Environment International 194 (2024) 109146

Contents lists available at ScienceDirect

Environment International

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

Full length article

Evaluating disparities in air pollution as a function of ethnicity, deprivation and sectoral emissions in England

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ARTICLE INFO

Keywords:
Ethnic inequality
NO_x
$PM_{2.5}$
Air pollution
Socioeconomic inequality

ABSTRACT

Macro-scale distribution of air pollution concentrations is influenced by factors including geography, weather, industry, transport and regulation. Pollution sources are unevenly distributed, with some communities disproportionately impacted by higher emissions. This study separates the effects of deprivation from ethnicity as factors that influence proximity to pollution sources. We combine recent decadal census data (2021) on socioeconomic deprivation and detailed population ethnicity at fine scales (Lower Super Output layer Area, LSOA n = 1600 people) with a 1×1 km sector-resolved atmospheric emissions inventory for NO_x and primary $PM_{2.5}$ in England. All 24 minoritised ethnic groups studied experienced higher average local NO_x and $PM_{2.5}$ emissions than socio-economically matched populations in the majority 'White: English, Welsh, Scottish, Northern Irish or British' ethnic group. Chinese, Arab and Bangladeshi communities experienced the largest disparity in NO_x, with weighted emissions 100%, 91%, 89% higher than white populations of matched deprivation status. Bangladeshi, Pakistani and Roma groups experienced on average 40%, 40%, 36% higher $PM_{2.5}$ emissions locally than matched white groups. For NO_x the largest contributors leading to disparity, were road transport (48%), domestic combustion (23%) and industry (15%). For $PM_{2.5}$ the greatest contributors to disparity were domestic combustion (53%), road transport (19%), and industry (11%). Living near to road transport and in city centres are frequently cited as primary drivers of ethnicity and deprivation-based disparities, however the analysis identifies that industrial, domestic and off-road sources create issues of the same magnitude, and disparities remain in suburban settings, smaller towns and some rural areas.

1. Introduction

Air pollution leads to detrimental impacts on the environment and public health (Public Health England, 2018; World Health Organisation, 2024; OAR. US EPA, 2015) across low, middle and high income countries (European Environment Agency, 2023, IPCC, 2014; UNEP, 2024). Nitrogen dioxide (NO_2) and $PM_{2.5}$ are two of the most significant pollutants that cause harm; these are regulated in many countries and guidelines for ambient concentrations have been issued by the World Health Organisation (World Health Organisation, 2024). Exposure to air pollution is not uniform however, being influenced by weather, geography, economic development, and regulatory systems. Exposure is significantly influenced by local to regional emissions sources such as transport, energy, and industry, and these in turn can be highly heterogeneous in their distribution. The likelihood of experiencing poor air quality has been shown to be associated with socioeconomic status: across a range of countries higher air pollution has been found in areas with increased levels of social deprivation. These associations have been shown in, amongst others, China (Schoolman and Ma, 2012; Ma et al., 2019), Canada (Jensen et al., 2023), Belgium (Verbeek, 2019), England (Gray et al., 2023; Milojevic et al., 2017), Ethiopia (Flanagan et al., 2021), Australia (Knibbs and Barnett, 2015), Korea (Choi and Min, 2020), across Latin America (Gouveia et al., 2022), and in various European regions (Fernández-Somoano et al., 2013; Occelli et al., 2016; Padilla et al., 2014; Morelli et al., 2016; Fairburn et al., 2019). The drivers of the association are complex; more deprived communities often live closer to industrial sources of pollution, near to major transport routes and can use more polluting appliances for cooking and home heating.

Minoritised ethnic groups within a country often (but not always) experience disproportionately higher levels of overall socioeconomic deprivation compared to the majority population. As a consequence

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https://doi.org/10.1016/j.envint.2024.109146
Received 25 July 2024; Received in revised form 24 October 2024; Accepted 11 November 2024
Available online 14 November 2024

they may experience a range of air pollution relevant disadvantages (Janevic et al., 2010; Song et al., 2018; Lessard-Phillips et al., 2018; Manekin and Mitts, 2022; Hall et al., 2015; Tai et al., 2021; Yip et al., 2019) including increased residential deprivation (Ailshire and Garcia, 2018) that can exacerbate exposure. General associations between ethnicity and ambient air quality have been shown in a range of countries. Racial inequity in air pollution exposure has been evaluated in the USA (Rosofsky et al., 2018; Su et al., 2011; Kravitz-Wirtz et al., 2016; Woo et al., 2019; Ard, 2016; Downey et al., 2008; Yoo et al., 2023), England (Fecht et al., 2015; Tonne et al., 2018), the Netherlands (Fecht et al., 2015), New Zealand (Pearce and Kingham, 2008) and Germany (Ehler et al., 2023), with all studies showing a disadvantage for minoritised ethnic groups. These studies all use concentrations or exposure as a measure to evaluate disadvantage, and how this arises through emissions is not explored.

Environmental injustice, which air pollution is an aspect of has been shown across the world. For example minoritised groups have been shown to bear the brunt of environmental issues in the Maghreb region of North Africa (Van Deursen Varga and Caubet, 2016), South Africa (Zenda, 2023) and areas of Canada (Deacon and Baxter, 2013), America (Parris et al., 2021; Powers et al., 2021; Grineski et al., 2013; Harris, 2019) and France (Harris, 2019). Environmental injustice along the lines of socioeconomic status, has also been shown in America (Tyree, 2021), Brazil (de Sousa et al., 2019; Gomes et al., 2021), Finland (Schonach, 2016), Ethiopia (Zhang et al., 2023) and China (The Centre for Social Justice, 2020). Previous work that informs this study has shown that minoritised ethnic groups experience poorer health outcomes in England (Caskey, 2013; Darlington-Pollock and Norman, 2017; Fecht et al., 2015; Friends of the Earth, 2022; Knibbs and Barnett, 2015). For example, minoritised ethnic groups experienced higher Covid-19 mortality rates (Ethnic minorities are bearing the brunt of COVID-19, 2021). Racial inequality in ambient NO_2 exposure has been demonstrated in London (Brook et al., 2023) and minoritised individuals have been shown to experience higher background concentrations of NO_2 and PM_{10} in England (Fecht et al., 2015). Separating the socioeconomic and ethnic components of air pollution based environmental injustice by looking at emissions allows evaluation of the extent to which socioeconomic disadvantage is driving environmental disadvantage for minoritised groups, and an identification of which source sectors are responsible.

A key evidential challenge in the field of air pollution inequalities is the ability to separate out factors associated with socioeconomic deprivation from those of ethnicity, since minoritised groups are often more likely to be deprived than the majority ethnic group. It has often been unclear whether minoritised groups are exposed to higher average pollution simply because they are, on average, more deprived or whether there is a further disparity once those deprivation effects have been accounted for. This subject has been investigated in America, finding that "emission sources that disproportionately expose [people of colour] are pervasive throughout society" (Tessum et al., 2021). More under-explored is the heterogeneity in the multiple ethnicities that make up catch-all groupings since to evaluate this requires highly granular sub-population ethnicity data. For example, the grouping "Asian" can be particularly non-specific and may refer to individuals of Chinese, Indian, Pakistani, Bangladeshi or other heritage, yet these groups are often distributed differently geographically based on histories of migration and employment and may experience notably different outcomes (Mok and Platt, 2020; Rubio et al., 2020; Chakraborty et al., 2017; Grineski et al., 2019a; Grineski et al., 2019b). Many studies use aggregate ethnicity categories for simplicity or because of national data and census limitations. However, the national census for England includes this information at a high level of granularity, enabling a finely detailed analysis of outcomes.

If the effects of deprivation, ethnicity and sub-group heterogeneity can be separated, then it becomes possible to produce well evidenced intervention policies. In essence the field of air pollution inequality research is often effective at identifying a problem, but less quantitative about possible solutions. A substantial amount of literature on air pollution and ethnicity considers the problem from the perspective of disparity in ambient concentrations experienced (either measured or modelled). Whilst past research has been crucial in helping with problem definition, knowing only associations with ambient concentrations does not necessarily directly guide sectoral interventions that may reduce the observed disparity.

The air pollution experienced by an individual is always some combination of pollution arising from transboundary, regional and local (neighbourhood to city scale) sources. The exact mix depends on location and the atmospheric lifetime of the pollutant. Since NO_2 has a relatively short life (minutes to hours), policy and technical levers for interventions lie predominantly at the local to city scale and there is little transboundary import or export. $PM_{2.5}$ however has an atmospheric lifetime measured in days, and forms as a secondary pollutant. Only a fraction of $PM_{2.5}$ experienced at any given location might be ameliorated through local actions on local primary emissions. National and international interventions to reduce emissions (e.g. CLRTAP) tend to generate broad benefits that improve air quality for all. The geographic scale of disparity in air pollution, as defined by either socioeconomic or ethnicity characteristics, is however on much finer geographic scale.

This work brings together highly detailed and contemporary datasets related to fine scale population, deprivation and ethnicities for England (National census from 2021) alongside a sectoral kilometre-scale resolution national atmospheric emissions inventory (NAEI) This is the most detailed national emissions inventory currently extant. Bringing together this unique combination of public data resources has allowed for deprivation-pollution associations to be separated from ethnicity, and for disparities to be evaluated across a wide range of minoritised ethnic sub-groups. When coupled to the NAEI this has provided unique insight into how individual emissions sectors (e.g. road transport, heating, industry, etc) contribute to an observed disparity. By focusing on the relationship between local emissions and local populations we have demonstrated ways of exploring the available data that enable the exploration of social and political decisions that influence where air pollution is emitted. Place of emission is important from an exposure perspective as modelled average concentrations smooth out days where atmospheric conditions result in emissions not being dispersed, magnifying the effect of local emission sources and leading to concentration spikes, with smog being a typical example. Pollution spikes have been linked to acute health effects (Mullins and Bharadwaj, 2015; Chen et al., 2024), for example, exposure to high levels of $PM_{2.5}$ significantly increases the risk of a stroke after exposure (Wellenius et al., 2012; Tan et al., 2022).

Emissions are the aspect of air pollution that is controlled by human decisions and actions. It is the aspect that air pollution legislation seeks to alter in order to deliver reductions in concentrations and exposure. Air pollution regulatory actions include blanket reductions such as lower regulatory thresholds, targeted reductions such as Ultra Low Emission Zones, and the distribution of planning permission for new high emission sites. Disparities in air pollution concentrations and exposure that are experienced by different communities are the result of decisions made which influence emission locations and magnitude. By investigating spatial emissions it becomes possible to identify more directly whether these decisions would improve or worsen inequality, and to propose policies which would target the sectors driving inequality.

2. Methods

2.1. Data sources

Data on annual NO_x and $PM_{2.5}$ emissions were obtained from the UK National Atmospheric Emissions Inventory (NAEI) (N. A. E. I., 2021) in the format of 1×1 km gridded emissions and with sectoral disaggregation across 12 major classes of source. Data from 2019 using the 2019 methodology was used in this study since 2020 and 2021 were considered to have overly distorted emissions due to national restrictions and reduced mobility as a response to the Covid-19 pandemic. Testing of outcomes reported in this paper using 2020 and 2021 revealed similar patterns, consistent with 2019 observations, although at lower overall absolute emissions. The uncertainty in emissions for NOx was 9%. The uncertainty in total emissions for PM2.5 was 55% (Jones et al., 2021). With the volume of data points available, and assuming a random distribution of error, this level of uncertainty would not drive the trends observed. The measure of deprivation used in this study is the Indices of Multiple Deprivation (IMD) data for 2019, obtained from the UK Department for Levelling Up, Housing & Communities (English indices of deprivation, 2019). This was the most up to date information available at the time of writing. IMD is calculated by ranking each LSOA within a range of deprivation domains, based on this ranking the LSOA receives a score between 0 and 100, based on an exponential transformation centred on 23. The scores are then weighted and combined, then ranked to produce a final measure of relative deprivation. Income and health deprivation have the highest weighting, followed by employment and education deprivation (Table 1).

Population census data for 2021 was obtained from the UK Office for National Statistics (Office for, 2021). This is collected via a decadal survey sent out by the UK government to all households containing many questions about demography. As such, all ethnicities are self reported. As the England and Wales census is taken every 10 years, this was considered the closest match to 2019 NAEI and IMD datasets. Whilst there is a 2 year disjoint between the census and the data used, this is insufficient time for a large national demographic shift, especially as house moves decreased during the pandemic (Lei and Liu, 2022; Chan et al., 2024). There will be areas which have experienced rapid demographic shifts, but due to the scale of the data and the reduction in residential mobility from the COVID 19 pandemic, this is insufficient to dramatically influence the results.

2.2. Conversion between 2011 and 2021 LSOAs

The 2021 England census data places populations into Lower Super Output Area (LSOA) geographies, each containing around 1600 people. The spatial size of the LSOAs flex to keep the sub-populations in each area broadly constant, typically resulting in a size between 0.1 and 3 km^2. Hence the LSOA are not absolutely fixed geographies; the 2021 ONS census LSOAs are not exactly identical to the LSOAs used for the 2019 IMD data (which are based instead on the 2011 definition). However, the vast majority have direct equivalents and the majority (93%) of LSOAs are geographically identical, with 2011 LSOAs being either renamed, split or merged to create the 2021 LSOAs. 0.03% of LSOAs were changed sufficiently such that there was no direct comparison possible between 2011 and 2021, so these LSOAs were excluded. For split LSOAs the IMD was applied to the two 2021 LSOAs, for merged LSOAs the average IMD rank of the two constituent LSOAs was used. In cases where the merged LSOAs had different rural urban classifications the resulting LSOA was excluded from LSOA based analysis as determining which of the classifications would be applicable is impossible using the dataset. This affected less than 0.01% of the dataset.

Table 1
IMD domains.

Domain	Weight
Income Deprivation	22.5 %
Employment Deprivation	22.5 %
Health Deprivation and Disability	13.5 %
Education, Skills and Training Deprivation	13.5 %
Barriers to housing and services	9.3 %
Crime	9.3 %
Living Environment Deprivation	9.3 %

2.3. Variables considered in this study

In addition to the use of IMD, ethnicity, NO_x and $PM_{2.5}$ emissions data, the effects of geographic 'type' data were also included, via Rural Urban Classification (RUC) datasets (Office for National Statistics, 2011). This places areas in one of eight classifications ranging from 'Urban major conurbation' to 'rural village and dispersed'. The RUC classifications with the stipulation "in a sparse setting" were merged with their equivalent outside a sparse setting. This is because their population numbers are low to analyse individually and they share sufficient traits to be merged. IMD deprivation decile was used rather than the IMD ranking or score as the volume of data is sufficient that using a discrete scale with 10 steps is appropriate. Using the IMD rankings or scores yields similar results.

2.4. Tools used for analysis

The previously published R package PRAWNS (Gray et al., 2023), which has been used for analysing emissions and deprivation was expanded on as part of this work. PRAWNS calculates the mean emissions within each LSOA by calculating the mean value from the 1×1 km NAEI an emission grids of the UK which fall within the area of each LSOA. With this value calculated it is then linked to other characteristics of the LSOA enabling analysis.

2.5. Population weighting

As minoritised ethnic populations are irregularly split across LSOAs, population weighting was used to calculate average values. The NAEI-based emission value of NO_x and $PM_{2.5}$ for each LSOA was multiplied by population of the target group in residence. This value was summed across all LSOAs, where n is the number of LSOAs in the IMD decile, then divided by the sum of individuals within the target group. This allowed for the uneven distribution of relevant populations across LSOAs and deprivation deciles to be accounted for in the averages. To calculate population weighted IMD decile the same general formula was used, but with the sum of all LSOAs and the IMD for each LSOA used.

$$\frac{P_{i_i} = 1^n Populationoftargetgroup_i * Emissions_i}{\sum_{\frac{i=1}{i \cdot i}}^{=n} Populationoftargetgroup}$$

2.6. Matching deprivation

To calculate emissions averages for 'White: English, Scottish Welsh or Northern Irish', for comparison with the emissions for minoritised ethnic groups the population weighted mean emissions for each deprivation decile were calculated. A linear model was fitted to this data, visible as the pink line in Figs. 6 and 7, determined to be appropriate by comparison with the mean, median, upper and lower quartiles of the data (Supplementary Figs. S1 and S2) and the values for emissions at each fractional IMD decile were calculated using this.

2.7. Relative population deciles

To investigate the relationship between the relative fraction of a minoritised ethnic population within an area and air pollution emissions, LSOAs were split into deciles where Group 1 contained the lowest percentage minoritised ethnic population and Group 10 contained the highest percentage minoritised ethnic population. This method was chosen as the populations for each minoritised ethnic group are distributed very differently as percentages and standardising allowed for a comparison of how relative minoritised populations were affected by emissions. The bounds of these deciles are included in the supplementary information (Supplementary Table S1).

3. Results and discussion

The population-weighted emissions in 2019 from six emission categories (Total emissions, Road transport, Domestic combustion, Industry and point sources, Other transport and mobile machinery, and all other), were calculated for 10 deprivation deciles, and by six broad ethnic groupings. The analysis covered the area of England and used geographic units containing roughly 1600 individuals, and typically between 0.1 and 3 km^2 in size. Maps of deprivation, NO_x emissions and percentage population in minoritised groups are shown below (Fig. 1). The distribution of emission values across LSOAs is highly skewed (Supplementary Figs. S3 and S4) and the mean was chosen as the summary statistic best representing both emissions as a whole and the presence of high emitting areas.

3.1. Populations experiencing high emissions

LSOAs were divided into deciles based on NO_x emissions, and the percentage of the population identifying as each broad ethnic group was plotted (Fig. 2).This shows that the population of minoritised ethnic groups inhabiting high emitting areas is far greater than in low emitting areas.

3.2. Differences in emission from each source sector

The total emissions trends in Figs. 3 and 4 show that for all ethnic groups, those with higher levels of deprivation (IMD 1,2 or 3) experience higher emissions than the less deprived. It is also clear that the absolute 'Total' amount of emissions is considerably higher for all minoritised ethnic groups than the majority 'White: English, Welsh, Scottish, Northern Irish or British' ethnic group, henceforth referred to as the majority white ethnic group, once deprivation has been accounted for.

For NO_x, road transport is the most significant emission source, however the disparity is actually largest for domestic combustion. Other NO_x sources such as Industry and Other transport/mobile machinery are also higher for minoritised ethnic groups. Only for 'Other sources', which includes farming and agriculture as well as solvents, natural sources and waste treatment and disposal, are majority-white populations exposed to higher emissions, however the absolute amounts (see y axis) are very small.

For $PM_{2.5}$ a similar picture emerges. The total emissions are higher for minoritised groups once deprivation is accounted for. For $PM_{2.5}$ the largest disparity in local emissions arises from domestic combustion, then road transport, and the other source sectors. The deprivation based disadvantage is not new, and has been noted in works examining aspects of racial inequality in England from the past 20 years (Becares et al., 2012; Karlsen et al., 2002; Chandola, 2001). What is striking here is the scale of disparity that exists after deprivation effects have been accounted for. Whilst the absolute differences may seem small, the percentage differences are all greater than 10%, and health effects are nonlinear.

To determine the contributions from the five different source sectors to the overall disparity observed, the average population-weighted emissions were calculated for each broad ethnic group. These values were then calculated as a percentage of the difference in total emissions compared to the majority white ethnic group. Table 2 shows the percentage contribution of each source sector to the overall disparity observed by minoritised ethnic groups compared to the majority white ethnic group. These values were similar for each more granular ethnic group (Supplementary Tables S2 and S3). For NO_x, road transport was the largest factor, whilst for $PM_{2.5}$ it was domestic combustion. It is notable however that in both cases various other emission sectors are substantial contributors to the overall disparity calculated.

3.3. Differences and disparities using more granular ethnicity data

As discussed in the introduction, it is important to acknowledge the significant ethnic diversity that exists in England, and some general categorisations contain people from very different ethnic backgrounds. A very powerful advantage in conducting this study on UK data is the level of detail that is captured in census data on ethnicity. In this section, we expand the analysis to use 24 ethnic groups for which data is collected in the Census (2021). The first stage in the analysis is to examine how different minoritised ethnic groups are distributed across the 10 IMD deciles. This is shown in Fig. 5, for 24 classifications, and attached in the supplementary is the ethnic composition of each IMD decile (Supplementary Table S4). As would be expected, when considering all residents in England, 10 % of people are in each of the 10 IMD deciles, since that is by definition how the deciles are constructed. For other groups the distributions are uneven. For example, a larger fraction of the Bangladeshi population are within the most deprived IMD Groups 1 and 2, than the least deprived in IMD groups 9 and 10.

Once the distribution of different ethnic groups across the IMD spectrum has been established it is then possible to construct a metric that is a mean IMD value for each group. To do this, the population weighted deprivation for each group and the associated emissions can then be compared against the linear deprivation – emissions relationship that exists for the population as a whole. This is shown in Figs. 6 and 7. Data points that sit above the national average linear line (blue line) experience, on average, higher emissions than would be expected based

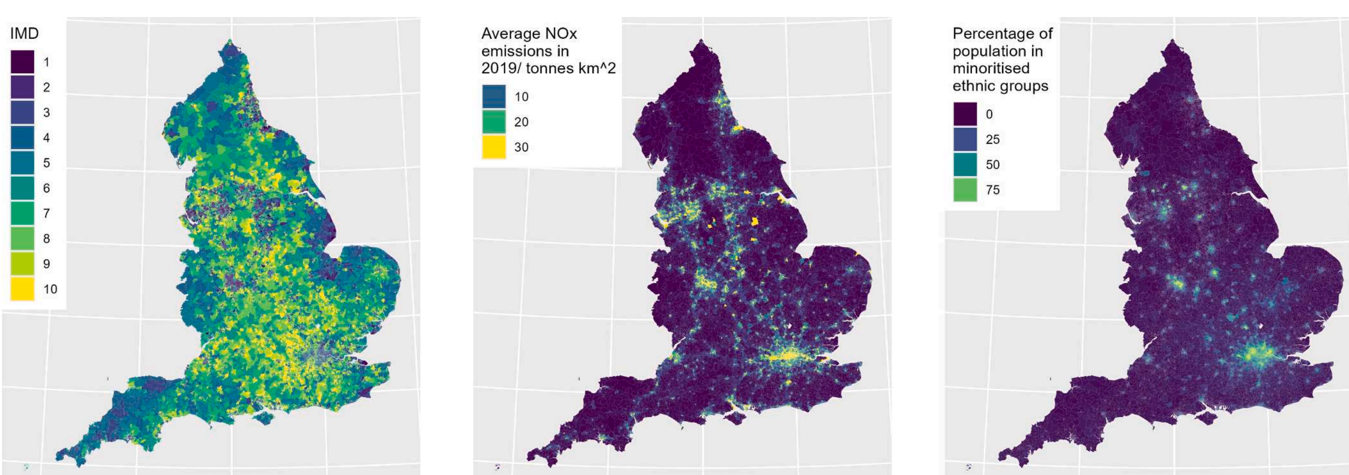

Fig. 1. Maps of IMD, mean emissions of NO_x and percentage population belonging to minoritised ethnic groups in England.

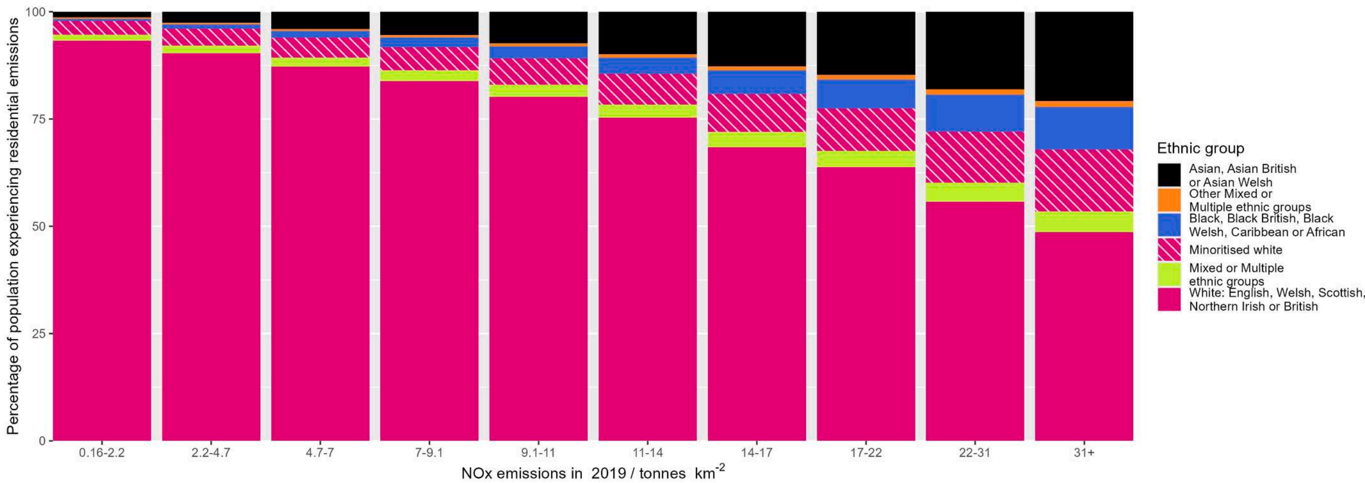

Fig. 2. The ethnic composition of populations experiencing NO_x emissions split into deciles where 1 is the lowest 10% of NO_xemissions and 10 is the highest 10% of NO_x emissions.

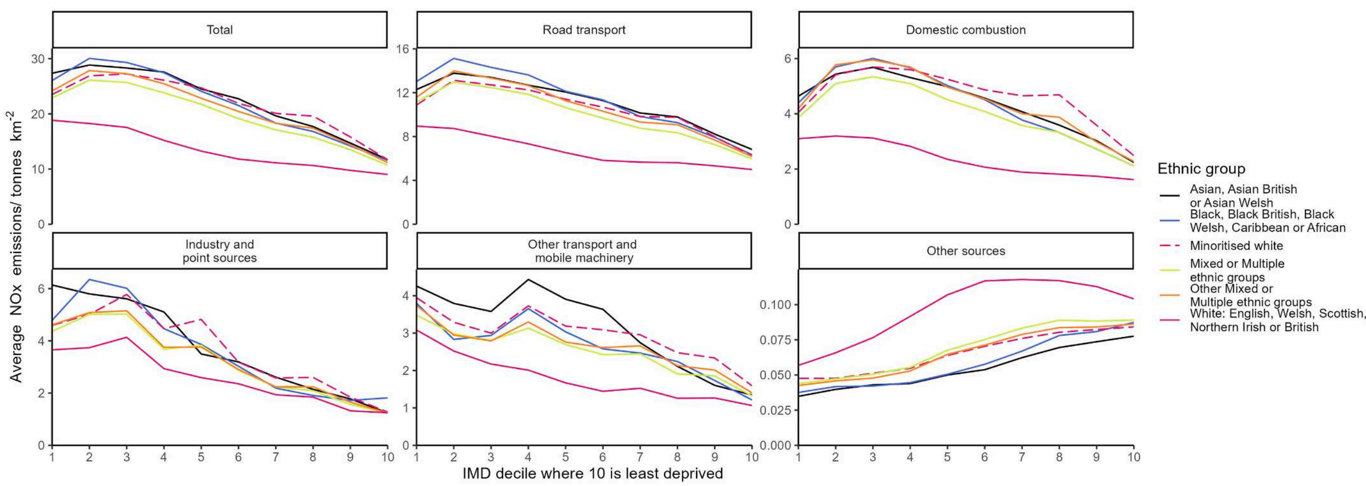

Fig. 3. Population weighted mean emissions of NO_x including 'Total' emissions (the sum of all sources in the NAEI) and five sub sectors for each IMD decile (1 is the most deprived, 10 is the least deprived). 'Industry and point sources' are the sum of industrial production, industrial combustion, energy production and point sources. 'Other sources' is the sum of solvent use, agricultural emissions, natural and waste treatment and waste disposal.

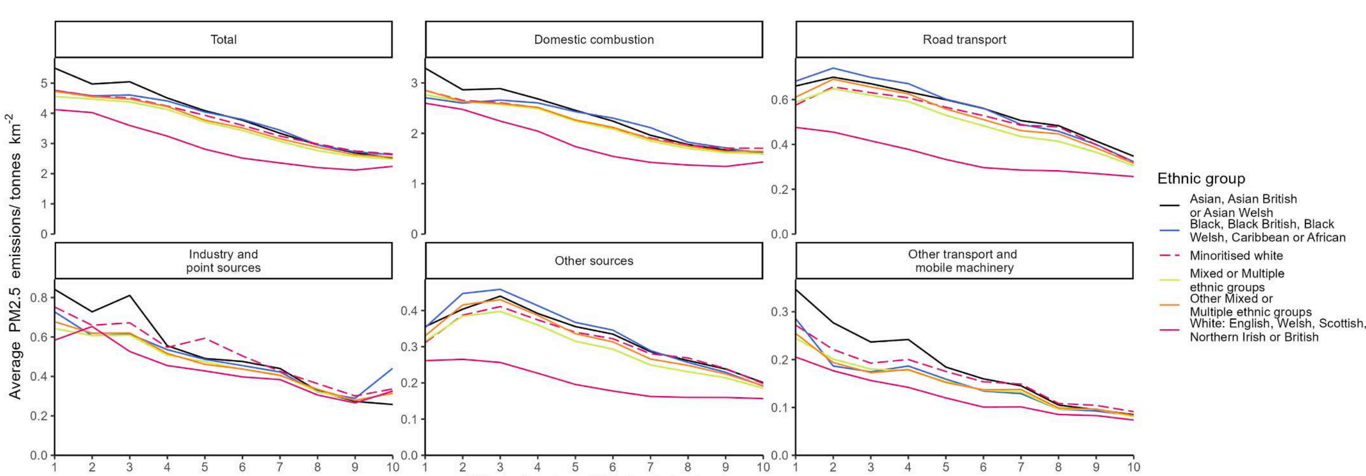

Fig. 4. Population weighted mean emissions of $PM_{2.5}$ including 'Total' emissions (the sum of all sources in the NAEI) and five sub sectors for each IMD decile (1 is the most deprived, 10 is the least deprived). 'Industry and point sources' are the sum of industrial production, industrial combustion, energy production and point sources. 'Other sources' is the sum of solvent use, agricultural emissions, natural and waste treatment and waste disposal.

Table 2
The percentage contribution of each major emissions sector to the total mean disparity in emissions between the majority"White: English, Welsh, Scottish or Northern Irish" ethnic group and all minoritised ethnic groups. The negative value present for other sources of NO_x is due to natural and agricultural emissions showing the opposite association.

Emission sector	NO_x	$PM_{2.5}$
Road transport	47.9	19.9
Other transport and mobile machinery	13.4	5.7
Domestic combustion	23.3	51.3
Industry and point sources	15.8	11.4
Other sources	−0.4	12.0

on deprivation as a factor alone. Datapoints below the line represent ethnic groups that experience, on average, lower emissions than would be expected based on deprivation alone. The pink line represents the emissions experienced by the majority "White, English, Scottish, Welsh, Northern Irish or British" ethnic group. To give an example of how to interpret this Figure: Bangladeshi and Pakistani ethnicities are on average the most deprived grouping in England with a mean IMD for that group of less than 3. They also experience considerably higher NO_x and $PM_{2.5}$ emission than would be anticipated for the national average for populations in IMD − 3. A clear pattern emerges, with virtually all minoritised ethnic groups lying above the national average line. At this level of census granularity, it becomes visible that some white minoritised ethnic groups also experience significant emissions disparities, for example White Roma communities. By removing the effects of deprivation some further insights emerge – for example Indian and Chinese communities are, on average, above the national average for IMD, but still experience considerably higher emissions of NO_x and $PM_{2.5}$ than would be expected for that IMD level. This is consistent with work showing different outcomes for more granular groups in England (Mok and Platt, 2020) and America (Grineski et al., 2013; Grineski et al., 2019a).

It is clear therefore that the use of broad umbrella categories for ethnicity can hide considerable variability and this can smooth out some of the larger disparities that exist. For example using 'Asian' as a category gives a lower overall estimate of emissions, and masks the disproportionately high emissions experienced by Bangladeshi and Pakistani ethnicities; aggregating 'White' as a single category masks the disparity for some minoritised white groups such as Roma. Due to ever diminishing populational numbers as we further sub-divide the datasets for this analysis, the five summary categories in the census have been used, with the white category split into minoritised white and 'White: English, Welsh, Scottish, Northern Irish or British', acknowledging the smoothing this brings due to heterogeneity within those categories.

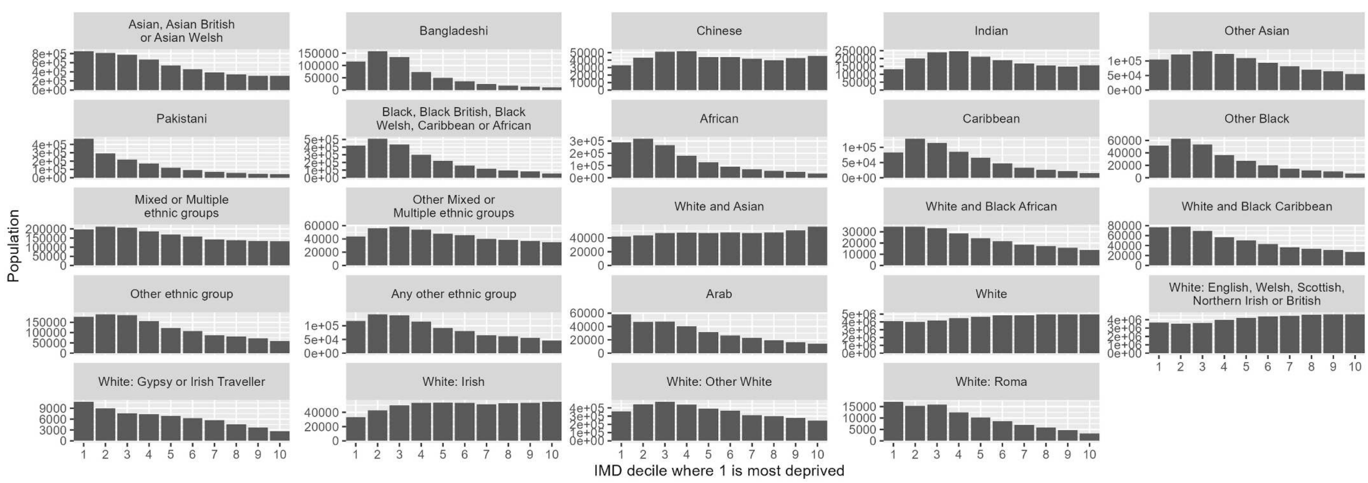

Fig. 5. How each ethnicity grouping is split across deprivation deciles 1 to 10. Data based on Census (2021), and IMD data (2019), See method section for data sources.

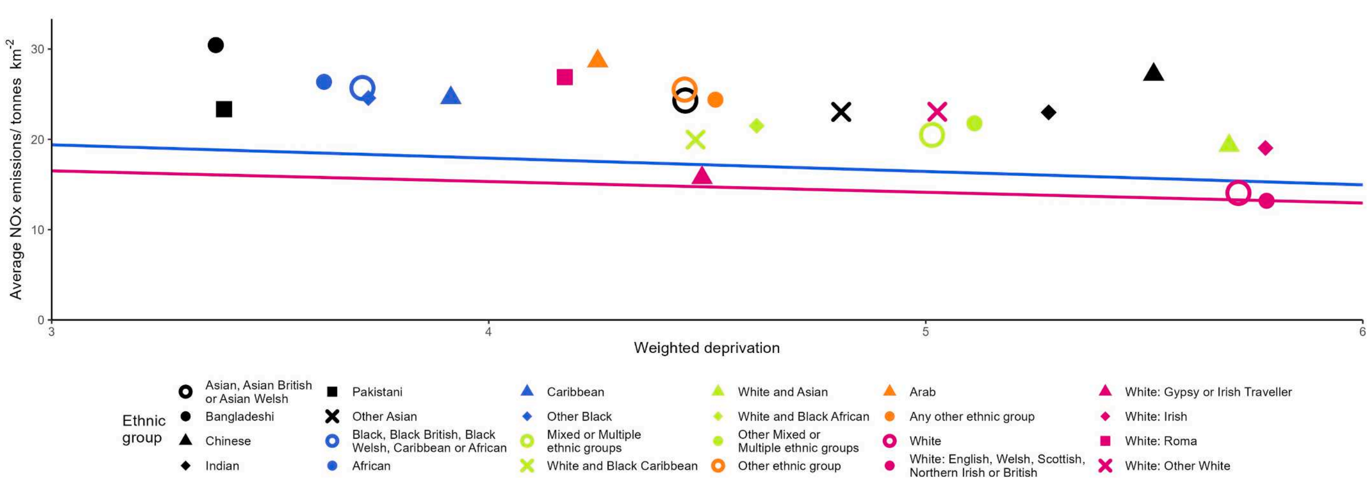

Fig. 6. Population weighted NO_x emissions for ethnic groups defined, in the 2021 census, with mean IMD classification based on 2019 data and emissions data taken from the NAEI for 2019. The blue line represents the deprivation based inequality present in the population as a whole. The pink line represents the deprivation based inequality present for the majority white ethnic group.

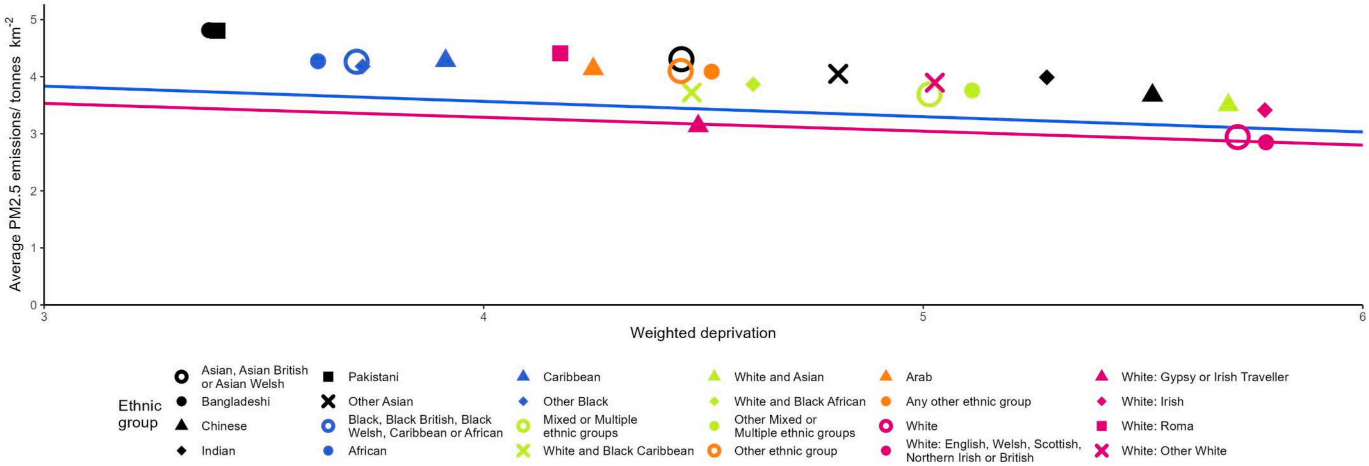

Fig. 7. Population weighted $PM_{2.5}$ emissions for ethnic groups defined, in the 2021 census, with mean IMD classification based on 2019 data and emissions data taken from the NAEI for 2019. The blue line represents the deprivation based inequality present in the population as a whole. The pink line represents the deprivation based inequality present for the majority white ethnic group.

3.4. Evaluating the causes of disparity in emissions

Whilst identifying disparities in air pollution emissions for minoritised ethnic groups is a valuable exercise in its own right, of greater value is a quantitative understanding of why this might occur, and how disparities may be reduced or eliminated through interventions. An obvious area for exploration is the extent to which disparity is raised because of different geographic and settlement differences and preferences.

Minoritised ethnic groups have a higher percentage of the population living in urban areas compared to White: English Scottish Welsh or Northern Irish individuals (supplementary Fig. S5). There is typically a difference between emissions in urban and rural areas (Gray et al., 2023; Al-Rashidi et al., 2018; Nunes et al., 2016; Blaszczyk et al., 2017), and the level of disadvantage faced by ethnic minorities has been shown to be connected to an areas heritage (Lymperopoulou and Finney, 2017) e.g. historic mining communities and rural areas have different outcomes. To explore this, we evaluate emissions for groups as a function of Rural Urban Classifications (RUCs). This analysis was not performed at the finest level of ethnicity classification as after splitting for RUC and IMD the sample size for some groups would be too small for reasonable analysis allowing outliers to skew the results. Using broad ethnic groups the classification 'Rural village and dispersed' still had some low population deciles, with a minimum value of n = 57. For all other RUCs the minimum population of a group within a decile was above 200.

Figs. 8 and 9 show NO_x and $PM_{2.5}$ emissions by ethnicity and deprivation for five different geographic types in England. It is clear that within urban and town settings (taken across the whole for England) minoritised ethnic groups experience, on average, higher emissions of both NO_x and $PM_{2.5}$ compared to majority white counterparts living in the same geographies and at the same level of social deprivation. It is notable however that the differences between minoritised ethnic groups and the majority white group narrows considerably for the least deprived deciles. For rural towns, fringe locations, villages and dispersed settings there is no clear disparity associated with ethnicity based on deprivation. However, due to the low population of some ethnic groups at low levels of deprivation in these deciles the association or lack thereof is unclear.

In urban RUCs, minoritised ethnic groups experience higher emissions of NO_x and $PM_{2.5}$ than the majority for most deprivation deciles. This difference narrows in the least deprived areas, and is very small for deciles 8 and 10 in urban minor conurbation. As minoritised ethnic groups are more likely to live in deprived areas, this has a large effect on national inequality. Non-urban RUCs show lower inequality between ethnic groups in the same deprivation decile. This is consistent with results from the USA showing greater exposure inequality for NO_2 and $PM_{2.5}$ in urban areas than rural ones (Rosofsky et al., 2018).

Aggregating data for the whole of England suggests that the higher

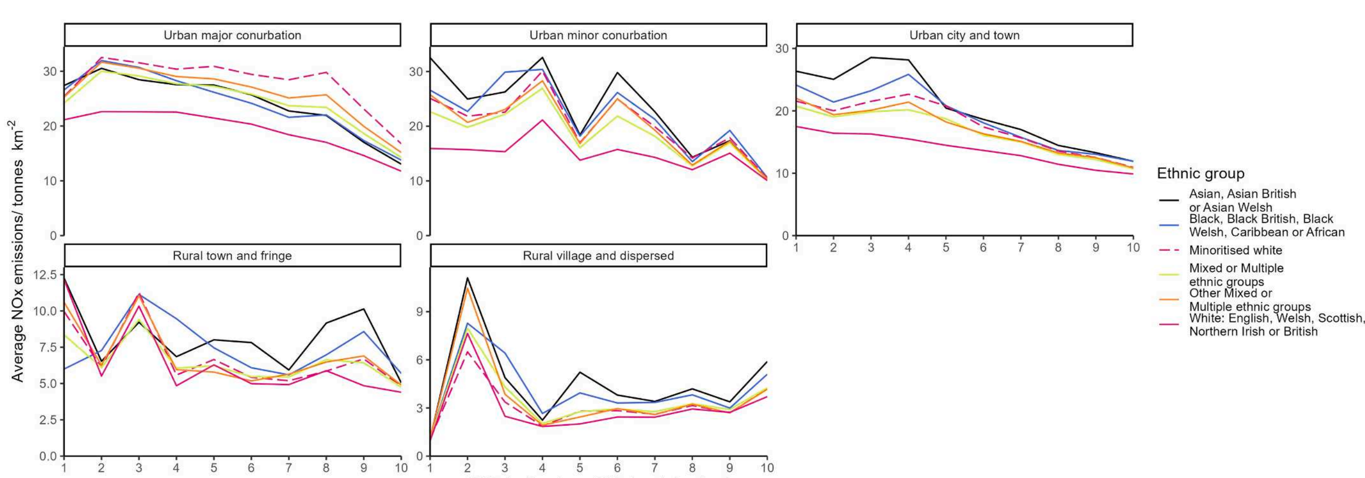

Fig. 8. Distribution of mean NO_x emissions for six ethnicity groups across the ten deprivation deciles as a function of different Rural Urban Classifications.

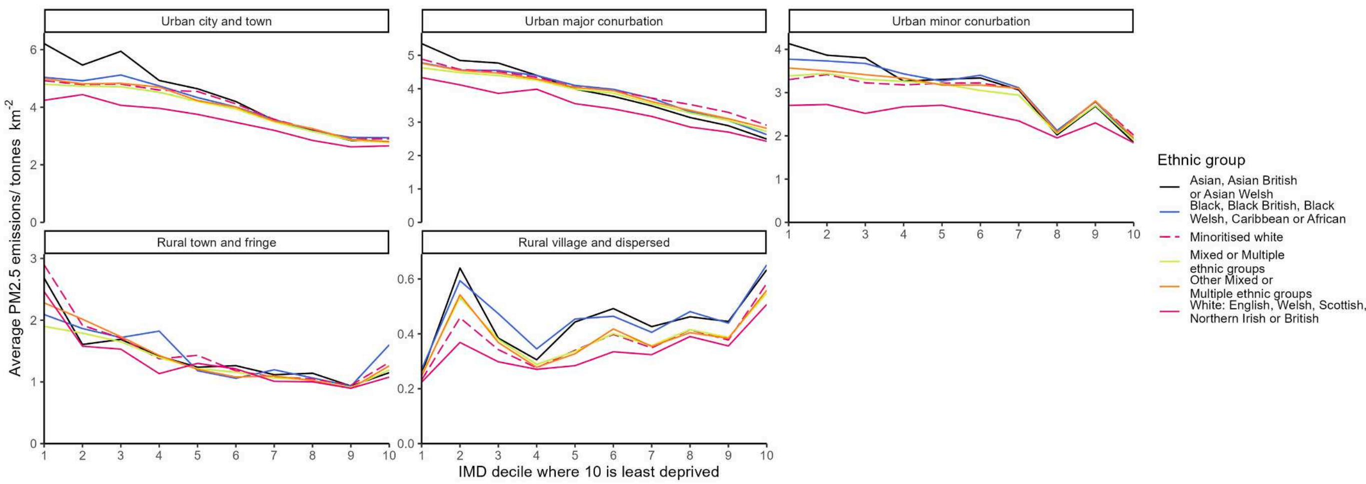

Fig. 9. Distribution of mean $PM_{2.5}$ emissions for six ethnicity groups across the ten deprivation deciles as a function of different Rural Urban Classifications.

proportion of minoritised ethnic groups who reside in urban locations is not in isolation a cause for the disparities observed. Majority white populations of matched socioeconomic status in the same geographies are, on average, exposed to lower emissions of both NO_x and $PM_{2.5}$.

An alternative approach to evaluating disparities and population was to consider how emissions changed as the relative fraction of a given population from a particular ethnicity changes. This allows an examination of how the phenomena of clustering of ethnicities (Lansley et al., 2011; Catney, 2017; Finney and Jivraj, 2013) in particular locations is related to local air pollution emissions. Figs. 10 and 11 show the relative populations of each broad ethnic group as deciles on the x axis, where Group 1 is the 10% of LSOAs with the lowest percentage population of that ethnicity group, and Group 10 is the 10% with the highest percentage population of that group. Two contrasting phenomena emerge. As locations have increasingly ‘White’ populations, on average, the NO_x and $PM_{2.5}$ emissions experienced fall (moving from 1 to 10). As locations have a higher population from minoritised ethnic groups, NO_x and $PM_{2.5}$ emissions increase. These trends are accounted for by steadily increasing road transport and domestic combustion sources moving from Groups 1 through to 10. Industrial combustion and production, and to a lesser extent point sources, show a steady upward trend then a spike for the final 20% for Asian, Black and Other ethnic groups, suggesting these sources are much more likely to be situated in population centres with a large fraction of these ethnic groups resident. These data are shown in the supplementary information (Supplementary Figs. S6 and S7).

3.5. *The effect of place within England*

Throughout data has been aggregated across the country to give an ‘on average’ picture of emissions and any disparities between deprivation and ethnicity. In the previous section comparing disparities as a function of RUCs the ‘on average’ included all similar geographic locations in the analysis. Disparities in air pollution emissions are present after deprivation and RUC had been accounted for. It is not simply therefore being deprived and being more likely to live in a city/town that creates differences between minoritised ethnic groups and majority white populations.

In reality, cities and towns in the England are not homogeneous. In simple terms the North and West of the UK benefits from better air quality than the South and East, in part because of higher wind speed and rainfall and more distance from continental European influence. From an emissions perspective there are structural differences, inland towns and cities are often circled by major transport infrastructure and industry in a way that is not directly replicated in coastal locations. Deprived coastal areas tend to have lower economic activity and as a consequence lower emissions than their inland equivalents.

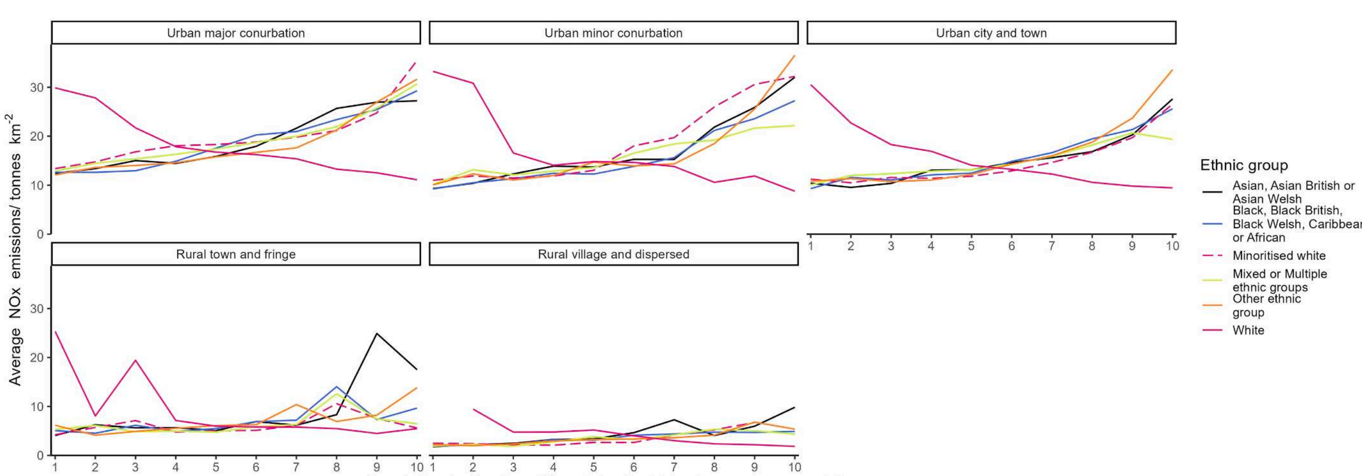

Fig. 10. Distribution of mean NO_x emissions for different RUCs as a function of changing population fraction from a particular ethnicity. Each decile contains 10% of all LSOAs, ranked based on their percentage population of each broad ethnic group. Group 1 contains the lowest fraction of that ethnicity, and Group 10 the highest fraction of that ethnicity. The 10th decile for all minoritised groups contains at least 4× the population of the 1st decile.

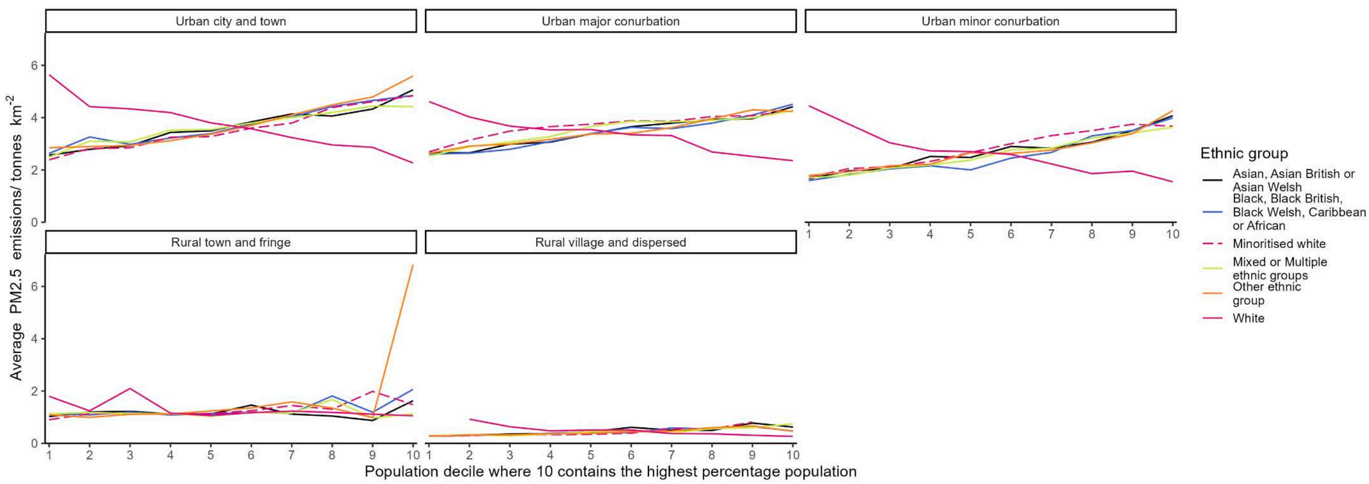

Fig. 11. Distribution of mean $PM_{2.5}$ emissions for different RUCs as a function of changing population fraction from a particular ethnicity. Group 1 contains the lowest fraction of that ethnicity, and Group 10 the highest fraction of that ethnicity. The 10th decile for all minoritised groups contains at least 4× the population of the 1st decile.

To visualise the effects of geography, the most deprived 20% of LSOAs in England are shown in Fig. 12, shaded according to their minority and majority populations. Differences are visible to the eye – deprived LSOAs with high fraction majority white populations are visible in coastal locations, notably on the North East and West coasts. The West Midlands and London have LSOAs with higher fractional populations of minoritised ethnic groups. Fig. 1 shows emissions by LSOA of NO_x (2019). The emission centres are major cities such as London, Birmingham, Manchester, and Liverpool. Structural differences in the nature of the economies of inland vs coastal towns and cities, coupled to historical drivers of migration to particular locations, may therefore be an important contributor to the disparities observed. Examples of coastal and inland cities in the north and south of England are in the supplementary (Supplementary Fig. S8), and show the variation in associations between emissions, deprivation and ethnicity at the local scale.

3.6. Limitations

The emissions used are at place of residence, which does not correspond directly to total exposure, but is a major contributing factor, especially for those who do not commute to a secondary location for work or education as part of their daily routine e.g. infants and retirees. Additionally, the height of emissions e.g. from an elevated factory chimney, is not considered and this may affect the distribution of some emissions.

$PM_{2.5}$ has a long atmospheric lifetime, and secondary $PM_{2.5}$ formed in atmospheric reactions contributes significantly to local concentrations. However, local emissions will still have an effect on background concentrations. The composition of $PM_{2.5}$ also varies by source, which can lead to variations in effect e.g. ash from industry may contain heavy metals, and dust from road wear may contain more silicates. If measures for $PM_{2.5}$ are targeted based on emissions, areas with higher emissions will experience more disruption from them, which is important to account for.

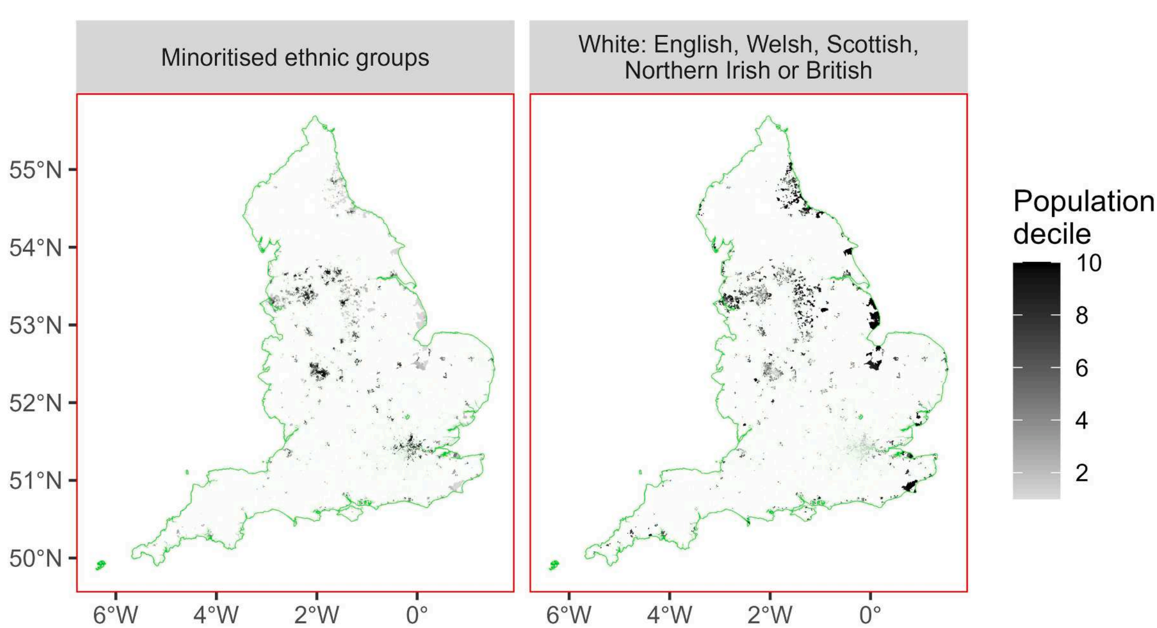

Fig. 12. The most deprived 20% of LSOAs, shaded by their relative population.

4. Conclusions

There are substantial disparities in emissions of NO_x and $PM_{2.5}$, with deprived groups experiencing higher emissions. Once deprivation as a factor is controlled for, minoritised ethnic groups experience on average higher emissions from all major source sectors than majority white populations of matched socioeconomic status. This is consistent with the body of work examining general air pollution based disadvantages in England (Fecht et al., 2015; Tonne et al., 2018) and across the world (Pearce and Kingham, 2008; Ehler et al., 2023; Rosofsky et al., 2018; Su et al., 2011; Kravitz-Wirtz et al., 2016; Woo et al., 2019; Ard, 2016; Downey et al., 2008; Yoo et al., 2023; Fecht et al., 2015). It means that the increased burden of air pollution faced by these groups is greater than what would be expected from an analysis using increased area deprivation as a proxy for ethnicity.

Considerable variability between minoritised ethnic groups exists and averaging via the use of broad categorisation such as 'Asian' can mask considerable differences. In this study Chinese, Arab and Bangladeshi populations experienced on average NO_x emissions than were nearly double those expected based on population averages for matched socio-economic status (100%, 91%, 89%). Bangladeshi, Pakistani and White Roma groups experienced on average 40%, 40% and 36% higher emissions of $PM_{2.5}$ compared to matched white English populations. For those minoritised ethinic groups with a mean IMD above 5 disparities still existed – for example Indian and Chinese populations are, as a whole, less deprived than the England all-population average but experienced higher emissions than a white population with matched socioeconomic status.

Across England as a whole, minoritised ethnic groups are more likely to live in cities however this 'place' factor was not the sole cause of the observed disparity. When urban and town populations were socio-economically matched substantial disparities remained with minoritised groups experiencing higher emissions for matched place settings. In general, as the fraction of minoritised ethnicity population increased in a location, air pollution emissions of NO_x and $PM_{2.5}$ also increased. By contrast, as the fraction majority white in a population increased emissions decreased.

Higher average levels of deprivation and propensity for urban living do not fully explain why minoritised ethnicity groups experience higher emissions as disparities still exist when these factors are controlled for. Deprived urban and town locations with high fraction white populations are often found in coastal settings in England, whereas the highest densities of minoritised ethnicity groups could be found in inland urban areas such as London and the west midlands. Longstanding differences in the economies, industries and transport infrastructure, coupled to historical patterns of movement and migration and employment may play a part in driving the observed differences in emissions experienced.

Examining the sectoral causes of disparities highlighted that for 2019 road transport was responsible for around 48 % of the ethnicity disparity once deprivation effects had been accounted for; this figure is likely to have fallen further over the intervening years. Other sectors such as heating, industry and off-road vehicles are also important to consider as routes to reduce NO_x disparities. For $PM_{2.5}$ domestic heating is the largest driver of ethnicity disparities with further contributions from a range of other sectors. As tailpipe emissions from vehicles further reduce, addressing non-road sources of both NO_x and $PM_{2.5}$ will be vital for the improvement public health more generally and the reduction of ethnicity-based disparities in exposure to local emissions.

Preprint submitted to Environment International, October 24, 2024.

CRediT authorship contribution statement

Nathan R. Gray: Formal analysis, Writing – original draft preparation, Visualization, Software, Methodology, Conceptualization. **Alastair C. Lewis:** Writing – review & editing, Supervision, Methodology, Conceptualization, Funding acquisition. **Sarah J. Moller:** Writing – review & editing, Supervision, Methodology, Conceptualization, Funding acquisition.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Nathan Gray, Ally Lewis and Sarah Moller report financial support was provided by United Kingdom Department for Environment Food and Rural Affairs. Ally Lewis and Sarah Moller report a relationship with DEFRA Air Quality Expert Group that includes: consulting or advisory. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was funded by the United Kingdom Department for Environment, Food and Rural Affairs (Defra). This research was made possible by publicly available emissions data from the UK National Atmospheric Emissions Inventory and census data from the UK National Archives.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2024.109146.

Data availability

Data will be made available on request.

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