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Reducing health inequality from air pollution requires action in deprived-ethnic neighbourhoods: An environmental justice analysis of air quality in England, 2001-2021

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Introduction

Environmental inequality in the UK

1 The environmental justice (EJ) movement has its deepest roots in the USA, where evidence of environmental inequality emerged in the 1980s, leading to social activism and national policy in the 1990s (Clinton, 1994). In Europe, the movement developed quite recently, except in the UK, where evidence was developed much earlier to support policy and planning (King and Stedman, 2000; FoE, 2001; Walker *et al.*, 2003; Fairburn *et al.*, 2005). In the USA, the focus was on the association of hazardous (particularly waste disposal) facilities, with race, reflecting deeper origins of EJ concerns in the civil rights movement. In contrast, UK EJ was framed with a broader environmental focus, considering both hazardous (e.g. flooding, air quality, industrial hazard) and salutogenic (e.g. green space) attributes, and where the social focus was deprivation, reflecting concern over poverty related health inequalities (Black, 1980; Acheson, 1998). The US movement was driven by grass roots activism, but in the UK the impetus was more top-down, with central government concerned to meet

commitments under the 1992 Rio declaration and UNECE Aarhus convention (UNECE, 1998).

2 Government attention on EJ issues declined with the defeat of the centre-left Labour administration in 2010, but attention persisted amongst health agencies and health equity professionals (e.g. Marmot, 2010). In this context, concerns over air quality became prominent, as analyses demonstrated how the burden of air pollution fell on more deprived populations and children under 10 years old (Mitchell and Dorling, 2003; Walker *et al.*, 2003b). Although air quality has undergone long term improvement in the UK, medical research has revealed its health impacts, especially from fine particulates, are worse than once thought (Manisalidis *et al.*, 2020; Schraufnagel, 2020), maintaining the imperative for improvement. Health impacts are now recognised at all life stages, with effects including low birth weight, asthma, slower lung function development, diabetes, COPD, stroke, heart attack and lung cancer (CMO, 2022), with a mortality burden from exposure to outdoor particulates and NO_2 in England in 2019 equivalent to 26,000 to 38,000 deaths a year (Mitsakou *et al.*, 2022). Recently, UK environmental regulators have begun to consider recognition and procedural justice issues in air quality management, through for example the Environment Agency's co-ordination of the 'air quality lived experience' network (Swift, 2022), and scrutiny of its own internal strategy and processes (Mitchell *et al.*, 2023). However, distributive analyses remain important in providing current evidence (Barnes *et al.*, 2019; Gray *et al.*, 2023) to support action on justice in UK air pollution.

UK air quality and ethnic status

3 The deprivation focus has meant that few UK EJ studies examined the distribution of air pollution relative to ethnicity until recently. An early analysis, of Birmingham, found non-White populations were exposed to higher CO and NO_2 emissions than White populations, an effect independent of deprivation (Brainard *et al.*, 2003). For London, Tonne *et al.* (2018) found higher residential exposure to NO_x and $PM_{2.5}$ concentrations for non-white populations, but that differences in exposure were small when adjusting for age and deprivation. Brook *et al.* (2023) found that Black Londoners and diaspora immigrant communities were likely to live in more polluted (NO_x and $PM_{2.5}$) areas, with less polluted areas, particularly in outer London, being mostly (71%) White. For Glasgow, Catalano (2024) found a higher burden of air pollution for non-White residents, with the most polluted (NO_x) decile home to 12-34% of the non-White groups, compared to 9% for Whites (comparable figures for $PM_{2.5}$ were 8-27% and 9%). National analyses also reveal that non-White groups are exposed to greater air pollution. Fecht *et al.*, (2014) found pollution concentrations in England were higher in neighbourhoods with >20% non-White (by 3.0 $\mu g/m^3$ for PM_{10} and 10.1 $\mu g/m^3$ for NO_2) after adjustment for urbanisation, age and deprivation. Similarly, Gray *et al.* (2024) found all minority ethnic groups experienced higher local NO_x and $PM_{2.5}$ emissions than socio-economically matched White populations (by 36-100% depending on group and pollutant), while Bennett *et al.* (2026) found large NO_x ethnic inequalities after accounting for area deprivation.

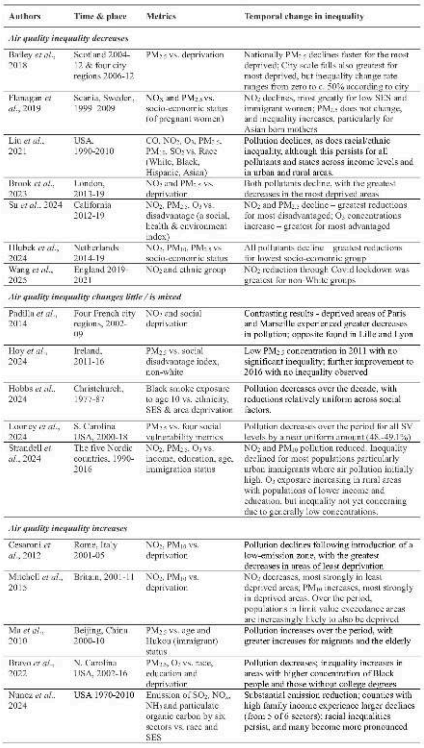
4 Evidence for health impact in ethnic groups from UK air pollution is less clear. A survey of 67,000 individuals found ethnic minorities self-report poorer health with increasing NO_2, SO_2 and particulate concentrations in comparison to White-British and UK-born

(Ahad *et al.*, 2023). Yet whilst GP visits and hospital admissions increase with air pollution there is no observed White/non-White difference (Ahad, 2022). Considering specific conditions, no ethnic air pollution effect is found with respect to newborn size (Schembari *et al.*, 2015), or adolescent blood pressure (Karamanos *et al.*, 2023), but effects are observed with respect to mental health (Ahad *et al.*, 2022) and adolescent behaviour problems (Karamanos *et al.*, 2021). There is good evidence that air pollution contributes significantly to asthma in the UK population as a whole (Khreis *et al.*, 2019; Singh *et al.*, 2024), and that asthma rates vary by race (Netuveli *et al.*, 2005), with genetic and environmental factors known to be influential (Forno and Celedón, 2009; Hernandez-Pacheco *et al.*, 2016). However, research has not yet specifically examined air pollution related asthma by ethnicity in the UK, except in South Asians born outside the UK who may have experienced acute air pollution in childhood (Busby *et al.*, 2024).

UK Longitudinal EJ analyses

Whilst the medical studies above often follow a cohort of individuals over time, EJ distributive studies are dominated by cross-sectional frameworks. However, longitudinal EJ studies are valuable as they reveal how environmental change is experienced by different social groups, important for just (i.e. ‘fair’) environmental management, and have potential to shed light on causal processes. Mitchell *et al.* (2015) reviewed 32 longitudinal EJ studies (most address industrial facilities) which reveal a range of processes thought to explain observed environmental inequality, including discriminatory siting of hazards, housing market dynamics, demographic and neighbourhood churn effects, community (in)capacity to resist hazards, and differential attitudes to environmental risk. Only five studies addressed air quality; four used temporally static deprivation data and air quality projections whilst Padilla *et al.* (2014) used observed data to track how improving NO_2 pollution 2002-09 was socially distributed in French cities. Results were mixed, with the most deprived areas experiencing greater pollution decreases in some cities, and the opposite in others. Bailey *et al.* (2018) hypothesise that the range of theories available to explain such relationships imply that cities cannot be expected to all converge on a universal norm (e.g. via a housing market model that sorts the deprived into more polluted areas).

Table 1. Temporal trends in air pollution inequality.



Authors	Time & place	Metrics	Temporal change in inequality
Air quality inequality decreases			
Bailey *et al.*, 2018	Scotland 2004-12 & four city regions 2006-12	$PM_{2.5}$ vs. deprivation	Nationally $PM_{2.5}$ declines faster for the most deprived; City scale falls also greatest for most deprived, but inequality change rate ranges from zero to c. 50% according to city
Flanagan *et al.*, 2019	Scania, Sweden, 1999–2009	NO_X and $PM_{2.5}$ vs. socio-economic status (of pregnant women)	NO_2 declines, most greatly for low SES and immigrant women; $PM_{2.5}$ does not change, and inequality increases, particularly for Asian born mothers
Liu *et al.*, 2021	USA, 1990-2010	CO, NO_2, O_3, $PM_{2.5}$, PM_{10}, SO_2 vs. Race (White, Black, Hispanic, Asian)	Pollution declines, as does racial/ethnic inequality, although this persists for all pollutants and states across income levels and in urban and rural areas.
Brook *et al.*, 2023	London, 2013-19	NO_2 and $PM_{2.5}$ vs. deprivation	Both pollutants decline, with the greatest decreases in the most deprived areas
Su *et al.*, 2024	California 2012-19	NO_2, $PM_{2.5}$, O_3 vs. disadvantage (a social, health & environment index)	NO_2 and $PM_{2.5}$ decline – greatest reductions for most disadvantaged; O_3 concentrations increase – greatest for most advantaged
Hlubek *et al.*, 2024	Netherlands 2014-19	NO_2, PM_{10}, $PM_{2.5}$ vs socio-economic status	All pollutants decline – greatest reductions for lowest socio-economic group
Wang *et al.*, 2025	England 2019-2021	NO_2 and ethnic group	NO_2 reduction through Covid lockdown was greatest for non-White groups
Air quality inequality changes little / is mixed			
Padilla *et al.*, 2014	Four French city regions, 2002-09	NO_2 and social deprivation	Contrasting results - deprived areas of Paris and Marseille experienced greater decreases in pollution; opposite found in Lille and Lyon
Hoy *et al.*, 2024	Ireland, 2011-16	$PM_{2.5}$ vs. social disadvantage index, non-white	Low $PM_{2.5}$ concentration in 2011 with no significant inequality; further improvement to 2016 with no inequality observed
Hobbs *et al.*, 2024	Christchurch, 1977-87	Black smoke exposure to age 10 vs. ethnicity, SES & area deprivation	Pollution decreases over the decade, with reductions relatively uniform across social factors.
Looney *et al.*, 2024	S. Carolina USA, 2000-18	$PM_{2.5}$ vs. four social vulnerability metrics	Pollution decreases over the period for all SV levels by a near uniform amount (48.-49.1%)
Strandell *et al.*, 2024	The five Nordic countries, 1990-2016	NO_2, $PM_{2.5}$, O_3 vs. income, education, age, immigration status	NO_2 and PM_{10} pollution reduced. Inequality declined for most populations particularly urban immigrants where air pollution initially high. O_3 exposure increasing in rural areas with populations of lower income and education, but inequality not yet concerning due to generally low concentrations.
Air quality inequality increases			
Cesaroni *et al.*, 2012	Rome, Italy 2001-05	NO_2, PM_{10} vs. deprivation	Pollution declines following introduction of a low-emission zone, with the greatest decreases in areas of least deprivation
Mitchell *et al.*, 2015	Britain, 2001-11	NO_2, PM_{10} vs. deprivation	NO_2 decreases, most strongly in least deprived areas; PM_{10} increases, most strongly in deprived areas. Over the period, populations in limit value exceedance areas are increasingly likely to also be deprived
Ma *et al.*, 2010	Beijing, China 2000-10	$PM_{2.5}$ vs. age and Hukou (immigrant) status	Pollution increases over the period, with greater increases for migrants and the elderly
Bravo *et al.*, 2022	N. Carolina USA, 2002-16	$PM_{2.5}$, O_3 vs. race, education and deprivation	Pollution decreases; inequality increases in areas with higher concentration of Black people and those without college degrees
Nunez *et al.*, 2024	USA 1970-2010	Emission of SO_2, NO_x, NH_3 and particulate organic carbon by six sectors vs. race and SES	Substantial emission reduction; counties with high family income experience larger declines (from 5 of 6 sectors); racial inequalities persist, and many become more pronounced

6 Wider literature supports this conclusion. Our extensive search (using Web of Science and Google Scholar) for air quality EJ analyses, whilst not executed to PRISMA review standards, revealed no consistent trends (Table 1). Air pollution improvements are variously greatest or least, or mixed, in areas where deprived and ethnic populations are more prevalent. Our following analysis therefore extends the evidence base on air quality-inequality in Europe and provides new insight into the social distribution of air quality in England. We: (i) extended our earlier small area analyses of NO_2 and particulates (Mitchell and Dorling 2003; Mitchell *et al.*, 2015) to provide insight into the changing social distribution of air quality over twenty years; (ii) addressed ozone (as recommended by Strandell *et al.*, 2024) for the first time in the UK; (iii) added the little studied ethnic dimension; and (iv) gave attention to peak values that are of most health concern. This final aspect was conducted with reference to air quality limit and WHO guideline values, which provide benchmarks against which claims of environmental injustice can most robustly be tested.

Data and methods

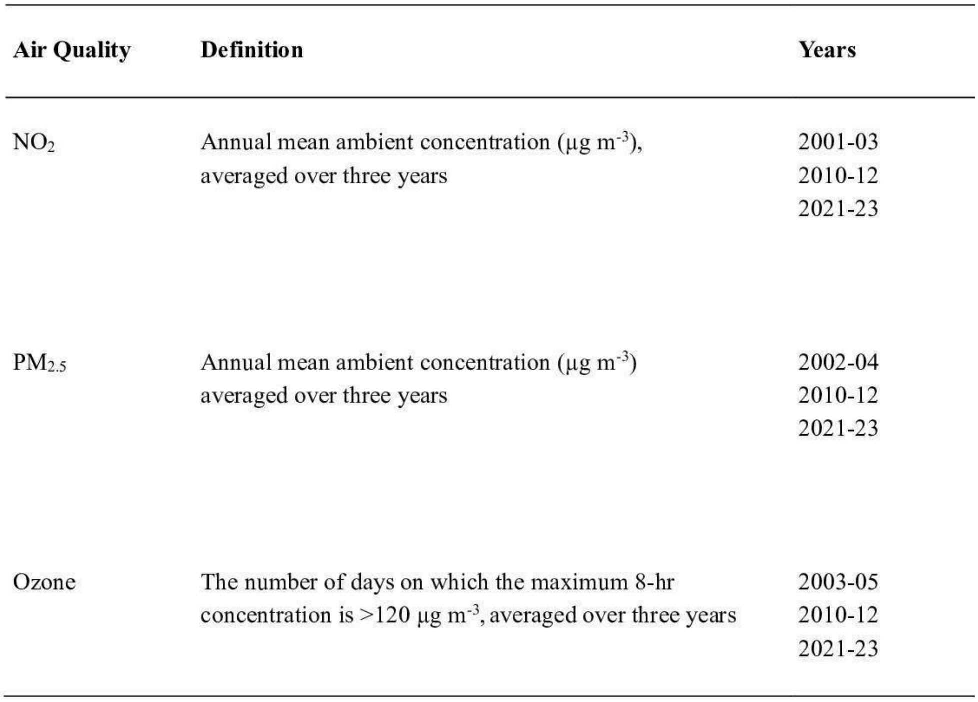
Air quality data

7 Pollution data for England, used by government for statutory air quality standards compliance reporting purposes, was sourced from DEFRA (no date). These data are 'background' (i.e. non-roadside) concentrations modelled on a 1x1 km grid, drawing on the National Atmospheric Emissions Inventory. Principal components are large source emissions (e.g. power stations) where concentrations are modelled from emissions using the ADMS dispersion model. Concentrations arising from small point sources (e.g.

schools and hospitals) and local area sources (including roads and domestic combustion) are modelled using a time varying dispersion kernel technique. These component concentrations, plus imports from long distance, are summed and the final annualised average concentrations validated against the national monitoring network. Note that as annual averages, these data will not adequately represent short term episodic peak concentrations. Background maps may also over/under estimate roadside concentrations, hence central government introduced a second national standards compliance process, where for a sub-set of pollutants, concentrations 4m from each of 9,000 major roads are modelled, and since 2020, validated against a network of several hundred roadside monitors. Thus the DEFRA background maps do not represent all the spatial and temporal heterogeneity in national air quality and require supplementing with additional assessment if concentration data at an individual property or road junction is required. However, the assessments are robust for evaluating average exposure and long-term trends. Detail on the national air quality assessment and modelling process can be found in Defra (2025) and Pugsley *et al.* (2025).

8 We used annual average concentrations of fine particulates ($PM_{2.5}$), nitrogen dioxide (NO_2) and for ground level ozone (O_3) the number of days on which the daily maximum 8-hr concentration is >120 µg m^3. To control for shorter term inter-annual variability and mitigate the effect of the Covid pandemic lockdowns in early 2021, we averaged data for each location across three years (Table 2).

Table 2. Air quality (ambient concentration) data: England.



Air Quality	Definition	Years
NO_2	Annual mean ambient concentration (µg m^{-3}), averaged over three years	2001-03 2010-12 2021-23
$PM_{2.5}$	Annual mean ambient concentration (µg m^{-3}) averaged over three years	2002-04 2010-12 2021-23
Ozone	The number of days on which the maximum 8-hr concentration is >120 µg m^{-3}, averaged over three years	2003-05 2010-12 2021-23

Source: DEFRA (no date): https://uk-air.defra.gov.uk/data/pcm-data

Social data

9 We used deprivation and ethnicity data from the national population census for Lower-layer Super Output Areas (LSOAs) (Table 3). In 2021 England had a population of 56.5 million across its 33,755 LSOAs, which typically have 1,000 to 3,000 residents. For deprivation, we used a long-run time-series of Townsend deprivation (Norman *et al.*, 2024) which focuses on 'material' deprivation (Townsend *et al.*, 1988, p.36) comprising census derived inputs on unemployment, home ownership, car ownership and household overcrowding. Although largely superseded in policy-related work by the Index of Multiple Deprivation (e.g. Noble *et al.,* 2019) the Townsend Index is the most comparable measure of deprivation over time, since the index, inputs and time-points of data collection are consistent. The deprivation data are also consistent with respect to our ethnic group population counts. The Townsend index was used to determine the dynamic relationship between deprivation and air quality from 2001 to 2011 in the UK (Mitchell *et al.*, 2015), and the 2021 Census data allowed this analysis to be extended to 20 years. We analysed changes in exposure across five ethnic group categories which can be consistently defined for the last three Censuses (Table 3).

Table 3. Deprivation and ethnic group population data: England.

Social metric	Definition	Years
Townsend Deprivation Index	Sum of the Z-scores of percentages of: Unemployment; Household Non-home ownership; No car; and Overcrowding	2001, 2011, 2021
Count of population by ethnic group	Ethnic groups: White; South Asian; Black; Mixed; and Chinese & Others	

Source: UK census data at https://www.nomisweb.co.uk/sources/census with additional processing to derive the deprivation index (Norman *et al*. 2024)

Methods

10 Data were analysed at LSOA level, with spatial reconciliation of grid based air quality data and vector based social data conducted using methods described in Mitchell *et al.* (2015). Raster and vector data are spatially inherently different, hence their reconciliation can introduce error and uncertainty through, for example, partial intersection, boundary effects, and loss of heterogeneity (Goodchild, 1992). However,

use of high resolution data (LSOAs; 1x1 km gridded air quality data) minimises these errors.

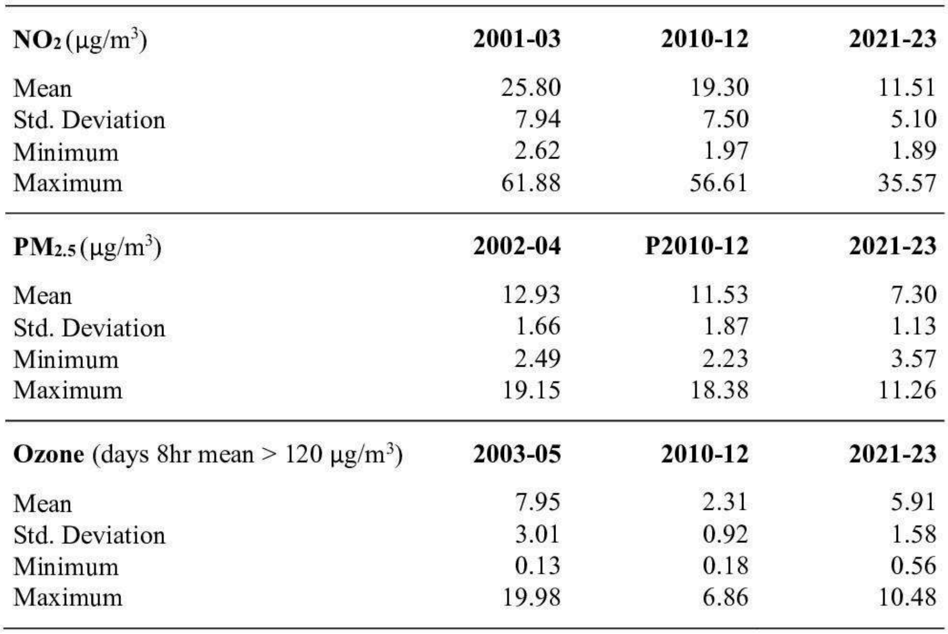
11 As our data coverage was national (total population), we were able to eliminate sampling error and to produce true population parameters rather than estimates. As such, we used descriptive statistics to characterise the changing social distribution of air quality in England. These show how ambient average concentrations have changed over two decades (2001-2023), whilst air quality-deprivation relationships were established using correlation, and boxplots of air quality across deprivation deciles at each of the three decadal time points. Differences by ethnic group were assessed via correlation of the proportion of each ethnic group in an LSOA with the associated air quality. Intersectional analyses (of air quality, ethnicity, and deprivation) were conducted using quasi-Lorenz curves and Gini coefficients (Boyce *et al.*, 2016), and by count of ethnic population in the most deprived quantile, most polluted quantile, and both, to reveal combined disadvantage. Using cartograms (Dorling, 2011) that aid visualisation by scaling LSOAs so that they are proportionate to their areal extent, we mapped combined disadvantage (top quantiles for air quality and deprivation), and compared this to cartograms of exceedance of WHO air quality guideline standards.

Results and Discussion

England's air quality change, 2001-2023

12 Although there is considerable inter-annual variation, air pollution in England has decreased substantially (Table 4) in recent decades due to national and EU environmental policy (Carnell *et al.*, 2019; Defra, 2024). Reduction in NO_x and particulate emissions have been achieved in transport through technological control on tailpipe emissions, and from 2016 a substantial switch in new car registrations away from diesel and petrol to electric and hybrid vehicles. Similarly, emissions from power generation have declined due to technological control on flue gases, and a switch away from coal. Ozone is not emitted directly but results from chemical reactions mediated by sunlight, with Volatile Organic Compounds (VOCs) acting as formation precursors, and other pollutants acting as scavengers, including NO_x, whose declining concentration is thought to account for a rising trend in urban ozone. A U-shaped distribution in ozone concentrations is indicated by Table 4 (and seen more clearly in annual data) and is attributed to successive particularly hot sunny summers in 2022-23 (Defra, 2024). These data reveal improving air quality, yet public health concerns remain due to concentrations being well above WHO guidelines, and the upward trend in urban ozone where population exposure is greatest.

Table 4. Air quality change in England, 2001-2023.



NO$_2$ (µg/m^3)	**2001-03**	**2010-12**	**2021-23**
Mean	25.80	19.30	11.51
Std. Deviation	7.94	7.50	5.10
Minimum	2.62	1.97	1.89
Maximum	61.88	56.61	35.57
PM$_{2.5}$ (µg/m^3)	**2002-04**	**P2010-12**	**2021-23**
Mean	12.93	11.53	7.30
Std. Deviation	1.66	1.87	1.13
Minimum	2.49	2.23	3.57
Maximum	19.15	18.38	11.26
Ozone (days 8hr mean > 120 µg/m^3)	**2003-05**	**2010-12**	**2021-23**
Mean	7.95	2.31	5.91
Std. Deviation	3.01	0.92	1.58
Minimum	0.13	0.18	0.56
Maximum	19.98	6.86	10.48

Air quality and social deprivation

13 Since 1971, levels of deprivation in England have improved but there has been a stagnation in recent decades (Norman *et al.*, 2024; Lloyd *et al.*, 2023), a suburbanisation of poverty (Bailey *et al.* 2019) and a mixed picture of change in some rural and coastal areas (Norman *et al.*, 2022). The relationship of deprivation to air quality over the last two decades shows strong correlations throughout ($p > 0.1\%$) (Table 5), with the social gradient previously observed for the UK in 2001 and 2011 (Mitchell *et al.*, 2015) persisting for 2021 (Figure 1). NO$_2$ and PM$_{2.5}$ concentrations are higher where deprivation is higher. For ozone, the reverse is true, with higher concentrations occurring in the least deprived deciles. This reflects that ozone concentrations are generally higher in rural areas, due to ozone formation reactions, with some of the rural-urban difference explained by lower rural concentrations of pollutants such as nitric oxide (NO) which can degrade ozone or inhibit its formation. Although air quality improved from 2001-21, the ratio of annual mean concentration in the least to most deprived deciles shows that the rate of improvement was slower for more deprived populations, particularly with respect to NO$_2$.

Figure 1. Distribution of air quality in England by deprivation.

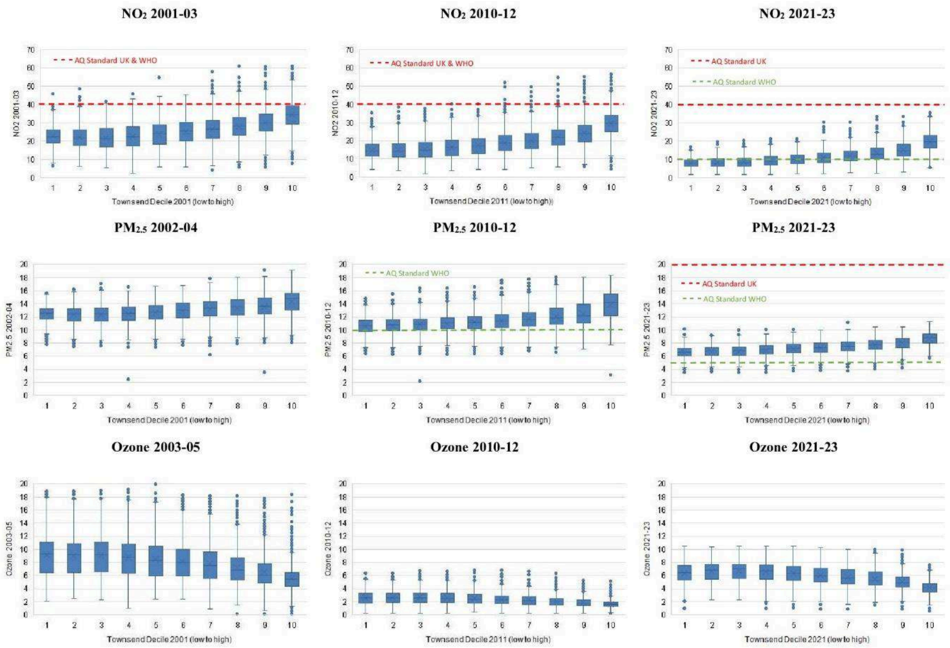
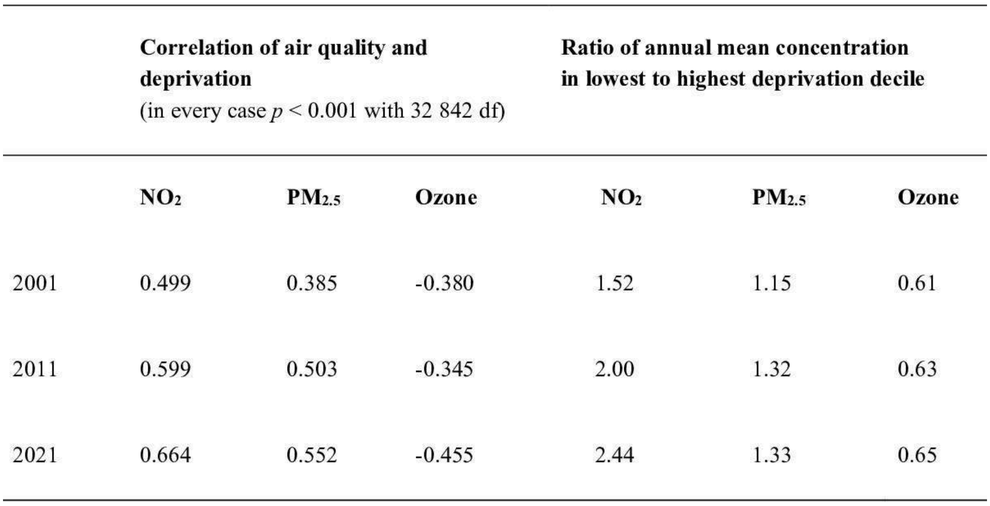


Table 5. Associations of air quality with Townsend social deprivation in England.

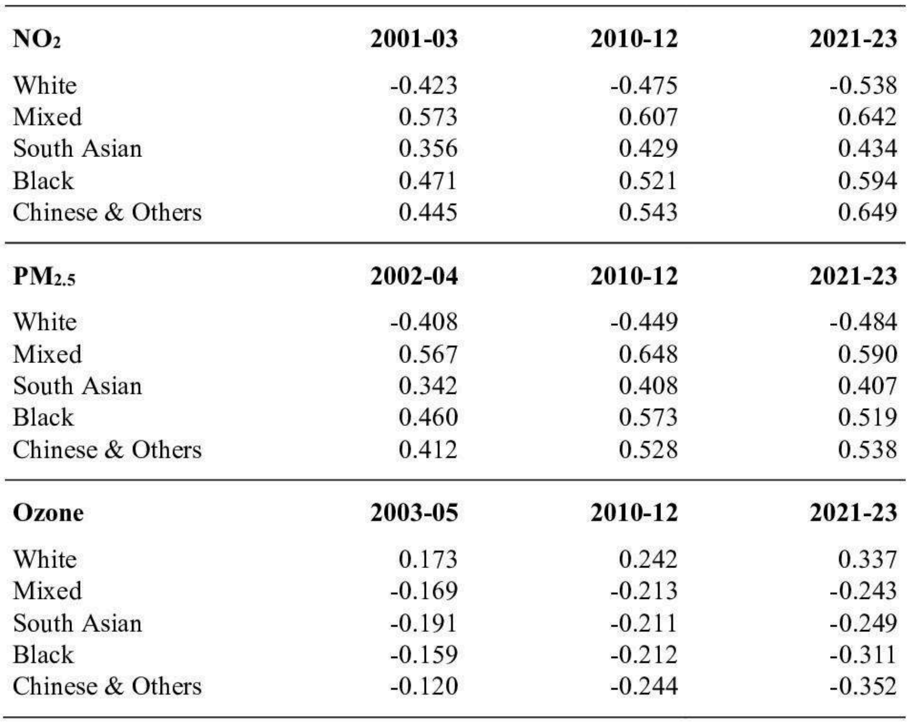


	Correlation of air quality and deprivation (in every case $p < 0.001$ with 32 842 df)			**Ratio of annual mean concentration in lowest to highest deprivation decile**		
	NO$_2$	**PM$_{2.5}$**	**Ozone**	**NO$_2$**	**PM$_{2.5}$**	**Ozone**
2001	0.499	0.385	-0.380	1.52	1.15	0.61
2011	0.599	0.503	-0.345	2.00	1.32	0.63
2021	0.664	0.552	-0.455	2.44	1.33	0.65

Air quality and ethnicity

14 Of particular relevance in EJ terms is the relationship between air quality and distributions of population by ethnic status. We found highly significant ($p > 0.001$) correlations between all three pollutants and all five ethnic groups (Table 6). For both NO$_2$ and PM$_{2.5}$ there are positive associations for all non-White groups, and negative associations with the White population, indicating that ethnic diversity was associated with higher pollution. For ozone, the reverse is the case, consistent with lower concentrations in urban areas which have a greater prevalence of more diverse populations.

Table 6. Correlations of Ethnic Group with air quality.



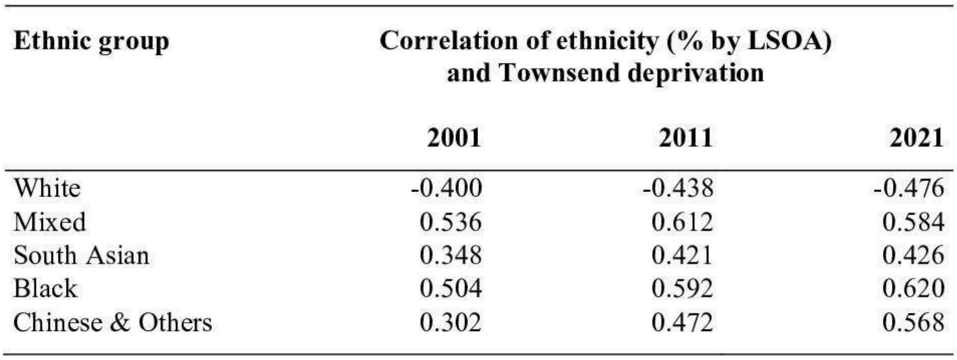
NO_2	2001-03	2010-12	2021-23
White	-0.423	-0.475	-0.538
Mixed	0.573	0.607	0.642
South Asian	0.356	0.429	0.434
Black	0.471	0.521	0.594
Chinese & Others	0.445	0.543	0.649
$PM_{2.5}$	**2002-04**	**2010-12**	**2021-23**
White	-0.408	-0.449	-0.484
Mixed	0.567	0.648	0.590
South Asian	0.342	0.408	0.407
Black	0.460	0.573	0.519
Chinese & Others	0.412	0.528	0.538
Ozone	**2003-05**	**2010-12**	**2021-23**
White	0.173	0.242	0.337
Mixed	-0.169	-0.213	-0.243
South Asian	-0.191	-0.211	-0.249
Black	-0.159	-0.212	-0.311
Chinese & Others	-0.120	-0.244	-0.352

$p < 0.001$ for all correlations

Intersectional (multiple disadvantage) analysis

There is a strong likelihood that ethnic minority groups live in more deprived neighbourhoods in England (Jivraj and Khan, 2015). We found that deprivation and ethnicity are highly correlated, with the strength of association increasing 2001-21 (Table 7). Over this period the White population fell from 91.3 to 81.7% of the national population, whilst other ethnic groups grew absolutely and approximately doubled (or more) their relative share. The non-White population grew most quickly in areas of higher social deprivation, which tend to be more urban and with greater concentrations of NO_2 and $PM_{2.5}$. The analyses above do not, however, convey the potential multiple disadvantage in air quality terms, of area deprivation and ethnicity in combination. Understanding this combined effect is important in terms of geographically targeting interventions that are intended to reduce health inequality arising from air pollution exposure.

Table 7. Correlation of Townsend and ethnicity by LSOA, England.



Ethnic group	Correlation of ethnicity (% by LSOA) and Townsend deprivation		
	2001	2011	2021
White	-0.400	-0.438	-0.476
Mixed	0.536	0.612	0.584
South Asian	0.348	0.421	0.426
Black	0.504	0.592	0.620
Chinese & Others	0.302	0.472	0.568

p < 0.001 for all correlations. There are 33,755 LSOAs in England

16 Figure 2 shows Lorenz curves constructed by counting the ethnic population in air quality deciles with further within decile sorting on deprivation (X-axis) with the cumulative ethnic population plotted on the Y-axis. As such, these cumulative population plots illustrate the extent to which pollution concentrates by deprivation and ethnic group. Most notable is the deprived Black population, which is relatively scarce in low NO_2 and $PM_{2.5}$ areas, and most strongly represented in high pollution areas, giving rise to the deepest curves, furthest from the equity line. Conversely, the White population has a close fit to the equity line, indicating that NO_2 and $PM_{2.5}$ is evenly distributed by deprivation status for this group, with the other ethnic groups taking intermediate positions. Ozone curves are above the equity line, indicating that the higher ozone concentrations are more prevalent at lower levels of deprivation (consistent with ozone concentrations being higher outside of urban areas, where rates of social deprivation tend to be lower).

Figure 2. Lorenz curves of ethnic groups by deprivation and air quality.

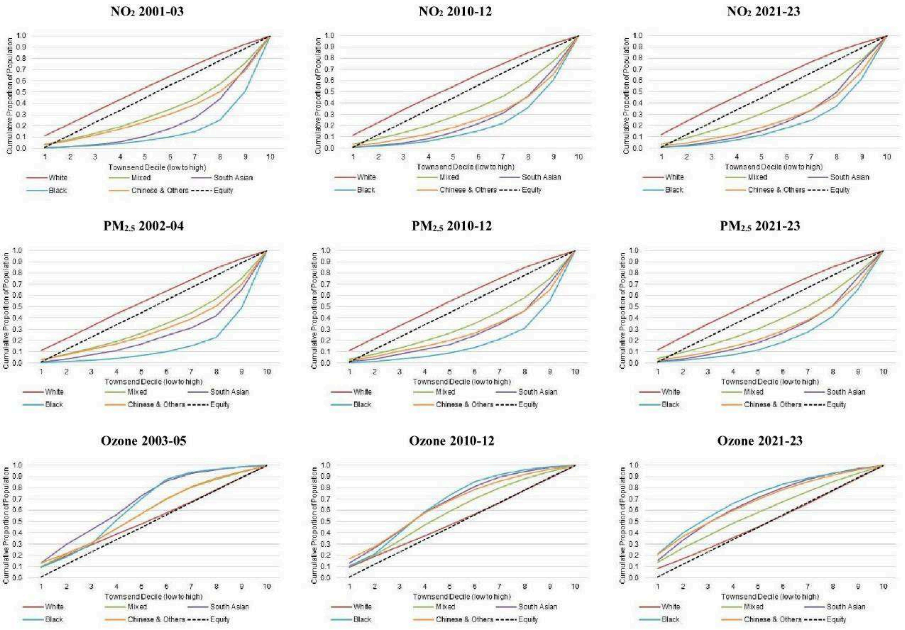
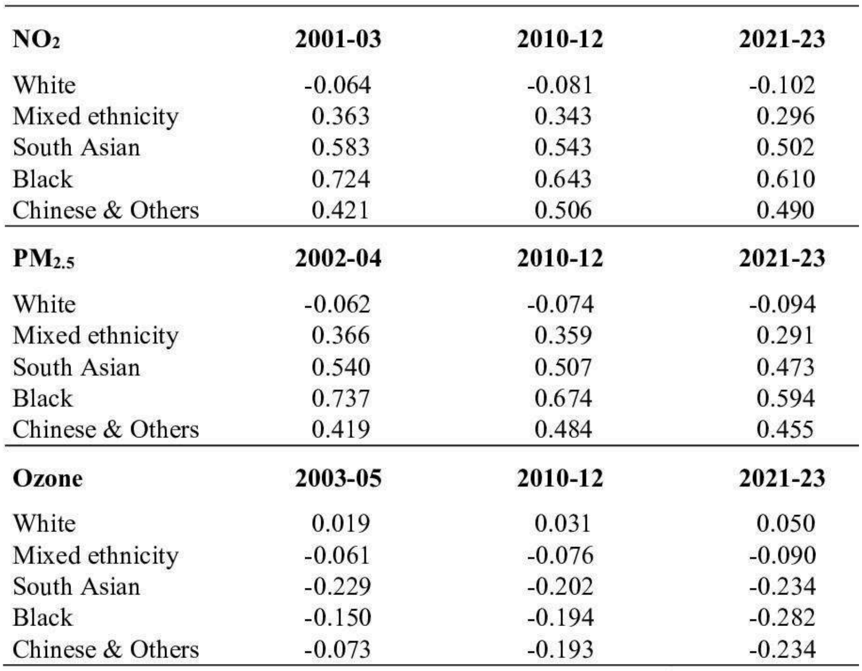


Table 8. Gini coefficients of Air Quality-deprivation by Ethnic Group.



NO_2	2001-03	2010-12	2021-23
White	-0.064	-0.081	-0.102
Mixed ethnicity	0.363	0.343	0.296
South Asian	0.583	0.543	0.502
Black	0.724	0.643	0.610
Chinese & Others	0.421	0.506	0.490
$PM_{2.5}$	**2002-04**	**2010-12**	**2021-23**
White	-0.062	-0.074	-0.094
Mixed ethnicity	0.366	0.359	0.291
South Asian	0.540	0.507	0.473
Black	0.737	0.674	0.594
Chinese & Others	0.419	0.484	0.455
Ozone	**2003-05**	**2010-12**	**2021-23**
White	0.019	0.031	0.050
Mixed ethnicity	-0.061	-0.076	-0.090
South Asian	-0.229	-0.202	-0.234
Black	-0.150	-0.194	-0.282
Chinese & Others	-0.073	-0.193	-0.234

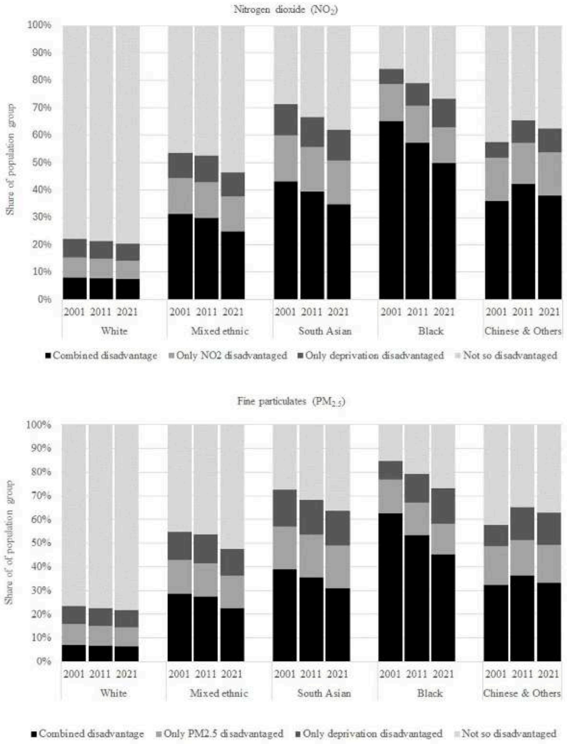
Note: 0 is perfect equality, 1 is absolute inequality. Gini coefficients are calculated from ethnic population count by air quality decile, with further within decile sorting by deprivation.

17 Gini coefficients (Table 8) summarise inequality in these distributions, and how inequalities changed over time. For the Black, South Asian and Mixed ethnic group, pollution-deprivation inequality declined. Over the time frame of this study, this is likely the result of counter-urbanisation of ethnic groups away from the traditional urban centres of immigration noted by Rees *et al.* (2011) for the first decade of the century, which continues in the next as a “clear diffusion of ethnic diversity beyond city boundaries” (Catney *et al.*, 2023, p. 70) where NO_2 and $PM_{2.5}$ concentrations are lower. This effect was not observed for the Chinese & Others group, and we speculate that this may be due to urban concentration of a growing population of Chinese international students in cities with large universities, plus the 150,000 arrivals from Hong Kong since 2021 on a British National Overseas visa. This group also experience the greatest change in social distribution of ozone over time, although from a relatively equitable position. During the 20-year period, the proportion of each ethnic group in urban areas falls, except for the Chinese & Others group. Against a backdrop of a 12% rise in total urban population between 2001 and 2021, the Mixed, South Asian and Black groups double in size while the Chinese & Others group increases by over 270%. All non-White groups increase in size in rural areas, but here the Chinese & Others grow less than the other groups.

18 Figure 3 extends this intersectional analysis through a multiple disadvantage analysis, where disadvantage is defined as being in the top 20% of LSOAs according to pollutant concentration or social deprivation, or both for a combined analysis. Data are presented by ethnic group and year. These quintile plots are similar for NO_2 and $PM_{2.5}$.

For both, 76-80% of the White population experience neither deprivation or air quality disadvantage, with c. 7% experiencing disadvantage on one metric, and just 7-8% experiencing high deprivation and pollution in combination. In contrast, the Black population has much higher rates of combined disadvantage (45-65% of population depending upon pollutant and year), with the remaining ethnic groups having intermediate positions. With the exception of the Chinese & Others group, the extent of combined disadvantage fell 2001-2021, likely reflecting some dispersal of non-White populations away from urban centres, but combined disadvantage remained highly concentrated in non-White populations.

Figure 3. Ethnic group disadvantage by deprivation, air quality and in combination.



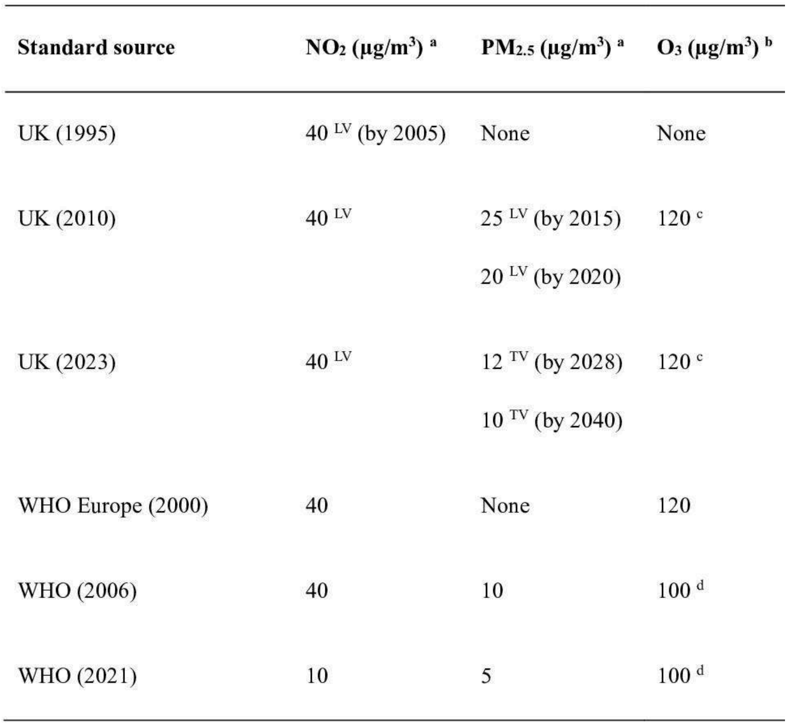
Note: Disadvantage is defined as most deprived or most polluted quantile of LSOAs.

Air quality exceedance analysis

19 Finally, we consider the social distribution of air pollution with respect to populations resident in areas that do not meet air quality standards. Exceedance analysis is important in air quality EJ studies for several reasons. First, a standard provides an agreed benchmark against which analyses can be compared over space and time. Second, standards set with reference to health impact are relevant to understanding inequalities in health. Third, statutory limit values are enshrined in law and are an expression of the social contract between citizen and state, whereby the citizen gives up certain rights and freedoms (e.g. to keep all their income) in return for protection from harm by the state, regardless of their social characteristics. Statutory standards thus provide the most unequivocal interpretation of when an unequal air pollution distribution becomes unjust.

20 In our prior analysis (Mitchell *et al.*, 2015) we found that whilst air quality had improved in Britain 2001-2011, the most deprived areas bore a disproportionate and rising share of declining air quality and of non-compliance with UK air quality standards (EU statutory limit values). Figure 1 includes air quality standards pertaining at the time and graphically illustrates how inequality in exceedance changed as social gradients in air pollution altered. A gradient means that the most deprived locations continued to bear the greatest burden of non-compliant air quality. Such analysis should encourage air pollution management that recognises social context (e.g. more intensive mitigation in ‘pollution-poverty hot spots’). However, it also illustrates how interpretation of inequality is sensitive to choice of benchmark (air quality standard). Application of WHO standards reveal very strong inequality in exceedance persists for 2021 (NO_2, $PM_{2.5}$) where no such inequality is observed when EU limit values are applied. WHO guideline standards are set only with reference to health impacts that can be confidently predicted and are much tighter than statutory limits which are politically determined according to health impact, plus feasibility and cost-benefit of attainment. Recognition of health impact means that over time, statutory limit values tend to converge on WHO guideline values (Table 9).

Table 9. UK (statutory) and WHO (guideline) air quality standards over study period.



Standard source	NO_2 (µg/m^3) ^{a}	$PM_{2.5}$ (µg/m^3) ^{a}	O_3 (µg/m^3) ^{b}
UK (1995)	40 ^{LV} (by 2005)	None	None
UK (2010)	40 ^{LV}	25 ^{LV} (by 2015) 20 ^{LV} (by 2020)	120 ^{c}
UK (2023)	40 ^{LV}	12 ^{TV} (by 2028) 10 ^{TV} (by 2040)	120 ^{c}
WHO Europe (2000)	40	None	120
WHO (2006)	40	10	100 ^{d}
WHO (2021)	10	5	100 ^{d}

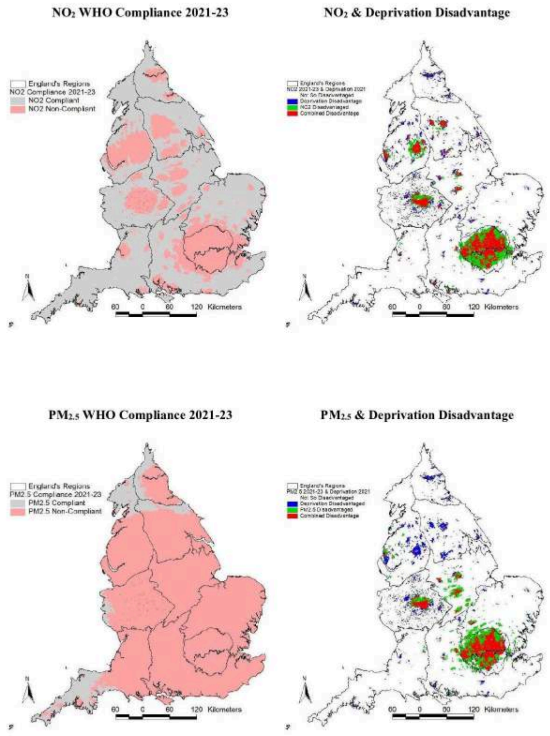
a. As an annual average; b. As a maximum 8-hr running mean per day c. Not to be exceeded >25 days a year, averaged over 3 years; d 99th percentile (3-4 exceedance days per year); LV is legally required limit value, TV is target value; WHO standards are guidelines.

21 Figure 1 illustrates with respect to deprivation the strong social gradients in non-compliance with WHO NO_2 and $PM_{2.5}$ guide values (there are insufficient exceedances of the O_3 guideline to merit consideration). Inequality in non-compliance changed over time as pollution concentrations and standards changed. By 2021 deprivation gradients

in non-compliance were similar to those for air pollution as a whole, because the WHO standards are at or well below observed mean concentrations.

22 Figure 4 uses cartograms to map and compare non-compliance with the WHO standards with combined deprivation ('pollution-poverty hotspots'). For $PM_{2.5}$ there is near universal non-compliance across England, but for NO_2, where compliance levels are higher, there is an obvious spatial divide, with urban areas, particularly London, port cities of the south, and cities of the midlands and the north, identifiable as areas of air quality that does not meet the WHO guideline. Should levels of compliance for $PM_{2.5}$ improve in future, we anticipate a broadly comparable pattern emerging but note this pattern may display regional differences to NO_2, given the prevalence of transboundary and secondary sources of $PM_{2.5}$ in the south and east of England (Lewis *et al.*, 2025). Rural-urban differences are also evident in the disadvantage analysis. For both NO_2 and $PM_{2.5}$, there are no rural areas which experience dual disadvantage (upper quantiles for deprivation and pollution). For NO_2 in urban areas, 14% of LSOAs experience dual disadvantage (and 18% either NO_2 or deprivation disadvantage). For $PM_{2.5}$ in urban areas 13% of LSOAs experience dual disadvantage (and 21% either $PM_{2.5}$ or deprivation disadvantage).

Figure 4. Cartograms of LSOA compliance with 2021 WHO air quality guide and multiple disadvantage.

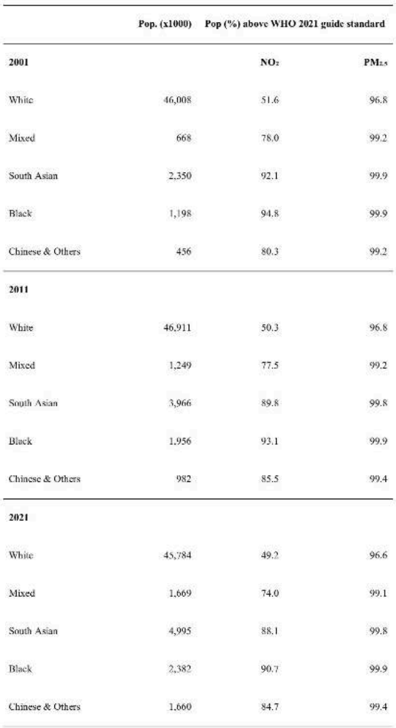


Note: The cartograms are based on the square root of each LSOA's area. This scales the size of urban and rural areas up and down respectively (See Norman *et al.*, 2024).

23 Changing ethnic distributions of air quality relative to 2021 WHO guideline values are shown in Table 10. It is important to note that in retrospectively applying these standards to prior years, we can consistently assess changing social distributions of air quality with potential health impact, but that understanding of health impact was

uncertain in prior years, as reflected in the less demanding WHO standards. These data reveal that non-compliance with the WHO NO_2 standard was strongly mediated by ethnicity, with greatest exposure in the Black population, least amongst Whites, with other groups taking intermediate positions. For $PM_{2.5}$ the same ordering occurs, but differences here were minor, as there is near saturation non-compliance. The rate of non-compliance fell over time for all groups except the Chinese & Others group – this is the smallest ethnic group but had the greatest growth, which as noted above, we speculate is focused in major urban areas where air quality is poorest. Overall, these data reveal potential for major health impact from exposure to NO_2 and $PM_{2.5}$, that health impacts will be highest in deprived and non-White groups, and that given the multiple disadvantage analysis above, health impact will be particularly prevalent in LSOAs with relatively large, socially deprived, Black populations.

Table 10. Ethnic distribution of non-compliance with WHO guideline standards, England.



	Pop. (x1000)	Pop (%) above WHO 2021 guide standard	
2001		NO_2	$PM_{2.5}$
White	46,008	51.6	96.8
Mixed	668	78.0	99.2
South Asian	2,350	92.1	99.9
Black	1,198	94.8	99.9
Chinese & Others	456	80.3	99.2
2011			
White	46,911	50.3	96.8
Mixed	1,249	77.5	99.2
South Asian	3,966	89.8	99.8
Black	1,956	93.1	99.9
Chinese & Others	982	85.5	99.4
2021			
White	45,784	49.2	96.6
Mixed	1,669	74.0	99.1
South Asian	4,995	88.1	99.8
Black	2,382	90.7	99.9
Chinese & Others	1,660	84.7	99.4

Conclusion

24 The social gradients in air pollution we previously identified for the UK (Mitchell and Dorling 2003; Mitchell *et al*., 2015) are seen here to have persisted for a further decade. The social gradients became less steep as air quality (NO_2, $PM_{2.5}$) improved, but more deprived areas continued to bear a higher burden of air pollution, and the slowest rates of air quality improvement. Our analysis of ozone reveals the reverse picture, with lower ambient concentrations at higher deprivation. This arises due to ozone formation chemistry that produces higher concentrations in rural areas, which typically have lower levels of deprivation than urban centres. Ozone concentrations are not yet at a level that pose a major health concern, but urban concentrations are increasing

towards those found in rural areas as concentration of scavenging NO_X species fall, hence the reverse social gradient in ozone is becoming much less pronounced, a trend that is likely to continue in future (Defra, 2025).

25 We also found strong ethnic gradients for all pollutants. As NO_2 and $PM_{2.5}$ increase, the non-White population share increases, and the White population declines. The reverse is true for ozone, which does not (yet) present the same health concerns. Our intersectional analysis (Gini coefficients, quantiles of combined disadvantage) extends the ethnic analysis and revealed very strong differences in combined deprivation/pollution experienced by different ethnic groups. Less than 8% of the White population experience combined disadvantage (high deprivation and high pollution) in any year, compared to up to 65% for the Black population, with the other ethnic groups had intermediate positions. The combined disadvantage occurs most strongly in London, port cities of the south and cities of the Midlands and northern England (observed for NO_2 in Figure 4). Except for the Chinese & Others group, the extent of this multiple disadvantage declined over the last two decades, an effect which is likely the result of counter-urbanisation of ethnic groups away from the traditional urban centres of immigration. However, these declines are modest, with all groups experiencing similar rates of decline, suggesting that these ethnic differences will persist.

26 This multiple disadvantage has real implications for public health, as highlighted by the case of nine year old Ella Adoo-Kissi-Debrah. Ella, who lived close to the busy South Circular Road in London, died of an asthma attack in 2013, and was the first person in the UK to have air pollution formally listed as a cause of death (BBC, 2020; Ella Roberta Foundation, no date; UK Parliament, 2025). Her multiple disadvantages included the high levels of air pollution that exceeded WHO and EU standards, her family's income (her mother explained that they could not afford to move away from their location), her age (making her dependent), and her ethnic status. As a Black person, Ella's genetics likely made her more susceptible to respiratory disease (Forno and Celedón, 2009; Hernandez-Pacheco *et al.*, 2016), whilst more systemically, racism is implicated in UK socio-economic inequality via more restricted pathways to quality education, housing and employment (Stopforth *et al.*, 2022; Marmot *et al.*, 2024). We observe that the pollution, deprivation and ethnicity profile of LSOAs within a 15 minutes' walk of Ella's home is similar to that of the wider borough (Lewisham), hence we can infer others are similarly at risk. This suggests a need for local air quality management that is more sensitive to social vulnerability (e.g. pollution-poverty-ethnicity hotspots) if health inequalities are to be reduced.

27 Finally, our analysis of air quality standard exceedance reveals the need for care in interpreting inequality when relying only on cross-sectional EJ analysis. Social gradients in air quality clearly persist as pollution declines, so over time (Figure 1) we can move from a situation of relative equality (high pollution – widespread exceedances), to high inequality (moderate pollution – some exceedances) back to relative equality (low pollution – no exceedances). A standards exceedance analysis is clearly valuable in understanding studies collectively, as it provides a benchmark allowing comparison over time and space. However, this dynamic effect should be recognised when evaluating equity and environmental improvement together. When deciding if social distributions of air quality are unfair, statutory standards provide a 'gold standard' benchmark, as they are rooted in the social contract and designed to provide equal protection for all. However, where reducing health inequality is the

primary concern, the WHO guide standards are more appropriate, as these are set only with reference to health impact, and not the cost-benefit and feasibility criteria that are also material in setting statutory standards. Application of the WHO standards to current air quality in England infers that health impacts can be expected across all social groups, and that inequality will increase as air quality improves, unless air quality management adopts a more socially focussed approach.

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ABSTRACTS

The changing social distribution of air pollution over 20 years is examined for England, using a range of descriptive statistical techniques, applied to fine scale pollution and population data. Levels of NO_2 and $PM_{2.5}$ are much higher where social deprivation and non-White population share are high, with the opposite for ozone, due to its chemical formation processes. Using Gini and quantile analyses, we find poor air quality is most common where high deprivation and above average non-White population share occur together. In 2001, 62.7% of the Black ethnic group were in the top quantiles for deprivation and $PM_{2.5}$ concentration (and 38.8% for S. Asian, 32.5% Chinese/Others, 28.6% Mixed ethnic), compared to 7.1% of the White population. Similar differences occur for NO_2. These combined disadvantage gradients ameliorate slightly by 2021 as ethnic populations diffuse away from urban centres. We discuss how statutory and guideline air quality standards are material in judging when unequal is unjust and show how exceedance analyses can reveal, under continual air quality improvement, a pattern of rising then falling inequality. Analysis against WHO health based standards shows widespread non-compliance (near saturation for $PM_{2.5}$) with exceedances expected to persist longest in the combined disadvantage areas. Reducing health inequality from air pollution could be accelerated by focussing mitigation on “pollution-poverty-ethnicity hotspots”.

L’évolution de la répartition sociale de la pollution atmosphérique en Angleterre sur une période de 20 ans a été étudiée à l’aide de diverses techniques statistiques descriptives, appliquées à des données démographiques et de pollution à fine échelle. Les analyses de Gini et de quantiles révèlent que les niveaux de NO_2 et de $PM_{2,5}$ sont nettement plus élevés là où la précarité sociale et la proportion de population non blanche sont importantes, contrairement à l’ozone, en raison de ses processus de formation chimique. En 2001, 62,7 % des personnes noires se situaient dans les quantiles supérieurs de précarité et de concentration de $PM_{2,5}$ (contre 38,8 % pour les personnes d’origine sud-asiatique, 32,5 % pour les personnes d’origine chinoise ou autres et 28,6 % pour les personnes d’origine mixte), contre seulement 7,1 % pour la population blanche. Des différences similaires sont observées pour le NO_2. Ces inégalités sociales combinées s’atténuent légèrement d’ici 2021, à mesure que les populations ethniques s’éloignent des centres urbains. Nous examinons en quoi les normes réglementaires et les recommandations relatives à la qualité de l’air sont essentielles pour déterminer si une inégalité est injuste et montrons comment les analyses de dépassement peuvent révéler, malgré l’amélioration continue de la qualité de l’air, une évolution des inégalités, passant d’une hausse à une baisse. L’analyse par rapport aux normes sanitaires de l’OMS montre un non-respect généralisé (proche de la saturation pour les $PM_{2,5}$), les dépassements devant persister le plus longtemps dans les zones les plus défavorisées. La réduction des inégalités de santé liées à la pollution atmosphérique pourrait être accélérée en concentrant les efforts d’atténuation sur les zones critiques où la pollution, la pauvreté et l’appartenance ethnique sont prépondérantes.

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Mots-clés: inégalités environnementales, défavorisation sociale, appartenance ethnique, pollution de l’air, longitudinal, norme de qualité de l’air, Angleterre
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