same for both sexes and virtually unaffected by exposure at workplace because the increase in median $PM_{2.5}$ exposure for the RWE scenarios is less than 0.05 $\mu g\ m^{-3}$.

Table 1. Descriptive statistics of population exposures for each pollutant and exposure scenario. Also shown are the absolute and relative differences in the means and medians between each of the RWE scenarios and the RE scenario. Units are μg m^{-3} unless stated otherwise. The notation RWE* in a column heading refers to either $RWE_{8\text{-}18}$ or RWE_{hw+} as indicated in the row header.

Pollutant	Exposure Scenario	Mean	Median	Q1	Q3	RWE*-RE (mean)	RWE*-RE (mean) %	RWE*-RE (median)	RWE*-RE (median) %
NO_2	RE	10.92	10.65	7.63	13.73	—	—	—	—
	$RWE_{8\text{-}18}$	11.25	11.02	8.14	14.00	0.33	3.0	0.37	3.5
	RWE_{hw+}	11.17	10.97	8.06	13.92	0.25	2.3	0.32	3.0
O_3	RE	58.50	58.58	55.66	61.48	—	—	—	—
	$RWE_{8\text{-}18}$	58.24	58.39	55.56	61.08	−0.26	−0.4	−0.19	−0.3
	RWE_{hw+}	58.29	58.41	55.61	61.12	−0.21	−0.4	−0.17	−0.3
$PM_{2.5}$	RE	7.63	7.66	7.17	8.08	—	—	—	—
	$RWE_{8\text{-}18}$	7.66	7.69	7.23	8.09	0.03	0.4	0.03	0.4
	RWE_{hw+}	7.65	7.69	7.22	8.08	0.02	0.3	0.03	0.4

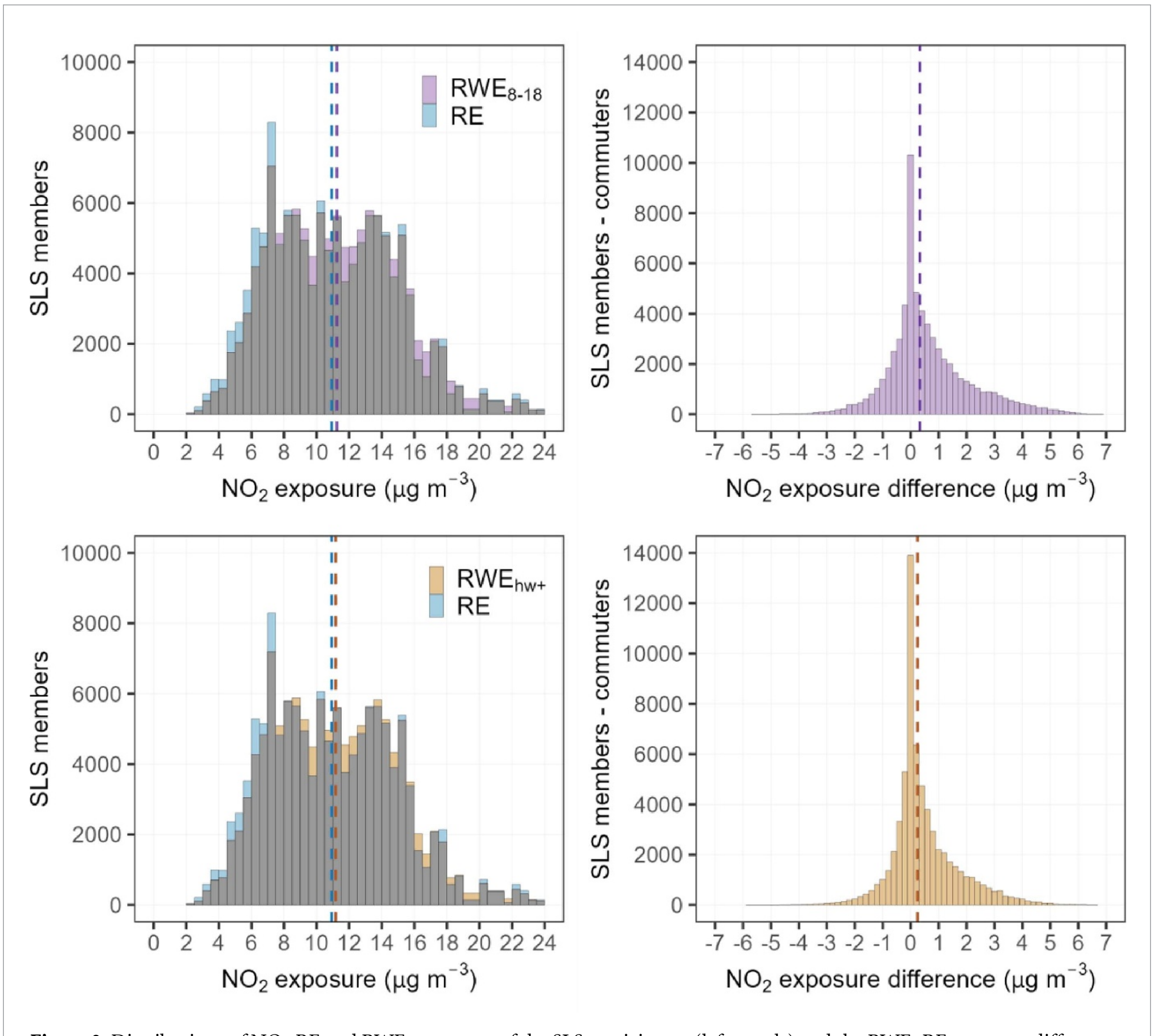

Figure 3. Distributions of NO_2 RE and RWE exposures of the SLS participants (left panels) and the RWE–RE exposure differences of only those participants who commute to a place of work or study (right panels). $RWE_{8\text{-}18}$ is shown in the top row, RWE_{hw+} in the bottom row. Grey shading in the left panels represents the distribution overlap. Dashed lines show the means of the distributions. Bins with fewer than 10 SLS participants are aggregated with a neighbouring bin and the aggregated participant number is normalised by the aggregated bin width. Source: Scottish Longitudinal Study.

The White ethnic group has substantially lower RE and RWE to NO_2 than the minority ethnic groups (figure 7). For example, the median NO_2 RE for the White group is 10.51 $\mu g\ m^{-3}$ whilst for the most exposed Arab group it is 14.08 $\mu g\ m^{-3}$. On the other hand, the White group's NO_2 exposure is most affected by the inclusion of the place of work or study in the assessment, with increases in exposure of 0.44 and 0.33 $\mu g\ m^{-3}$ for $RWE_{8\text{-}18}$–RE and RWE_{hw+}–RE, respectively. For O_3 (figure S3), the White ethnic group has the highest median RE (58.59 $\mu g\ m^{-3}$). The difference in median exposure tends to be negative except for the $RWE_{8\text{-}18}$ scenario and the Caribbean or Black group. The magnitude of change is largest for the White group and the RWE_{hw+} scenario (-0.21 $\mu g\ m^{-3}$), whilst for the $RWE_{8\text{-}18}$ scenario the Arab group experiences the largest magnitude change (-0.39 $\mu g\ m^{-3}$). For $PM_{2.5}$, the White group has the lowest exposure (figure S4), but the observed increase in median $PM_{2.5}$ exposure for the RWE scenarios is less than 0.05 $\mu g\ m^{-3}$ across all the groups.

The NO_2 exposure pattern for the population stratified by age (figure 8) shows a peak of 12.21 $\mu g\ m^{-3}$ in median exposure for young adults (21–25) sharply increasing from the lowest median exposures in childhood before slowly decreasing again through the latter years. This pattern likely reflects the tendency of young adults to live and work in urban centres before searching for more space in the suburbs to raise a family later in life. We observe the largest increase in RWE–RE values (0.46–0.73 $\mu g\ m^{-3}$) for the 31–55 age groups which further demonstrates the tendency of those age groups to commute for work from suburban areas into more polluted inner urban areas where NO_2 concentrations are higher. There is little change in NO_2 exposure for the RWE scenarios for the very young and very old. For O_3, the pattern in exposure and the direction of change for the RWE scenarios (figure S5) are the opposite to that for NO_2; young adults have the lowest median O_3 exposure but also their decrease in exposure in RWE scenarios is less than for older

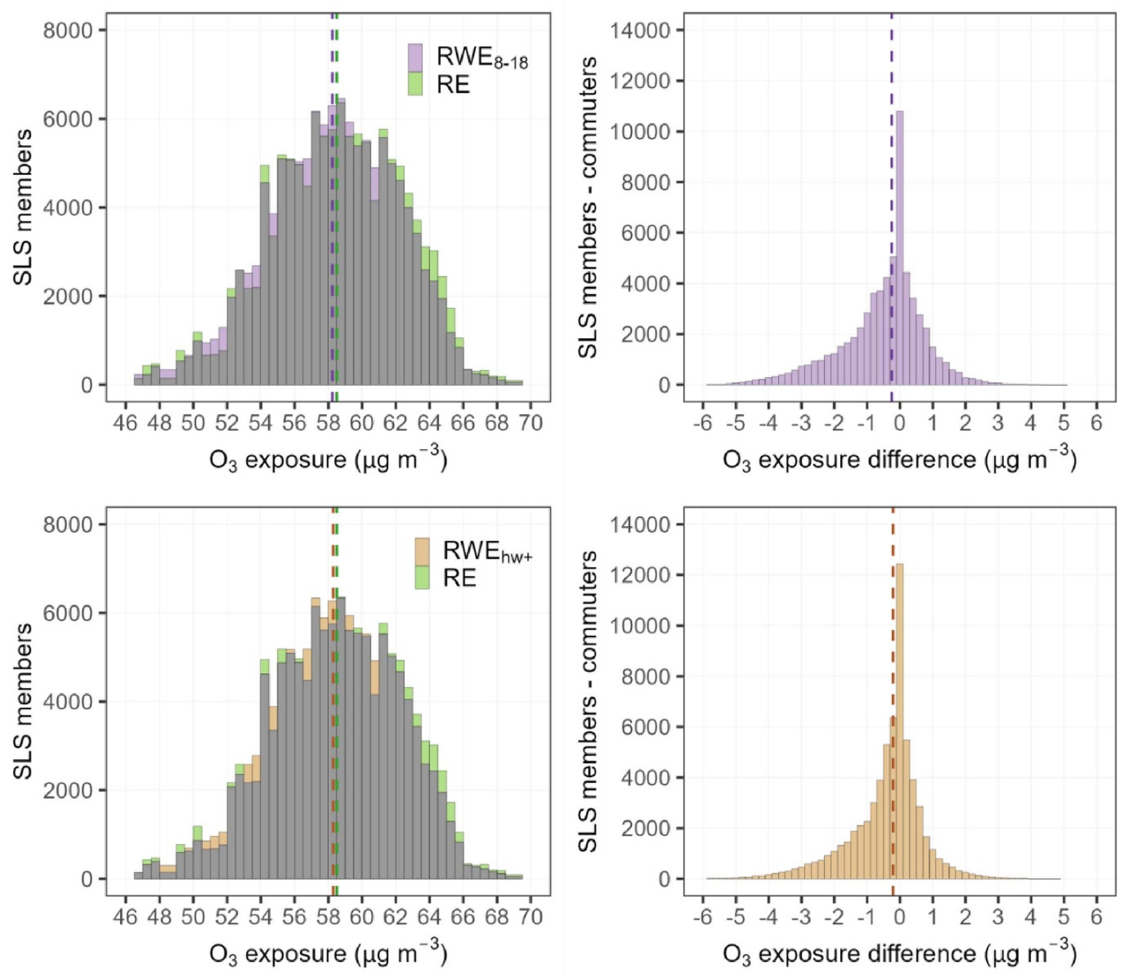

Figure 4. Distributions of O_3 RE and RWE exposures of the SLS participants (left panels) and the RWE–RE exposure differences of only those participants who commute to a place of work or study (right panels). $RWE_{8\text{-}18}$ is shown in the top row, RWE_{hw+} in the bottom row. Grey shading in the left panels represents the distribution overlap. Dashed lines show the means of the distributions. Bins with fewer than 10 SLS participants are aggregated with a neighbouring bin and the aggregated participant number is normalised by the aggregated bin width. Source: Scottish Longitudinal Study.

working age groups. For $PM_{2.5}$, the exposure pattern is very similar to that for NO_2, but much smaller in magnitude, with the maximum change in median exposures for the RWE scenarios reaching approximately 0.05 $\mu g\ m^{-3}$ (figure S6).

Figure 9 shows a pattern of generally increasing NO_2 exposures as the level of deprivation increases with the median NO_2 RE increasing from 9.51 $\mu g\ m^{-3}$ for the least deprived decile 1–12.73 $\mu g\ m^{-3}$ for the most deprived decile 10. There is also a substantial increase in RE of 1.39 $\mu g\ m^{-3}$ between deciles 9 and 10. On the other hand, the least deprived deciles show the largest increases in median NO_2 exposure when workplace exposure is included, reaching almost 0.8 $\mu g\ m^{-3}$. This corresponds to an 8.5% increase in exposure to NO_2 on average for this population sub-group. The increases in exposure to NO_2 in RWE scenarios tends to decrease as the level of deprivation increases. The patterns for O_3 exposure (figure S7) are generally opposite to NO_2 patterns; decile 1 has the highest RE of 59.76 $\mu g\ m^{-3}$ and decile 10 the lowest at 56.79 $\mu g\ m^{-3}$, yet the decrease in median exposure when accounting for workplace exposure exceeds 0.3 $\mu g\ m^{-3}$ for the former and is essentially zero for the latter. The patterns of exposure to $PM_{2.5}$ (figure S8) follow NO_2 but with smaller magnitudes. The median RE for decile 1 is 7.42 $\mu g\ m^{-3}$ whereas for decile 10 it is 7.87 $\mu g\ m^{-3}$.

4. Discussion

In this study, we used anonymised personal data to quantify demographic inequalities in exposure to ambient NO_2, O_3 and $PM_{2.5}$ of more than 124 000 individuals living and working in the Central Belt of Scotland whilst also accounting for exposure to these pollutants at the place of work or study. The cohort of individuals is representative of the full population. The inequalities in exposure between different demographic groups were compared to those quantified assuming the population spent all their time at their

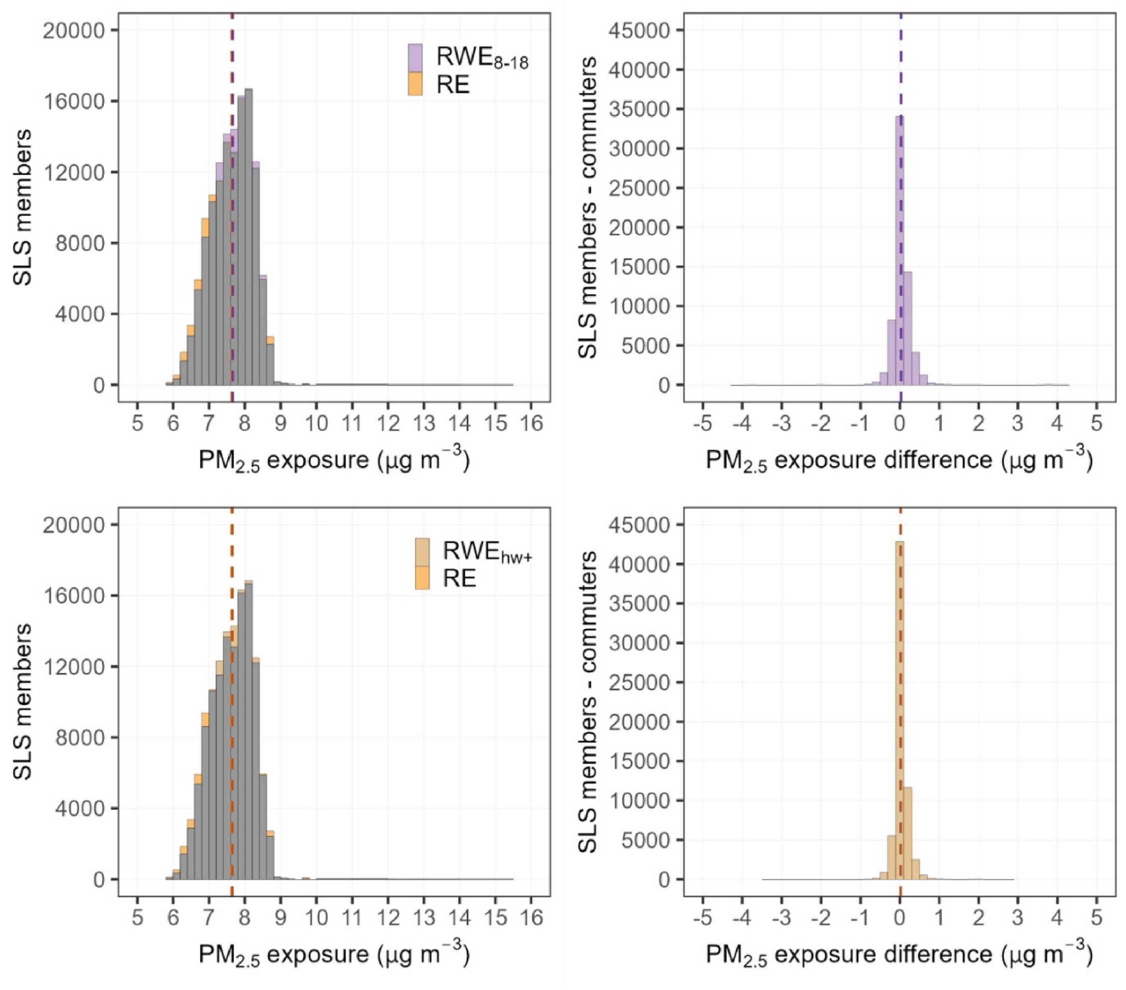

Figure 5. Distributions of $PM_{2.5}$ RE and RWE exposures of the SLS participants (left panels) and the RWE–RE exposure differences of only those participants who commute to a place of work or study (right panels). $RWE_{8\text{-}18}$ is shown in the top row, RWE_{hw+} in the bottom row. Grey shading in the left panels represents the distribution overlap. Dashed lines show the means of the distributions. Bins with fewer than 10 SLS participants are aggregated with a neighbouring bin and the aggregated participant number is normalised by the aggregated bin width. Source: Scottish Longitudinal Study.

place of residence, which is the typical approach in cohort studies examining the health effects of air pollution. Since we did not have data on specific times spent at place of work or study we considered two combined home + workplace scenarios to estimate the potential impact on population exposure—one ($RW_{8\text{-}18}$) based on prescribed fixed hours and the other (RWE_{hw+}) on typical hours worked. The $RWE_{8\text{-}18}$ scenario yields greater changes, on average, in exposures relative to residential exposure only since it assigns workplace exposure for 50 h per week. This is more than the typical ∼35–40 work hours for full-time workers and was selected to account for all time spent away from home. The changes in exposures in the other scenario (based only on hours spent at work) were smaller in comparison. Although the RWE_{hw+} scenario does not take into account temporal variability of concentrations, it better represents part-time workers and workers working variable shifts. Both scenarios provide plausible estimates of population exposures whilst accounting for exposure at the place of work or study.

Compared with the estimates of residential exposure only, the changes in exposure to NO_2, O_3 and $PM_{2.5}$ in the Central Belt study area are small but comparable to those reported for the whole of the UK (Reis *et al* 2018) and in other parts of the world (Ragettli *et al* 2015, Nyhan *et al* 2016, Shafran-Nathan *et al* 2017). It is worth noting that approximately 50% of the population in the study area does not work or study, or does so from home.

Considering residential-only exposure of the study population stratified by sex, ethnicity, age and SES, the following patterns have emerged. There is no difference in residential exposures between males and females. The White ethnic group has a considerably lower exposure on average to NO_2 and $PM_{2.5}$, and higher exposure to O_3, than all other ethnic groups in the Central Belt region which is likely due to minority ethnic groups predominantly living in the cities and towns whilst the rural areas (which have less NO_2 and $PM_{2.5}$

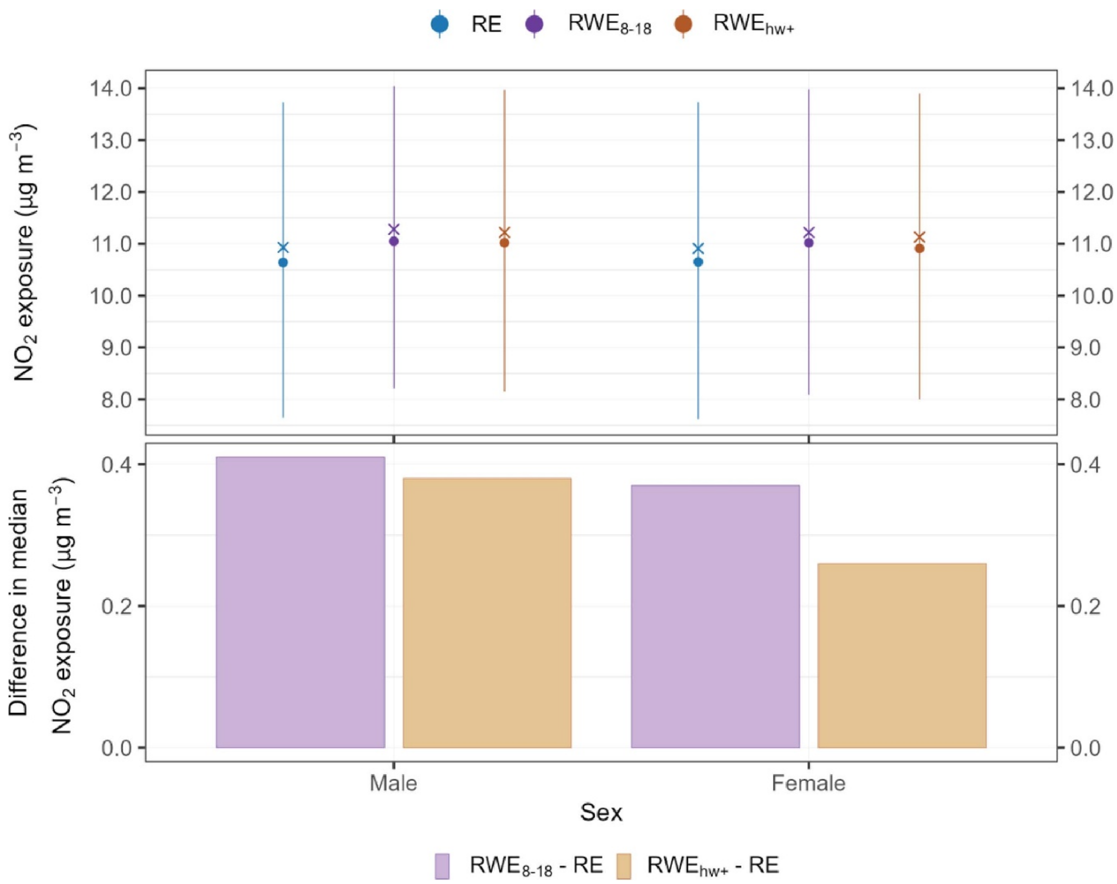

Figure 6. NO_2 exposure means (×), medians (•) and interquartile ranges (|) by sex and exposure scenario (top panel), and the differences in medians between each RWE scenario and the RE scenario (bottom panel). Source: Scottish Longitudinal Study.

but more O_3) are predominantly inhabited by the White population (https://sls.lscs.ac.uk/). This observation is consistent with Fecht *et al* (2015) who found that in England and the Netherlands, at regional level, neighbourhoods with <20% non-White ethnic individuals had lower concentrations of NO_2 than those with >20% non-White ethnic individuals. Fecht *et al* (2015) observed similar for PM_{10} in the majority (but not all) of the regions too. Given the small numbers (4.6%) of ethnic minorities in the population sample in this study (table S1) it is possible that some of our observations may not be fully representative of the exposure of the minority groups.

We found a clear pattern in residential exposure versus age. We found highest median exposure to NO_2 and $PM_{2.5}$ (and lowest for O_3) for those aged between 16 and 35. Mitchell and Dorling (2003) and Barnes *et al* (2019) also observed that young adults tend to live in more polluted areas in their study of age-related exposure inequality to NO_2 across the whole of Great Britain, and England and Wales, respectively. The pattern is due to the trend of young adults moving to inner urban areas for work, university and socialising purposes (where NO_2 and $PM_{2.5}$ are higher but O_3 is lower), before starting a family and moving out into the suburban areas to raise their children (Bromley *et al* 2007, Thomas *et al* 2015). The explanation is further supported by the youngest age group (<6 years old) in our study having on average slightly higher NO_2 and $PM_{2.5}$ exposure than older children (between 6 and 16 years old). In our study children always had a lower-than-average exposure to NO_2. Whilst this contrasts with the observation by Mitchell and Dorling (2003) of above-average exposure of children up to the age of about 10, Moreno-Jiménez *et al* (2016) also found lower exposure to NO_2 of children under the age of 5 than the population average in Madrid and Barcelona. However, they observed above-average exposures of the 80+ age group in Madrid and approximately average exposures in Barcelona whereas we found that the oldest age group has lower-than-average exposure to NO_2. In England, Fecht *et al* (2015) found mixed results when comparing NO_2 exposures in neighbourhoods with low and high proportions of children, but lower NO_2 exposure in neighbourhoods with the largest proportion of the over 65 s. The advantage of our study compared with the others is that it uses individual level data rather than area averages.

The least deprived tend to be exposed to the lowest NO_2 and $PM_{2.5}$ concentrations and the highest O_3 concentrations. The complex relationship between SES and residential exposure observed here is consistent

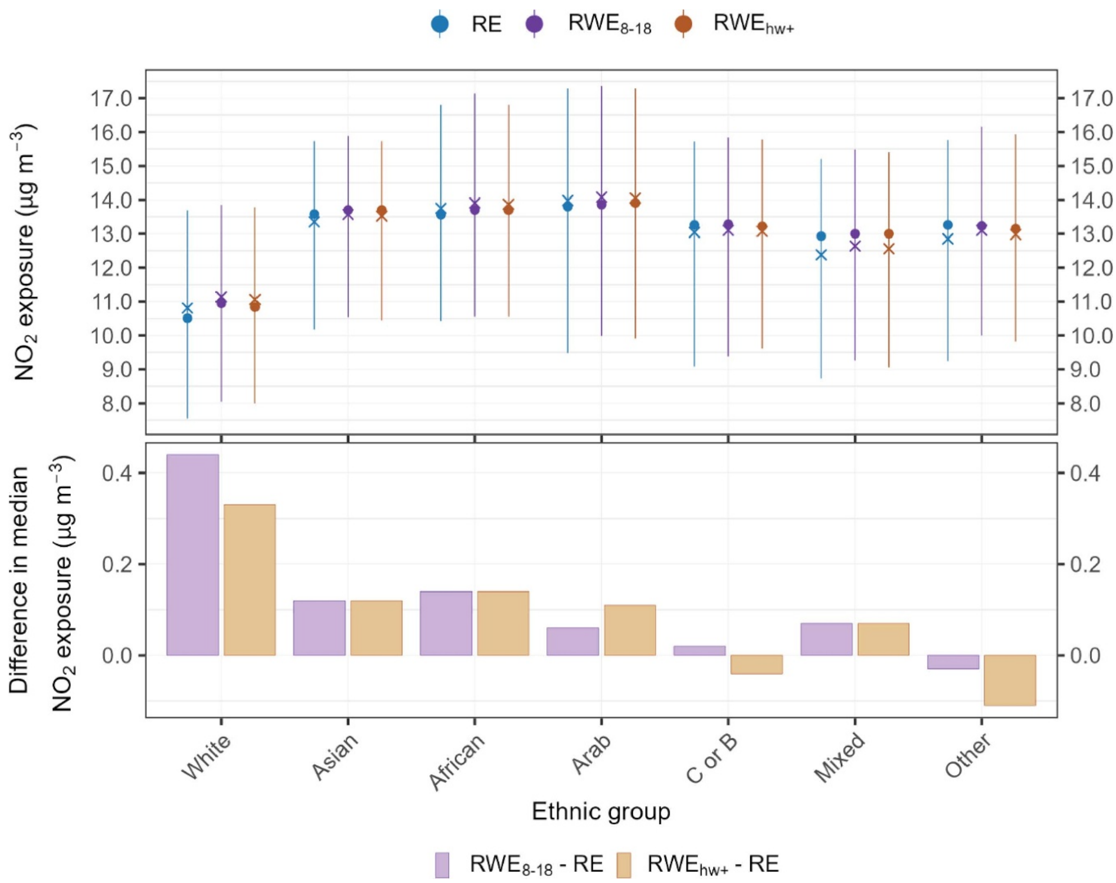

Figure 7. NO_2 exposure means (×), medians (•) and interquartile ranges (|) by ethnic group and exposure scenario (top panel), and the differences in medians between each RWE scenario and the RE scenario (bottom panel). C or B = Caribbean or Black. Source: Scottish Longitudinal Study.

with other studies in Europe, which also argue that the relationship between air pollution and SES is area specific (e.g. Fecht *et al* 2015, Temam *et al* 2017). Unlike the other investigated social characteristics in this study, the SES variable was only available as an Output Area average which may have masked higher gradients in exposure inequalities between people of differential SES.

The inclusion of place of work or study in quantification of exposure has a differential impact on exposure inequalities across population subgroups and pollutants compared with quantification using residential address only. The impacts of including place of work or study on $PM_{2.5}$ exposure tend to be very small; they are rarely larger in magnitude than 0.05 μg m^{-3}. For all three pollutants, males' exposures are more affected (on average) by time spent at workplace than are females' exposures. When stratifying exposure by ethnicity the impact of including exposure at workplace is variable but, as mentioned before, the low numbers in many ethnic minorities mean that any conclusion is unlikely to be robust and generalizable beyond this study.

The picture is much clearer for the age and SES based strata. The largest changes in exposure when including time spent at work or study are seen in the working age population between approximately 31 and 50 years old. This is clearly a result of a large proportion of suburban dwelling adults commuting to urban centres for work. A positive finding of this study is that young children's exposure appears to be largely unaffected by the exposure at school which is likely due to the typically short distance between home and school. A higher spatial resolution model might however indicate more substantial differences in exposure. The exposure of the very old is also unaffected since the vast majority of this age group did not indicate in the Census that they routinely spent time elsewhere. There is evidence in this study that exposure at the place of work/study tends to attenuate but not cancel out the inequalities in exposure between people of differential SES. Despite this mitigating effect on exposure inequality, the most deprived subgroup still experiences an increase in NO_2 exposure when exposure at work or school is considered.

Only a few studies have investigated differential population exposure in a socially stratified population. (Dhondt *et al* 2012) stratified population by age and gender whilst considering mobility of a synthetic population. In their study, annual exposure to NO_2 and 1 h max O_3 was comparable between males and

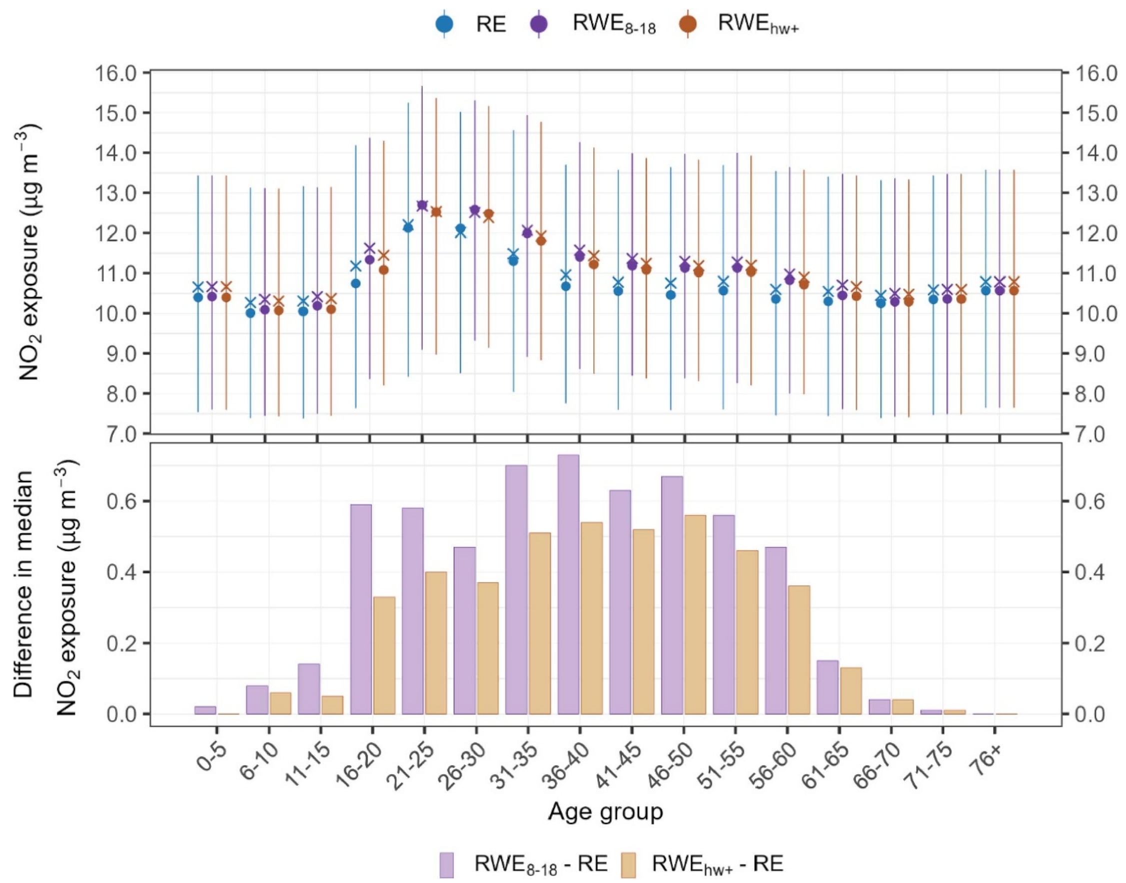

Figure 8. NO_2 exposure means (×), medians (●) and interquartile ranges (|) by age group and exposure scenario (top panel), and the differences in medians between each RWE scenario and the RE scenario (bottom panel). Source: Scottish Longitudinal Study.

females, whilst 18–34 and 35–54 year-old groups had higher exposure to NO_2 and lower exposure to O_3 than older age groups. The authors did not investigate exposure of children under the age of 18. In London, Tonne *et al* (2018), using a comprehensive exposure model (Smith *et al* 2016), found differences in exposure according to age and area-level income deprivations. However, since they included data for infiltration rates of outdoor to indoor concentrations, which yielded large reductions in personal exposures, their results are not easily comparable with the findings here.

4.1. Limitations

Due to the restrictions in population data access, we could not feasibly include exposure in other potentially important microenvironments in the assessment, particularly exposure during commuting between home and place of work or study. However, data presented by Ragettli *et al* (2015) suggest that in the Basel region commuting increases exposure to NO_2 by approximately 0.8% on average compared to a home-only scenario. Shafran-Nathan *et al* (2018) also argue that contribution of commuting to overall exposure to NO_2 is small. On the other hand, de Nazelle *et al* (2013) suggest an 11% contribution of commuting to NO_2 exposure based on a small sample in Barcelona. Whilst on average the contribution of commuting to overall exposure may be small (particularly to NO_2 but to some extent to $PM_{2.5}$), for some individuals commuting for longer time periods and/or on busy roads it may be substantial (Ragettli *et al* 2015). It is also likely that clustering of communities with similar social characteristics, and propensities of groups to use a specific mode of transport (e.g. use of cars by less deprived and buses by more deprived), may further affect the observed exposure inequalities (Tonne *et al* 2018). We have used a high-resolution atmospheric chemistry transport model in this study; however the model is still unable to resolve the highest spatial concentration gradients observed in the vicinity of air pollution sources. This issue is likely to have resulted in smaller calculated differences in exposure to NO_2 in particular. Finally, some types of jobs which are mostly undertaken by low skilled and low SES people, such as cleaners, handymen, taxi drivers, delivery drivers etc do not have a fixed place of work and would have therefore been excluded from the analysis. Furthermore, it is unlikely that those who report to a depot, and were therefore included in the analysis, were exposed during

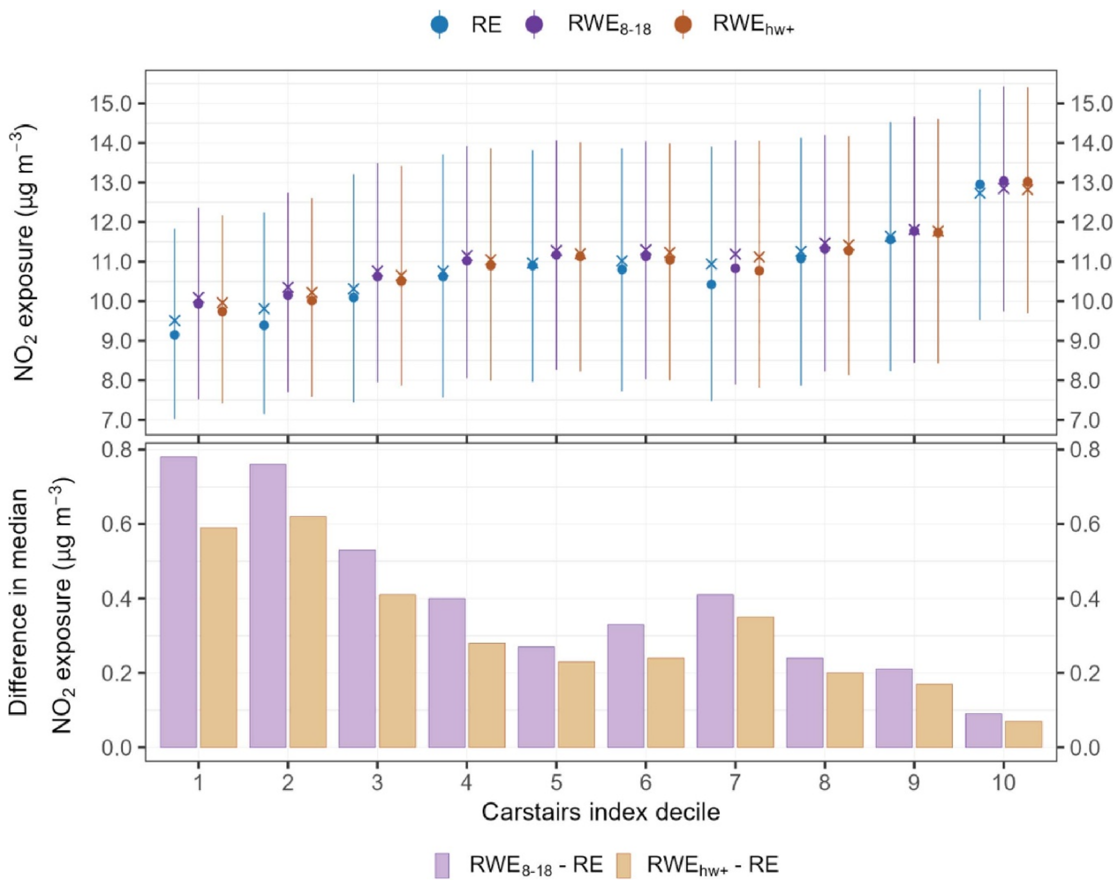

Figure 9. NO_2 exposure means (×), medians (•) and interquartile ranges (|) by socioeconomic status and exposure scenario (top panel), and the differences in medians between each RWE scenario and the RE scenario (bottom panel). Decile 1 is the least deprived. Decile 10 is the most deprived. Source: Scottish Longitudinal Study.

work to the same air pollution concentrations as at the depot location (as was assumed here) which potentially introduces bias of unknown direction for the lower ranking SES groups.

5. Conclusions

In this study we considered the exposure during time spent at the place of work or study alongside residential exposure in the assessment of inequalities in exposure to the ambient air pollutants NO_2, O_3 and $PM_{2.5}$ stratified by sex, ethnicity, age and socioeconomic status. At the population level, accounting for the place of work or study results in only small adjustments, on average, in exposures to NO_2 and O_3 compared with residential-only exposures, and negligible changes for exposures to $PM_{2.5}$. Both the absolute exposures, and the changes in exposures relative to residential exposure when including workplace exposures, are in all cases not shared equally among groups of different social characteristics. The patterns of exposure within and between different social characteristics are complex and, from comparison with other studies, can vary geographically. However, a general conclusion is that accounting for exposure at the place of work or study seems to attenuate but not cancel exposure gradients between subgroups of different ethnicity and SES.

Data availability statement

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

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Author contributions

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