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Greenspace and Air Pollution Disparities in Urban Northern England

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Greenspace and Air Pollution Disparities in Urban Northern England

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Abstract

Urban environmental inequalities remain a critical public health concern in the UK, particularly in regions with legacies of industrial development. This study examines the spatial distribution of air pollution (NO_2) and greenspace exposure across ten cities in Northern England, focusing on urban neighborhoods. Using Lower-layer Super Output Areas (LSOAs) and data from the Access to Healthy Assets & Hazards and Index of Multiple Deprivation, we compare environmental burdens across two city types: large, industrial-era conurbations (Major cities) and smaller cities more influence by rural-to-urban transition (Regional cities).

Our results show that in urban areas of Major cities, deprived and ethnically diverse communities face significantly higher NO_2 concentrations and lower NDVI, a measure of greenspace density and health, despite physical proximity to green areas. In the most deprived LSOAs, NO_2 levels are 33% higher than in the least deprived, more than twice the national average disparity. While greenspace accessibility is often greater in deprived areas, these spaces are frequently located near major roads or pollution hotspots, limiting their health benefits. About 83% of the most vegetated urban areas in Major cities still exceed WHO NO_2 guidelines, highlighting the limited capacity of greenspace alone to mitigate pollution in dense, traffic-dominated environments. In contrast, urban areas in Regional cities show lower pollution and more consistent greenspace provision, with fewer social disparities.

These findings highlight the need for targeted, locally informed strategies that combine green infrastructure with robust emissions reduction, particularly in cities with dense industrial legacies. As the UK seeks to deliver on the goals of its Clean Air Strategy and 25-Year Environment Plan, understanding how environmental burdens are associated with social inequality and urban form at the local level will be essential for designing fairer, healthier cities and meeting broader Agenda 2030 commitments.

Keywords: Environmental inequality; Urban air pollution; Greenspace exposure; Socioeconomic disparities; Northern England

1. Introduction

Urban areas face multiple environmental pressures that contribute to health inequalities, with air pollution and limited access to greenspace among the most pressing issues. In the UK, nitrogen dioxide (NO_2), a traffic-related pollutant, remains a key urban air quality concern, particularly for vulnerable populations (DEFRA, 2025a). Both short-term exposure, which can exacerbate asthma and other respiratory conditions, and long-term exposure, linked to cardiovascular and respiratory diseases and increased mortality, pose serious public health risks (COMEAP, 2018).

With over 80 % of the UK population living in urban areas (DEFRA, 2025b), recent studies have highlighted persistent social and spatial inequalities in air pollution exposure, with disproportionately high concentrations found in more deprived and racially diverse communities (e.g., Fecht et al, 2015; Fairburn et al, 2023; Gray et al., 2025). However, significant gaps remain in our understanding of local-scale air pollution disparities, particularly regarding their spatial overlap with deprivation, ethnicity, and urban form, and there is a growing need for fine-scale spatial tools to guide targeted, equitable interventions (DEFRA, 2025c).

Greenspaces provide a range of co-benefits that can mitigate some of these environmental risks. Vegetation helps reduce air pollution through deposition and dispersion processes (e.g., Pugh et al., 2012; Hewitt et al., 2019), and regular access to green areas is linked to improved mental and physical health, reduced stress, and lower mortality (e.g., Maas et al., 2006; Kondo et al., 2018; Kuman et al., 2019). However, greenspace access and quality are also unequally distributed. In England, deprived urban areas often have less vegetative cover and fewer safe or usable green areas (e.g., Mears et al., 2019, 2020; Garkov et al., 2024).

Vegetation indices, such as the Normalized Difference Vegetation Index (NDVI), are widely used in environmental health research as indicators of greenness or vegetative density, but they do not capture the broader concept of greenspace quality. Quality is a multidimensional concept that can include factors such as park safety, maintenance, amenities, biodiversity, aesthetic value, and perceived social usability (e.g., Brindley et al., 2019; Mears et al., 2020; Koohsari et al., 2023). As such, NDVI reflects only one aspect—vegetative coverage—and cannot be treated as a comprehensive measure of greenspace quality. Alternative approaches, including field audits or user-perceived quality assessments, have been used, but these remain difficult to standardize across large-scale studies (Koohsari et al., 2023). Despite these measurement challenges, access to high-quality greenspace remains a central goal of environmental and health policy in the UK and beyond.

In the UK, for example, the Environmental Improvement Plan 2023 includes a policy commitment to ensure everyone in England lives within a 15-minute walk of high-quality green or blue space, recognizing this as critical infrastructure for health, social equity, and environmental resilience (Office of Environmental Protection, 2025). However, national-level mapping shows over one-third of local authorities still have more than 70% of their population lacking such access, with more than one in ten neighborhoods having 90% or more of households with no green space within a 15-minute walking distance (Wildlife and Countryside Link, 2025).

However, proximity alone does not guarantee benefit. For example, higher vegetation density often coincides with lower air pollution, but features like urban street canyons, legacy park sitting near industrial corridors, or vegetation structure can trap pollutants, complicating assumptions that proximity to greenspaces ensures cleaner air (e.g., Abhijith et al., 2017; Venter et al., 2024). Additionally, in deprived areas, greenspaces are often smaller and of lower quality, with poor maintenance, lower biodiversity, and inadequate safety, therefore undermining potential health gains (e.g., Jones et al., 2009; Gidlow & Ellis, 2011; Mears et al., 2019).

Although individual studies have explored either air pollution or greenspace inequalities, few have examined how these environmental exposures co-vary across different urban contexts. For example, Garkov et al. (2024) assessed environmental exposures across England, examining over 1.2 million residential postcodes. Their study found that more deprived and urbanized areas tend to experience higher levels of NO_2 and fine particulate matter ($PM_{2.5}$) and lower levels of greenspace, showing a socioeconomic gradient in environmental risk. Their results also confirmed an inverse association between greenness and air pollution in urban settings. However, their cross-sectional design focused on urban-rural disparities, not intra-urban or city-level scale variations. Moreover, less is known about how these disparities are associated with sociodemographic characteristics, such as ethnicity, across cities with distinct urban forms.

This study fills these gaps by investigating NO_2 exposure alongside greenspace NDVI (as measured of vegetation density and health, often used as proxy to reflect aspects of greenspace "quality") as well as greenspace accessibility and sociodemographic inequality across ten Northern England cities. We examine how NO_2 and greenspace metrics are associated with relative deprivation and ethnic composition using Access to Healthy Assets & Hazards (AHAH) and Index of Multiple Deprivation (IMD) spatial indicators at a small local area level (i.e., Lower-layer Super Output Areas, LSOA). By comparing major and regional urban settings, based on size, development history, and urban structure, our aim is to determine whether environmental inequalities are more acute in cities shaped by industrial growth than in those with more mixed or rural-urban development. We also examine how these disparities correlate with socio-demographic factors, and how our findings can inform local and regional efforts to design more equitable and health-promoting green infrastructure through urban planning and environmental policy.

2. Methodology

2.1 Study region and selection of cities

Our analysis focused on cities located in Northern England, selected to represent a spectrum of urbanization contexts using the DEFRA 2021 Census Rural Urban Classification (DEFRA, 2021) (**Fig. 1**). Within this classification, five cities—Liverpool, Leeds, Manchester, and Newcastle—are classified as Urban with Major Conurbation, and Sheffield as Urban with Minor Conurbation. Lincoln is classified as Urban with City and Town, while Chester, Scarborough, and Carlisle are classified as Urban with Significant Rural. Finally, Durham is labeled Largely Rural, although it includes an urban population exceeding 200,000.

For the purpose of the analysis, we grouped these into two categories: Major Cities (major and minor conurbations) and Regional cities (all other classifications). This division was based on differences in urban development history and structure. Major cities (Liverpool, Leeds, Manchester, Newcastle and Sheffield) are large conurbations influenced by industrial growth. In contrast, Regional cities (Lincoln, Chester, Scarborough, Carlisle, and Durham) are smaller and have evolved through more gradual rural-to-urban transitions. **Table 1** summarizes the main characteristics of the cities used in the study.

Figure 1. Location of the 10 study cities in Northern England. Cities are grouped into major cities (Liverpool, Leeds, Manchester, Newcastle, and Sheffield) and regional cities (Lincoln, Chester, Scarborough, Carlisle, and Durham). Birmingham and London are included for geographic reference.

Table 1. Summary of the 10 study cities in Northern England, including the official DEFRA 2021 urban classification, the classification used in this study, population, and number of LSOAs. Mean and standard deviation (SD) values are reported for key variables, annual NO_2 (µg/m³), IMD score, greenspace NDVI, greenspace accessibility (distance to nearest greenspace in km), and percentage of non-White population, calculated across all urban LSOAs within each city.

City[a]	Study Urban Type	Total Popul. (Urban)	Total LSOAs (Urban)	NO_2 (µg/m³)	IMD Score	Greensp. NDVI	Greensp. Access. (km)	Non-White (%)
Leeds	Major	751,485 (694,878)	488 (456)	14.8±3.2	28.7±19.8	0.40±0.10	0.50±0.26	20.9±19.4
Sheffield	Major	552,698 (529,939)	343 (337)	11.4±2.3	27.1±19.2	0.42±0.10	0.48±0.23	19.4±18.6
Manchester	Major	503,127 (503,127)	295 (295)	16.4±1.9	36.1±18.1	0.40±0.12	0.47±0.25	36.0±20.7
Liverpool	Major	466,415 (466,415)	302 (302)	15.3±2.6	42.5±20.5	0.35 ± 0.11	0.57±0.31	13.3±11.4
Newcastle	Major	280,177 (274,444)	180 (173)	13.2±2.4	13.2± 2.4	0.39±0.09	0.53 ±0.32	17.6±15.4
Chester	Regional	329,608 (243,307)	222 (171)	9.6± 1.8	19.9±14.7	0.47±0.09	0.54±0.30	4.8 ±2.9
Durham	Regional	513,242 (200,674)	330 (190)	6.8±1.3	27.3±5.8	0.42±0.09	0.57±0.32	3.5± 3.9
Lincoln	Regional	93,541 (93,541)	60 (60)	9.5±1.1	26.7±16.6	0.63±0.34	0.63±0.34	6.5±3.8
Carlisle	Regional	107,524 (78,470)	71 (53)	5.6± 1.1	23.9±13.5	0.41±0.11	0.42±0.21	3.7±2.6
Scarborough	Regional	108,793 (61,749)	68 (47)	6.1±1.4	29.8±17.6	0.37±0.13	0.45±0.24	3.7±2.2

[a] DEFRA 2021 Urban Classification: Urban with Major Conurbation (Liverpool, Leeds, Manchester, and Newcastle); Urban with Minor Conurbation (Sheffield); Urban with City and Town (Lincoln); Urban with Significant Rural (rural including hub towns 26-49%) (Chester, Scarborough, and Carlisle); Largely Rural (rural including hub towns 50-79%) (Durham).

2.2 Spatial unit of analysis

The analysis was conducted at the level of LSOAs, that is, small statistical units defined by the Office for National Statistics (ONS) and used in England and Wales, that typically contain around 1,500 residents (ONS, 2024). LSOAs provide a robust spatial unit, as it offers a high-resolution view of intra-urban patterns while maintaining population sizes large enough to reduce statistical variability and avoid biases from very small areas. (Mears et al., 2020).

To focus the analysis on urban settings, we removed all LSOAs classified as rural under the 2021 Urban-Rural classification (ONS, 2021), which excluded about 10% of the total LSOAs. Rather than comparing entire cities, our analysis focused only on LSOAs defined as urban within each city, ensuring consistent spatial units with comparable built environments across different urban contexts (**Table 1**). In the final dataset, we analyzed a total of 2,154 urban LSOAs: 1,639 in Major cities and 515 in Regional cities.

2.3 Greenspace indicators

To capture complementary dimensions of greenspace exposure, we extracted two indicators from the AHAH database (Daras et al., 2019; Green and Berragan, 2024). Greenness was measure using the active greenspace indicator from AHAH version 4, which is based on average NDVI values within a 900 m buffer around each postcode for each LSOA (ah4gpas) (Green and Berragan, 2024). NDVI values were derived from Sentinel-2 satellite imagery using a cloud-free filter and a date range of April to September 2020, with data aggregated at a 10 m resolution. For each postcode, NDVI was calculated within a 160 mx160 m buffer and then averaged across all postcodes within the LSOA (Hyman et al., 2024). This satellite-derived metric reflects vegetation density and greenness in the local environment, but it does not account for broader greenspace quality dimensions as safety, maintenance, or design (Koohsari et al., 2023). We therefore acknowledge its use in prior studies as a proxy for greenspace 'quality' although here we refer to it as vegetation density and health or greenness.

Greenspace accessibility was evaluated using the distance to nearest greenspace variable from AHAH version 2 (ah2gact) (Daras et al., 2019). This measure reflects the shortest road network distance (in km) from each postcode centroid to the closest publicly accessible greenspace extracted from OpenStreetMap. The accessibility indicator includes only greenspaces classified as publicly accessible in OpenStreetMap, including a wide range of land types such as parks, nature reserves, commons, recreation grounds, and woodlands, among others. While some land types (e.g., golf courses) are typically private, they were included when public access—such as footpaths—was explicitly mapped. According to AHAH, this approach allows for a broader representation of spaces that may provide opportunities for passive or active use (Daras et al., 2019).

The AHAH v4 follows the 2021 LSOA classification, whereas AHAH v2 is based on the 2011 LSOA classification. We verified that all selected urban LSOAs had the same designation in the 2011 classification, so no LSOAs were excluded due to changes in designation (ONS, 2011).

Both indicators have been widely used in previous studies to assess greenspace exposure in relation to environmental and health inequalities (e.g., Mears et al., 2020; Garvok et al., 2024). These two variables capture distinct aspects of greenspace exposure: ah4gpas represents the vegetation density or greenness of nearby areas, while ah2gact reflects physical accessibility. That is, spaces classified as 'green' that are nearby may not be green per-se, and highly vegetated areas may not be easily reachable, particularly for socioeconomically disadvantaged populations.

2.4 Air pollution data

Air pollution exposure was assessed using annual average NO_2 concentrations (ah4no2) from the AHAH v4 database (Daras et al., 2019; Green and Berragan, 2024). These values were derived from DEFRA's modelled pollution surfaces at 1x1 km resolution, which combine data from monitoring stations with spatial estimates based on road traffic, industrial emissions, land use and meteorological conditions to produce ground-level NO_2 concentrations across the UK. For each LSOA, AHAH considers the mean value of all modelled grid cells overlapping its area, providing a representative exposure estimate at the neighborhood scale.

We focused on NO_2 as it is a key traffic-related air pollutant in urban environments and widely used as a proxy for specific urban emissions (e.g., DEFRA, 2025d). NO_2 exposure is also commonly used in environmental justice research to assess inequalities, with recent studies documenting disproportionately high concentrations in more deprived and racially diverse communities across the UK (Gray et al., 2025; DEFRA, 2025c).

The NO_2 data used in this study were from the year 2019, which may slightly overestimate current exposure levels, as national monitoring data show that NO_2 concentrations in the UK have declined over the past decade (DEFRA, 2025a), particularly in urban areas, due to stricter emission standards, cleaner vehicle technologies, and broader air quality policies. However, because our analysis compared urban areas, this limitation is unlikely to affect the interpretation of regional inequalities or within-city disparities.

2.4 Socioeconomic and Demographic Indicators

To assess socioeconomic inequality, we used the Index of Multiple Deprivation (IMD) 2019, a widely used composite measure of relative deprivation in England (MHCLG, 2019). IMD scores are calculated at the LSOA level and incorporate seven weighted domains: income, employment, education, health, crime, housing, and the living environment. Higher IMD scores indicate higher levels of deprivation. For the analysis, we used both the raw IMD score and the IMD decile, where decile 1 corresponds to the 10% most deprived areas nationally, and decile 10 to the least deprived. As with AHAH v2, the IMD 2019 is based on the 2011 LSOA classification. However, we confirmed that our selected IMD data aligned consistently.

To account for socio-demographic disparities, we calculated the ethnic composition of each LSOA using 2021 census data from the ONS (ONS, 2021). The census records ethnicity using 20 categories grouped, which are group by the ONS into five standard ethnic groups: White; Mixed or Multiple ethnic groups; Asian or Asian British; Black, Black British, Caribbean or African; and Other ethnic group. For this study, we recorded data into two broad categories: "white" (including all residents identified as White: English, Welsh, Scottish, Northern Irish or British, White: Irish, White: Gypsy or Irish Traveller, White: Roma, or White: Other White) and "non-white" (including all other ethnic categories). We then calculated the percentage of white and non-white residents for each LSOA.

2.5 Statistical analysis

We used descriptive statistics and non-parametric correlation analyses to assess spatial relationships between environmental and sociodemographic indicators. Specifically, we computed Spearman's rank correlation coefficients to evaluate monotonic associations between annual NO_2 concentrations, greenspace indicators (NDVI and greenspace accessibility), IMD scores, and percentage of non-White residents across urban LSOAs. To assess the significance of these relationships, we used two-tailed p-values with a threshold of $p<0.05$. We also used the Wilcoxon rank-sum test (two-tailed) to determine whether differences between the most and least deprived LSOAs were statistically significant. Non-parametric tests were selected because key variables (e.g., NO_2 and NDVI) exhibited non-normal, skewed distributions.

All analyses were conducted in Python 3.11 with the *scipy.stats* libraries. No multivariable regression or predictive modelling was employed, as the study's aim was to provide a descriptive, exploratory assessment of spatial disparities.

3. Results and Discussion

We examined spatial relationships between NO_2 concentrations, greenspace NDVI, greenspace accessibility, deprivation (IMD Score and IMD Decile), and ethnic composition (% White and % Non-White) across urban areas, distinguishing between Major and Regional cities. Detailed city-level correlations are presented in the Supplementary Materials (**Figs. S1–S5**) and average indicator values by city are summarized in **Table 1**. To illustrate these patterns, **Figure 2** shows the spatial distribution of annual NO_2 and NDVI at an LSOA level in Lincoln (Regional city) and Liverpool (Major city).

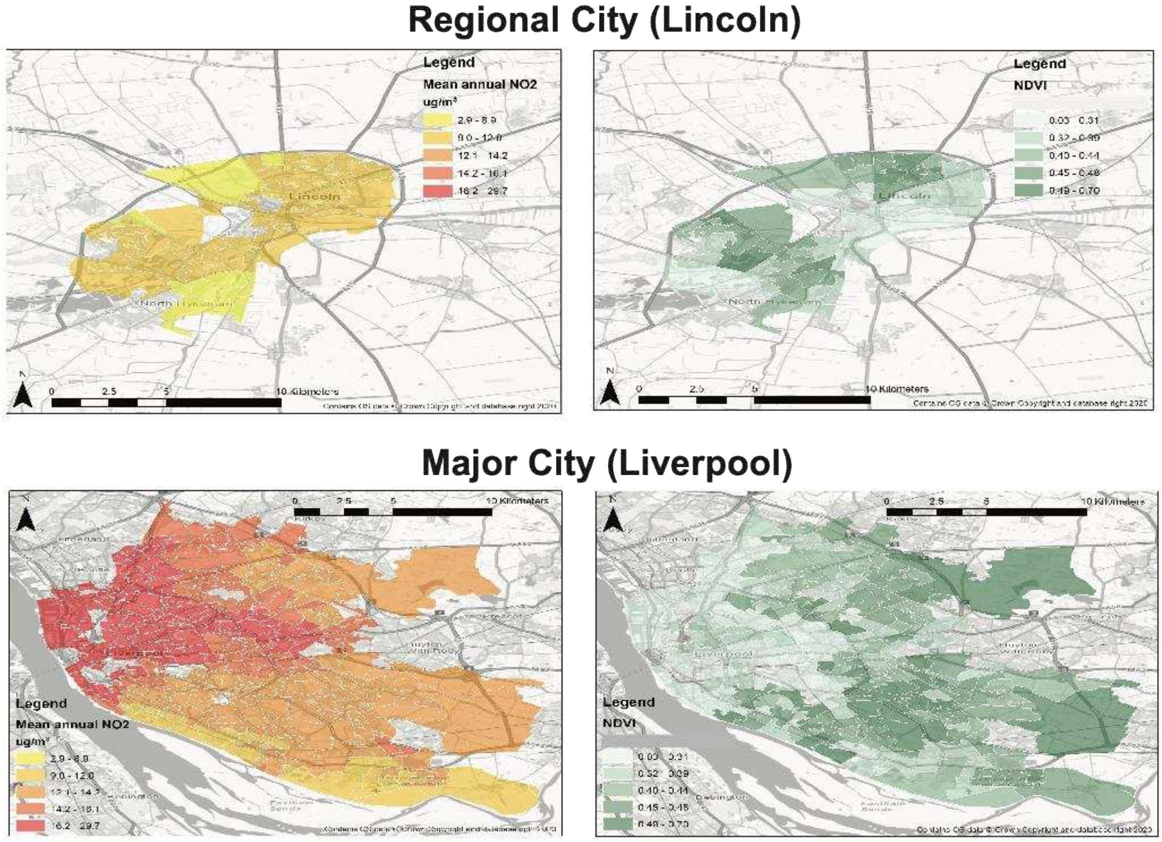

Figure 2. Annual NO_2 levels (μg/m^3) and greenspace NDVI across LSOAs identified as urban in Lincoln (Regional city) and Liverpool (Major city).

3.1 Inequality through NO_2, greenspace, and deprivation patterns

To explore the relationship between air pollution and greenness, we examined the distribution of NO_2 concentrations as a function of NDVI across all urban LSOAs in the selected cities (**Fig. 3**). Each data point is colored by IMD decile to highlight potential deprivation patterns.

In Major cities, urban LSOAs with lower NDVI values generally have higher NO_2 concentrations and tend to be among the most deprived deciles, reflecting the co-location of environmental and social disadvantages. These results are consistent with previous national-scale studies showing that wealthier urban neighborhoods are typically greener and less polluted, showing established spatial inequalities in both environmental quality and socio-economic status (e.g., Fench et al., 2015; Fairburn et al., 2019; Garkov et al., 2024).

In Regional cities, the number of LSOAs classified as urban was smaller (515 versus 1,639) although it still allowed to identify patterns. NDVI values are generally higher and more tightly clustered, indicating more consistent vegetation cover. NO_2 concentrations are also lower and less variable across LSOAs. Although the association between NDVI and NO_2 is weaker than in Major urban settings, there is still a noticeable deprivation gradient, that is, more deprived LSOAs tend to have lower NDVI values. However, this pattern is less pronounced than in Major cities.

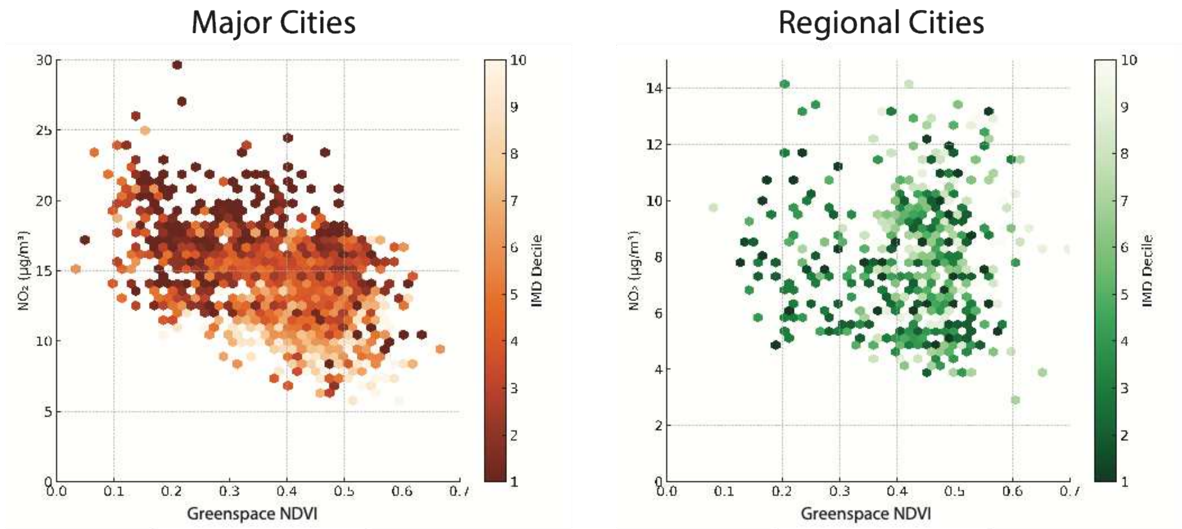

Figure 3. Relationship between annual NO_2 concentrations and greenspace NDVI across urban regions in Northern England, color-coded by IMD decile. Each hexagon represents one LSOA, with color indicating IMD decile (1 = most deprived, 10 = least deprived), for Major (orange) and Regional (green) urban areas.

We also examined how NO_2 concentrations varied with physical accessibility to greenspaces (**Fig. 4**). In Major cities, urban LSOAs closest to public greenspaces tend to show higher NO_2 concentrations and are generally more deprived. This pattern may reflect the spatial configuration of large parks and formal greenspaces in dense urban environments, where parks are often bordered by major roads and traffic corridors. As a result, greenspaces may be physically accessible but co-located with pollution hotspots, limiting their health benefits (Abhijith et al., 2017; Venter et al., 2024).

These patterns must also be considered in relation to the urban geography of Northern England. Many of the Major cities in this region, such as Manchester, Liverpool, Leeds, and Sheffield, originated or expanded rapidly during the Industrial Revolution and retain compact, high-density cores, major arterial roads, and historically segregated residential zones (Mears et al., 2020; Whitten, 2022). Public parks in these cities were often established during the Victorian era, strategically placed to serve working-class populations living in densely populated inner-city areas (Crompton, 2006). While these parks remain highly accessible today, they are frequently bordered by heavy traffic and high emissions. This urban legacy may help explain why, in more deprived LSOAs, proximity to greenspace does not coincide with lower air pollution levels, and why deprived areas in Northern England are more likely to experience co-exposure to poor air quality and environmentally compromised green infrastructure (Mears et al., 2020).

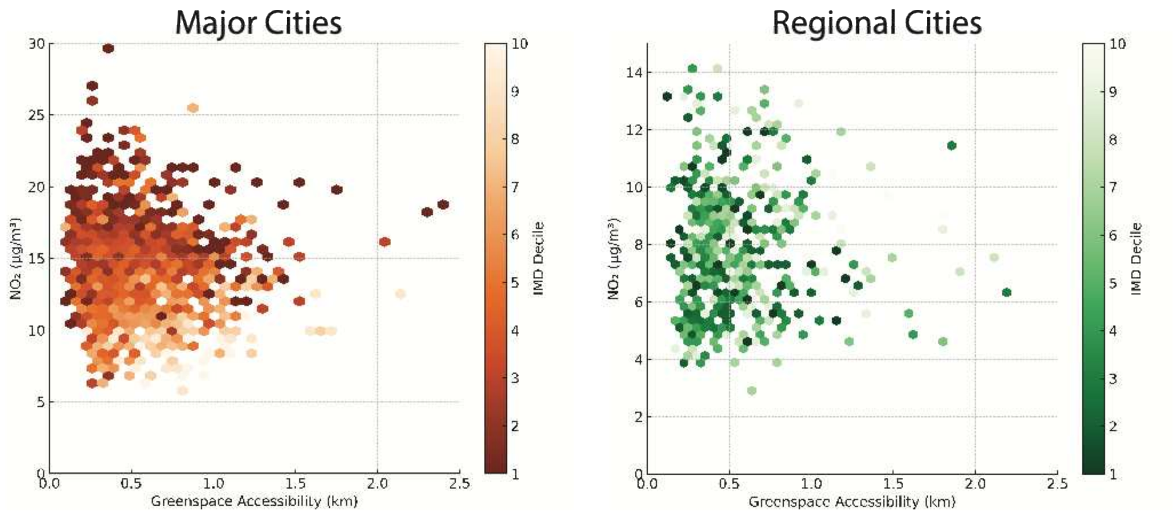

Figure 4. Relationship between annual NO_2 concentrations and greenspace accessibility across urban regions in Northern England, color-coded by IMD decile. Each hexagon represents one LSOA, with color indicating IMD decile (1 = most deprived, 10 = least deprived), for Major (orange) and Regional (green) Urban areas.

In contrast, Regional cities show a much narrower range of air pollution exposure, with NO_2 levels remaining consistently below 15 µg/m³ across all urban LSOAs. While 93% of these areas have access to greenspace within 1 km, similar to Major cities, there is no clear link between proximity to greenspace and NO_2 levels. IMD decile distributions are also flatter, suggesting weaker spatial alignment between deprivation, air pollution, and greenspace access. This likely reflects the less stratified urban form of smaller cities, where urban development may have been less influenced by the industrial-era spatial inequalities observed in larger conurbations.

City-level correlations (**Figs. S1–S3**) support these findings. In Major cities (Leeds, Sheffield, Manchester, Liverpool and Newcastle), NO_2 shows statistically significant correlations with both greenspace NDVI and deprivation, reinforcing the spatial overlap of environmental and social inequality. For example, in Leeds and Sheffield, NO_2 and NDVI are negatively correlated ($\rho=-0.45$ and -0.42, respectively; $p<0.05$), while NO_2 and IMD score are positively correlated ($\rho=0.56$ and 0.54, respectively; $p<0.05$), indicating that more polluted areas are both less green and more deprived. The negative association between NO_2 and greenspace accessibility, i.e., shorter distances in more polluted areas, is also evident, particularly in Newcastle ($\rho=-0.31$; $p<0.05$), highlighting the mismatch between physical proximity and environmental quality in dense urban cores.

In contrast, Regional cities (Chester, Durham, Lincoln, Carlisle and Scarborough) show fewer consistent patterns. Only four of five cities showed significant NO_2–NDVI correlations, and associations with accessibility or deprivation are generally weak or absent.

These results are consistent with national-scale patterns. Garkov et al. (2024), in a postcode-level study across England, found that the most deprived areas experienced 14% higher NO_2 and significantly lower NDVI than the least deprived. Our study extends these insights by showing that such disparities are not uniform across urban contexts. In Northern England, they are especially significant in Major cities, where NO_2, deprivation, and limited greenspace density are more spatially clustered. While Ngan et al. (2025) focused on access to health-related assets, their findings similarly show that deprivation is spatially linked to poorer urban environmental conditions, reinforcing the need to address inequality at the neighborhood scale.

3.2 Social disparities in exposure to air pollution and greenspace

Building on the previous analysis of deprivation, we examined whether similar patterns of inequality exist with respect to ethnic composition. **Figure 5** presents NO_2 concentrations as a function of greenspace NDVI, with each data point color-coded by the percentage of residents defined as non-White (section 2.4).

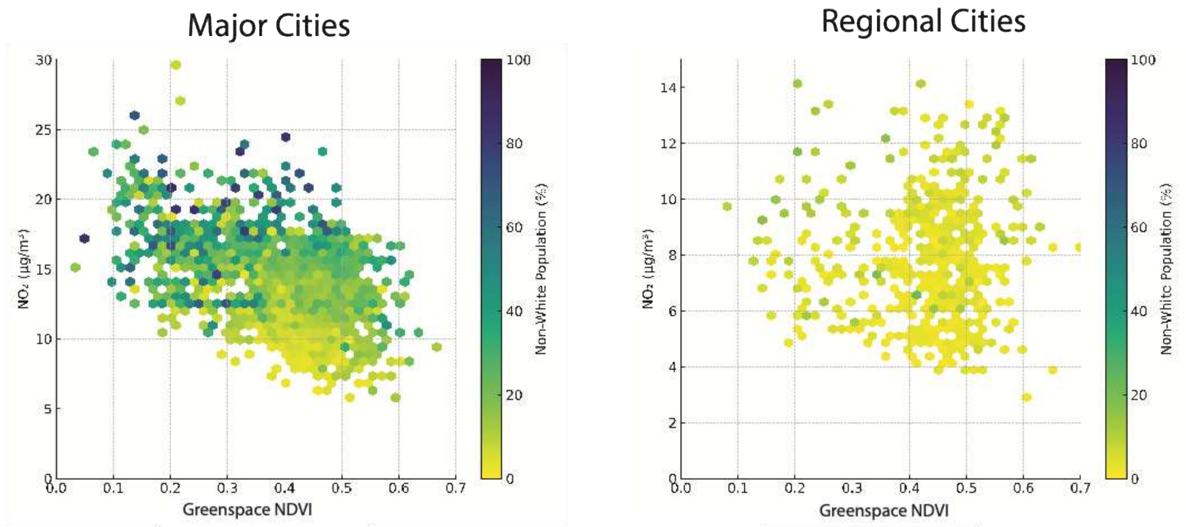

Figure 5. Relationship between annual NO_2 concentrations and greenspace NDVI across urban regions in Northern England, color-coded by the percentage of Non-white population. Each hexagon represents one LSOA, with color indicating the degree of ethnic composition, for Major (right) and Regional (left) urban areas.

The results show a consistent spatial alignment between higher percentages of non-White residents and increase environmental burdens. LSOAs with a greater share of non-White population tend to cluster in areas with both lower NDVI and higher NO_2 levels. Conversely, areas with better vegetation cover and lower NO_2 pollution are more often predominantly White populations. These patterns mirror those observed from national studies (e.g., Fecht et al., 2015; Gray et al., 2025), which have documented the co-location of air pollution and social disadvantage, particularly in racially diverse neighborhoods. However, by using fine-scale spatial data across multiple Northern cities in England, our analysis provides new local-level insight into how environmental inequality crosses with ethnic composition.

In Regional cities, this relationship is less pronounced. These areas are characterized by demographic homogeneity, with most urban LSOAs having predominantly White populations and very few exceeding 20% non-White residents. This limited variation in ethnic composition constrains the ability to identify spatial disparities in NO_2 exposure or greenspace access. In contrast to the more stratified patterns seen in Major cities, Regional urban areas show a more uniform sociodemographic and environmental profile.

A similar pattern is observed for greenspace accessibility (**Fig. S6**). In Major cities, urban LSOAs with the shortest distances to public greenspaces correspond to those with higher percentages of non-White residents. As discussed in Section 3.1, these greenspaces are commonly located in more disadvantaged areas near busy roads and high-pollution environments. This co-location of greenspace and air pollution may limit the potential health benefits of greenspace exposure for racially minoritized communities, despite nominal proximity.

In Regional cities, this pattern is again less apparent. Most urban LSOAs are both demographically homogeneous (i.e., predominantly White) and experience uniformly NO_2 levels and relatively equal greenspace access. These differences suggest that in Northern England, environmental and social disparities are more closely linked, and more structurally embedded, in the spatial and demographic configurations of larger urban conurbations. The relative demographic uniformity of regional, smaller cities may help explain the weaker environmental inequalities observed.

City-level correlation analyses (**Figs. S4–S5**) strengthen this interpretation. In all five Major cities, NO_2 concentrations are significantly associated with both deprivation and percentage of non-White residents, underscoring the spatial clustering of disadvantage. For example, Leeds and Sheffield show the strongest correlations between NO_2 and the percentage of non-white residents (ρ=0.58 and 0.66, respectively; p<0.05), as well as positive associations between IMD and non-white population (ρ=0.49; p<0.05). These associations are not consistently present in Regional cities, where ethnic diversity is lower and more geographically uniform.

These spatial disparities align with findings from national emissions-based research. Gray et al. (2024) examined 24 minoritized ethnic groups, disaggregating the standard census categories, to show all these ethnic groups were exposed to higher NO_x emissions than their White counterparts of comparable deprivation. For example, Bangladeshi and Chinese populations experienced NO_x exposure nearly double what would be expected based on deprivation alone. While our study focuses on ambient NO_2 concentrations rather than emissions, we similarly find that LSOAs with higher percentages of non-White populations tend to have significantly poorer greenspace provision and higher air pollution exposure. These parallels suggest that structural inequalities in urban environments persist across both emissions and concentration-based indicators and reinforce the need for targeted interventions that address both ethnic and environmental justice.

3.3 Disparities in air pollution and greenspace exposure, and ethnicity in urban settings

To further assess the urban air pollution and social disparities in Northern England, we compared NO_2 levels, greenspace exposure and ethnic composition, between the most and least deprived LSOAs within each urban classification (**Fig. 6**). These groups were defined using IMD scores, selecting the top and bottom 20% of LSOAs within each category. In Major cities, each group was formed by 328 urban LSOAs, with the most deprived corresponding to IMD decile 1 and the least deprived to deciles >7. In Regional cities, the groups consisted of 103 urban LSOAs each, with IMD deciles <2 and >8, respectively.

We used Wilcoxon rank-sum tests to assess whether differences between the most and least deprived groups were statistically significant within each urban classification. In Major cities, all variables show highly significant differences ($p < 0.001$), indicating strong disparities in air pollution, greenspace provision, and ethnic composition. In Regional cities, only greenspace NDVI and accessibility differ significantly between deprivation groups, with moderate evidence of disparity ($p < 0.01$). No significant differences are found in NO_2 levels or ethnic composition. Levels of statistical significance are reported in **Fig. 6**.

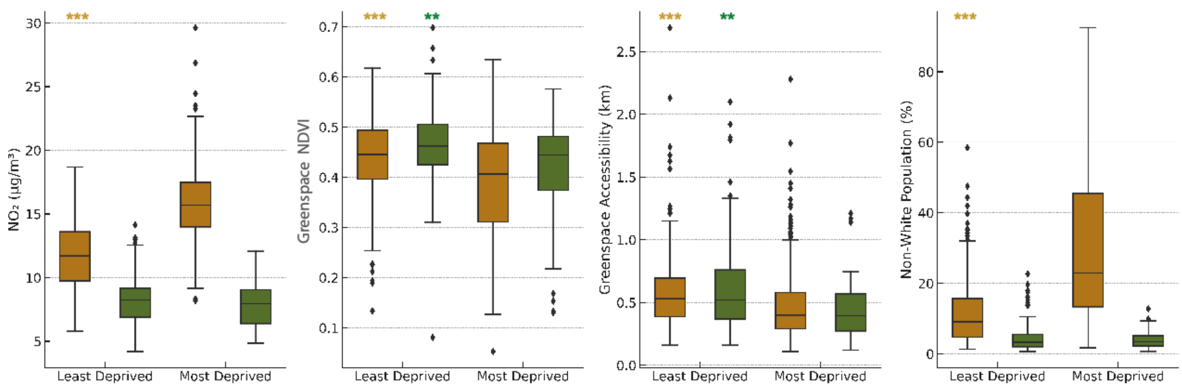

Figure 6. Distributions of annual NO_2 concentrations, greenspace NDVI, greenspace accessibility, and non-White population percentage for the most and least deprived LSOAs in Major (orange) and

Regional (green) urban areas. Deprivation groups are based on IMD scores, with the most deprived defined as the bottom 20% and the least deprived as the top 20% of LSOAs within each urban category. Significance levels are indicated on top of the Least Deprived distribution as follows: ***$p < 0.001$, **$p < 0.01$, *$p < 0.05$.

In Major urban areas, the most deprived LSOAs experience significantly higher NO_2 concentrations, lower greenspace NDVI, and a markedly higher proportion of non-White residents than the least deprived group. Greenspace accessibility was slightly better in the most deprived areas, reflecting patterns observed in national wide studies (e.g., Garkov et al., 2024), where proximity to greenspace is not always indicative of quality or environmental benefit.

In Regional urban areas, deprivation-related differences are more limited. NO_2 concentrations and ethnic composition do not differ significantly between the most and least deprived LSOAs. However, greenspace indicators show moderate disparities with the most deprived areas having significantly lower vegetation cover (NDVI) and slightly better greenspace accessibility. This suggests that while physical access to greenspace may be equitable, differences in environmental quality persist even in smaller urban settings.

Comparisons between Major and Regional urban LSOAs also show important differences. In both the least and most deprived groups, Major cities have significantly higher NO_2 concentrations and a larger proportion of non-White residents than Regional cities ($p < 0.001$). In contrast, NDVI is generally higher in Regional cities, although this difference is only statistically significant in the least deprived group ($p < 0.01$). Greenspace accessibility does not differ significantly between urban types, suggesting that physical proximity to green areas is generally consistent across city classifications.

These results highlight that environmental and social inequalities are more pronounce in larger urban conurbations. In Major cities, the most deprived urban LSOAs face a triple burden of higher air pollution, less greenness, and greater ethnic diversity, confirming patterns reported in national studies (e.g., Fecht et al., 2015; Fairburn et al., 2019; Garkov et al., 2024), but we show them clearly at a local scale for Northern England.

In contrast, Regional cities exhibit fewer and less severe disparities, with significant differences observed only in vegetation cover. This suggests that in regional cities, deprivation does not necessarily coincide with worse environmental conditions. These results reinforce earlier work by Garkov et al. (2024), which found that greenspace proximity was often better in deprived areas, but quality was consistently lower, particularly in more urbanized settings. Our analysis refines this understanding by showing that in larger cities, greenspace proximity often overlaps with higher NO_2 concentrations, reinforcing the mismatch between access and benefit.

We find that the most deprived LSOAs in Major urban areas experience mean NO_2 concentrations of 16 µg/m³, compared to 12 µg/m³ in the least deprived group, a 33% increase. This local disparity is substantially larger than the national average difference of 14% reported by Garkov et al. (2024), suggesting that environmental inequalities may be more pronounced in Northern conurbations, due to the enduring legacy of industrial-era development and spatial segregation. In some cities, these disparities can be even greater. For example, in Leeds NO_2 levels in the most deprived LSOAs are over 40% higher than in the least deprived areas.

Together, these results suggest that environmental inequalities are not simply a consequence of deprivation but are shaped by broader structural and spatial processes, particularly in historically industrial cities of the North. This supports the view that urban scale, demographic stratification, and spatial legacies of infrastructure and planning are key drivers of environmental injustice across England's urban regions.

3.4 Air pollution and vegetation exposure across urban contexts

To better understand how NO_2 and greenspace exposure varies across urban contexts, we compared air pollution levels in the most and least vegetated urban LSOAs in both Major and

Regional cities (**Fig. 7**). These groups were identified by selecting the top and bottom 20% of LSOAs based on NDVI values, calculated separately within each urban category. This resulted in 329 urban LSOAs per group in Major cities and 103 urban LSOAs per group in Regional cities.

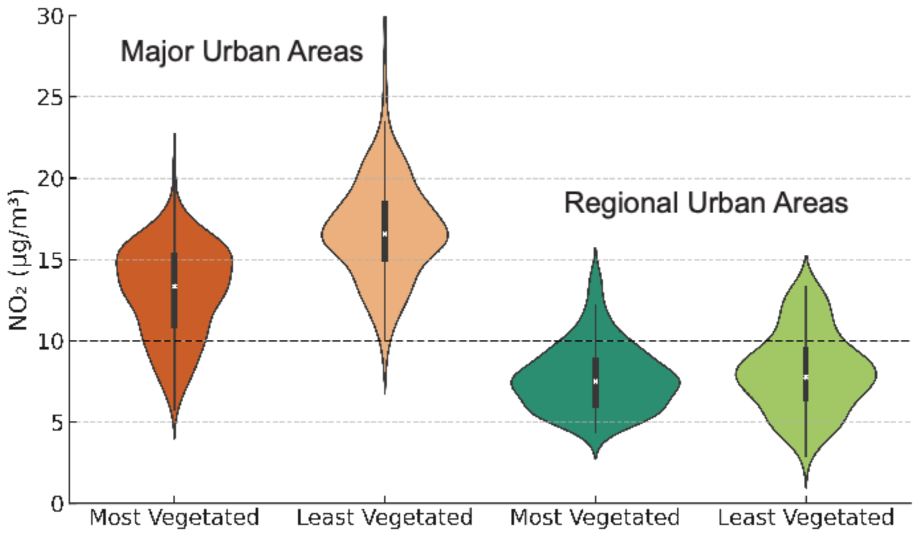

Figure 7. Distribution of NO_2 concentrations (µg/m³) across vegetation cover in major and regional urban areas. The violin plots show the kernel density estimates of annual mean NO_2 LSOAs falling within the top 20% ("Most Vegetated") and bottom 20% ("Least Vegetated") of NDVI for Major and Regional cities. Each violin includes a boxplot indicating the interquartile range and median. The dashed line marks the WHO annual guideline for NO_2 (10 µg/m³).

In Major cities, annual NO_2 levels frequently exceed the WHO guideline of 10 µg/m³, even in the most vegetated urban LSOAs, where 83% remain above this threshold (99% in the least vegetated). These findings highlight the limited capacity of greenspace alone to mitigate pollution in dense, high-emission environments. While vegetation provides important health co-benefits—including reduced stress, improved cardiovascular outcomes, and enhanced physical activity opportunities (e.g., Rigolon et al., 2021; Belcher et al., 2024), its potential to buffer urban air pollution appears constrained in traffic-intensive city cores.

Greenspace interventions are increasingly promoted for their environmental and public health benefits (DEFRA, 2023). However, our results suggest that in larger, historically industrial cities, such efforts must be complemented by robust emission reduction strategies. Passive exposure to green environments offers limited benefit if ambient pollution remains high. These conclusions align with Gray et al. (2024), who stress the need to tackle emissions at their source to address spatial inequalities in exposure.

Although our analysis used NDVI as a measure of vegetation density and health, not all vegetation delivers the same environmental benefits. Greenspace quality, including vegetation type, canopy density, species composition, and spatial configuration, can significantly influence ecosystem services, such as air pollutant mitigation, temperature regulation, and reduction of noise and flood risk (e.g., Tzoulas et al., 2007; Abhijith et al., 2017; Jato-Espino et al, 2023). For example, mature tree canopies and well-designed vegetated barriers have greater capacity to intercept airborne pollutants and cool local microclimates than short or sparsely distributed vegetation (e.g., Abhijith et al., 2017). Improving greenspace structure and design may help maximize its pollution-mitigating benefits in high-exposure areas.

By contrast, Regional cities show much lower NO_2 concentrations overall. Only 12% of the most vegetated and 21% of the least vegetated urban LSOAs exceed the WHO guideline. This suggests that vegetation may be more effective in supporting air quality in smaller, less dense cities with lower background emissions. It also points to a different planning challenge, which is maintaining and enhancing green infrastructure to preserve these environmental benefits as cities grow.

These findings underscore the importance of context-specific urban greening strategies. In larger cities, the placement and structure of vegetation, such as tree belts, street canopies, or roadside buffers, should be aligned with air quality action plans. In regional urban areas, urban greening offers a window of opportunity to reinforce low pollution levels and protect public health as part of proactive urban design.

4. Limitations

This study has several limitations that should be considered when interpreting the findings. First, our analysis is based on modelled annual average NO_2 concentrations for the year 2019, obtained from the AHAH v4 database. Since then, Clean Air Zones and other local interventions have been implemented in several Major urban areas across Northern England, including Sheffield, Leeds, and Manchester, which are likely to have contributed to reductions in NO_2 concentrations (DEFRA, 2025a). These interventions may have disproportionately improved air quality in Major cities relative to Regional urban areas. While our study offers a valid baseline for understanding spatial disparities before these policies, future assessments should incorporate more recent data to evaluate how inequalities have evolved in response to local improvements.

Our analysis focused solely on NO_2 as a marker of urban air pollution. However, $PM_{2.5}$ also plays a critical role in environmental inequalities, particularly in Northern England, where fuel poverty and poor housing insulation increase reliance on solid fuels. Horsfall et al. (2025) mapped domestic wood burning across England and Wales and found that $PM_{2.5}$ emissions from residential heating are concentrated in colder, more deprived regions, including many of the cities studied here. $PM_{2.5}$ data were not available at the LSOA level within AHAH v4 and including $PM_{2.5}$ from alternative datasets would have introduced inconsistencies in spatial resolution and time period. A minor temporal mismatch also exists across our core indicators: IMD and NO_2 are based on 2019, NDVI is derived from 2020 satellite observations and ethnicity data are from the 2021 Census. These were selected to align as closely as possible with the available IMD baseline (2019). While the COVID-19 pandemic disrupted urban activity, NO_2 data pre-date it, NDVI represents peak summer greenness and shifts in ethnic composition are unlikely to have changed significantly over this short period. Future work should revisit these patterns using the updated English IMD 2025 (MHCLG, 2025), alongside NO_2 and $PM_{2.5}$ data from the same period, to assess recent changes in air pollution and inequalities and better understand combined and seasonal exposure patterns.

Second, our selection of cities focused on ten urban centers in Northern England—five Major cities and five Regional cities—intended to reflect a balance of urban form, population, and regional representation. The sample was designed to capture two contrasting settlement types, cities with strong industrial legacies and cities influenced by more rural-to-urban transitions, but its geographic focus limits to generalize to other parts of the UK. Although exploratory tests including cities such as Birmingham and Norwich produced similar results, we cannot rule out that including additional or more diverse cities might influence the patterns observed.

Third, like other spatial studies of environmental inequality (e.g., Mears et al., 2020; Garkov et al., 2024), we were unable to account for either comprehensive quality measures or actual use of greenspaces. We relied instead on satellite-derived vegetation indices (NDVI), used here as a measure of vegetation density and greenness, and estimated proximity via road network distance. While these proxies are widely used and offer consistent national coverage, they do not distinguish vegetation type, canopy structure, or seasonal variability, which are factors that influence ecological function, usability and air pollution capture. Likewise, neither indicator captures important wider aspects of greenspace quality (e.g., safety, maintenance, facilities) or population-level patterns of use, which are known to vary by gender, age, ethnicity, and health status (e.g., Jones et al., 2009; Seaman et al., 2010; Brindley et al., 2019; Koohsari et al., 2023). We also acknowledge that NDVI values in the AHAH dataset were calculated using a fixed 900 m buffer around each postcode, which may not align with all relevant spatial scales of greenspace exposure. Future work could strengthen these insights by incorporating greenspace classification or perceived quality indicators and by exploring sensitivity to buffer size or alternative greenspace metrics to better reflect functional aspects of urban green infrastructure.

Fourth, we recognize the inherent limitations of using LSOAs as the spatial unit of analysis. Although LSOAs are designed to represent neighborhood-level populations and offer consistent coverage for deprivation, ethnicity, and environmental indicators, they do not necessarily reflect residents' lived environments. People may interact with green or polluted spaces outside their LSOA, especially during commuting or leisure travel. The use of fixed administrative units also raises the risk of ecological fallacy, where group-level associations may not hold at the individual level. In addition, our use of a binary ethnicity classification ("White" vs "non-White") may obscure within-group differences, particularly for smaller minority communities; future work using a larger sample of LSOAs from additional cities could support a more detailed assessment of group-specific patterns.

Lastly, our analysis is cross-sectional and descriptive. While we identify statistically significant spatial disparities in exposure to air pollution and greenspace, we cannot make claims about causality or long-term health outcomes. Our correlation-based methods and group comparisons are appropriate for exploratory analysis but do not account for confounding variables or complex interactions, which may limit the strength of direct policy applications. Future work should incorporate longitudinal designs, individual-level data, or mixed-method approaches to better understand causal relationships. In addition, using distributional inequality metrics, such as Lorenz curves or concentrations indices, could help quantify disproportional exposure and assess non-linear associations in environmental justice research.

5. Conclusions

This study examined spatial inequalities in air pollution and greenspace exposure across ten cities in Northern England, highlighting how environmental burdens and benefits are unevenly distributed along lines of deprivation and ethnicity. Comparing patterns between Major and Regional urban areas using high-resolution LSOA-level data, we show that disparities are more pronounced and structurally embedded in larger, historically industrial cities.

In Major cities, which developed around industrial sectors, deprived and racially diverse communities face a triple burden of higher NO_2 pollution, lower greenspace density, and proximity to green areas that are often environmentally compromised. These inequalities are less evident in Regional cities, which are typically influenced by more mixed-use or rural-to-urban development and tend to show more uniform demographic and environmental conditions along with lower air pollution levels. The most deprived urban LSOAs in Major cities face NO_2 levels 33% higher than the least deprived—more than double the national disparity reported by Garkov et al., (2024), emphasizing the scale of local environmental injustice in the North. Future research should explore whether similar patterns are present in Southern England, where cities may lack the same industrial legacies and spatial configurations observed in the North. This would help determine whether these disparities reflect broader national trends or are tied to region-specific urban histories and planning trajectories.

These findings reinforce the importance of context-specific strategies for addressing urban environmental disparities. In high-density urban cities, where traffic emissions remain high and greenspaces are often embedded within degraded environments, green infrastructure alone is insufficient to mitigate air pollution exposure. In such contexts, interventions should prioritize integrated approaches that combine robust emission control policies (e.g., clean air zones, active travel infrastructure) with targeted green planning, such as street tree belts, vegetated barriers, or green walls. In contrast, more Regional cities, which exhibit lower baseline air pollution and less pronounced environmental disparities, present an opportunity to proactively preserve and improve greenspace networks as part of long-term growth planning. Here, maintaining high-quality green cover and ensuring accessibility could play a stronger role in supporting clean air.

Our results also underscore the need for more targeted, equity-oriented planning approaches to address persistent environmental disparities in urban Northern England. By assessing how air pollution, greenspace access, deprivation, and ethnicity are linked across city types, this study provides new evidence to support place-based interventions. These findings align with global commitments, such as the United Nations' Agenda 2030, particularly SDG 3 (Good Health and Well-being), SDG 10 (Reduced Inequalities), and SDG 11 (Sustainable Cities and Communities) as well as national priorities outlined in the UK's Clean Air Strategy and 25-Year Environmental Plan. Reducing air pollution exposure and ensuring equitable access to high-quality greenspaces are essential for advancing sustainable urban development and improving public health across the UK.

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Declaration of competing interest

Maria Val Martin is part of the DEFRA Air Quality Expert Group that includes consulting and advisory activities.

Data availability

All data used in this study are publicly available. Full details and sources are provided in the Methodology section and cited in the References.

Author Statement

Maria Val Martin: Conceptualization, Methodology, Formal analysis, Investigation, Visualization, Writing - Original Draft; Supervision, Project administration, Funding acquisition**;** **Leah Holland**: Software, Investigation; **Paul Brindley**: Conceptualization, Methodology, Resources, Visualization, Writing - Review & Editing;

Declaration of interests

☐The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☒The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

MARIA VAL MARTIN reports financial support was provided by UK Research and Innovation. Maria Val Martin reports 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.

SUPPLEMENTARY MATERIALS

Greenspace and Air Pollution Disparities in Urban Northern England

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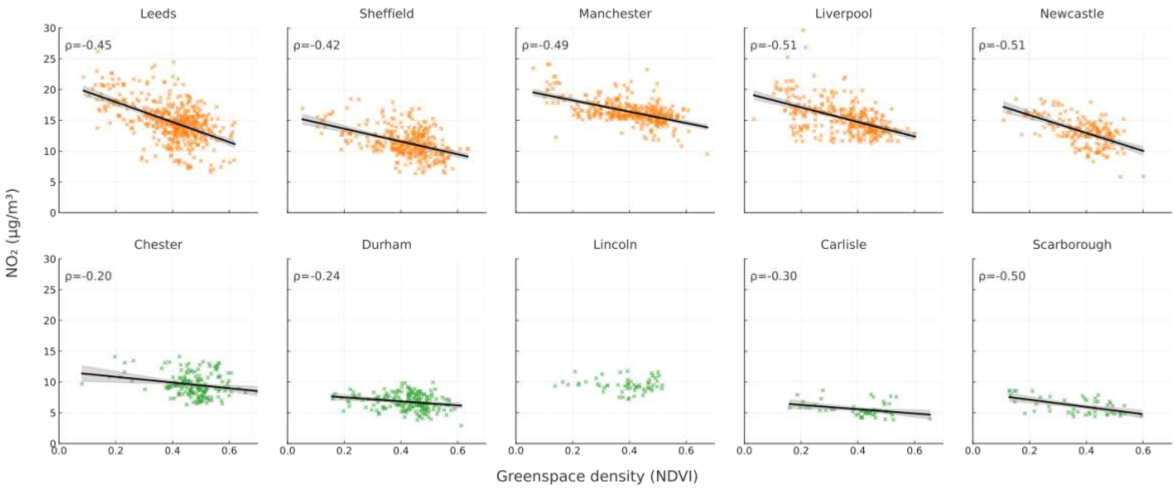

Figure S1. Correlation between mean annual NO_2 concentration and greenspace density (NDVI) across 10 cities in northern England. Major urban areas are shown in orange and regional urban areas in green. A linear regression line with 95% confidence interval for the fitted mean and Spearman correlation coefficient (ρ) are displayed only for cities where the relationship is statistically significant ($p < 0.05$, two-tailed test).

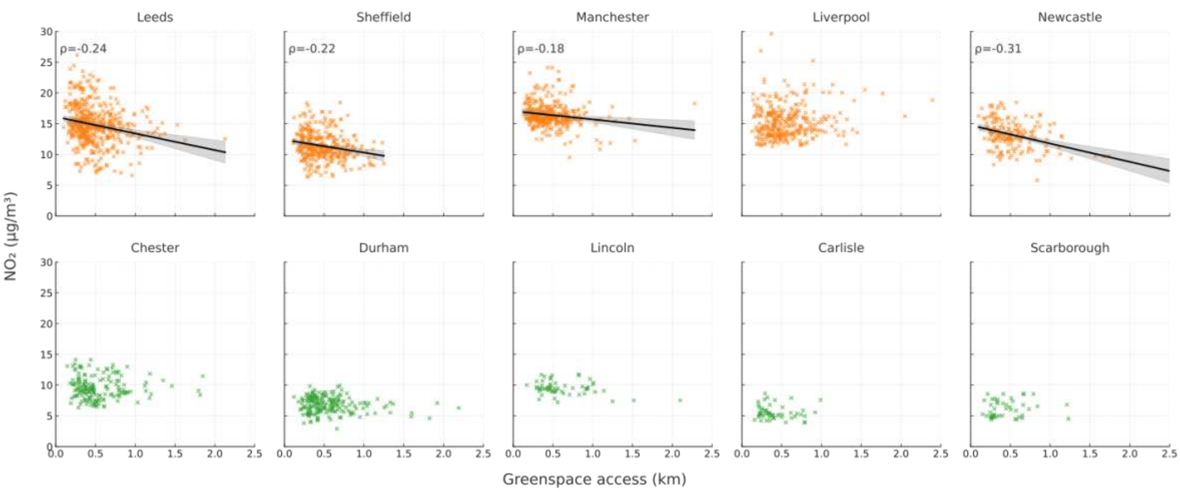

Figure S2. Correlation between mean annual NO_2 concentration and greenspace accessibility across 10 cities in northern England. Major urban areas are shown in orange and regional urban areas in green. A linear regression line with 95% confidence interval for the fitted mean and Spearman correlation coefficient (ρ) are displayed only for cities where the relationship is statistically significant ($p < 0.05$, two-tailed test).

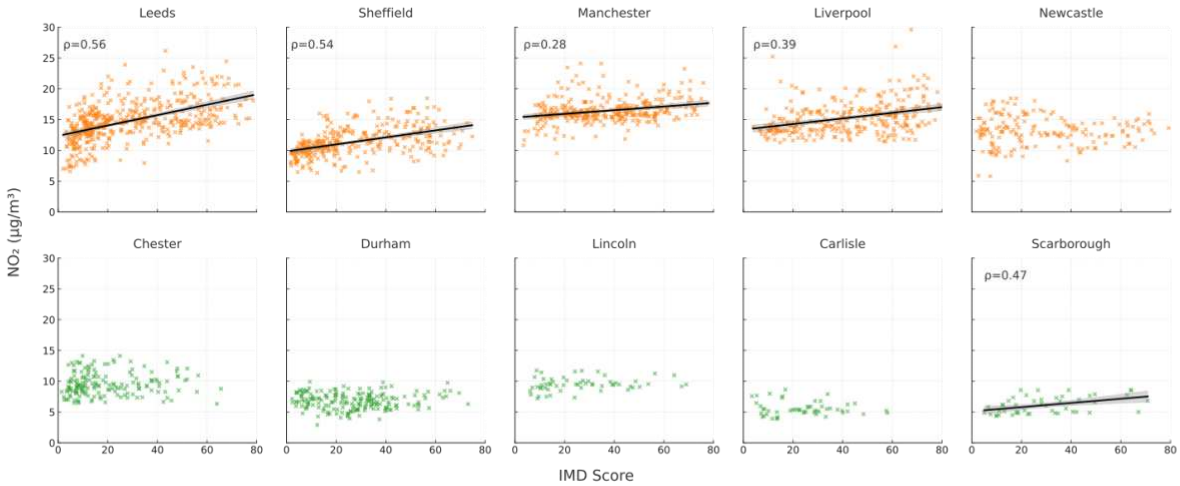

Figure S3. Correlation between mean annual NO_2 concentration and IMD score across 10 cities in northern England. Major urban areas are shown in orange and regional urban areas in green. A linear regression line with 95% confidence interval for the fitted mean and Spearman correlation coefficient (ρ) are displayed only for cities where the relationship is statistically significant ($p < 0.05$, two-tailed test).

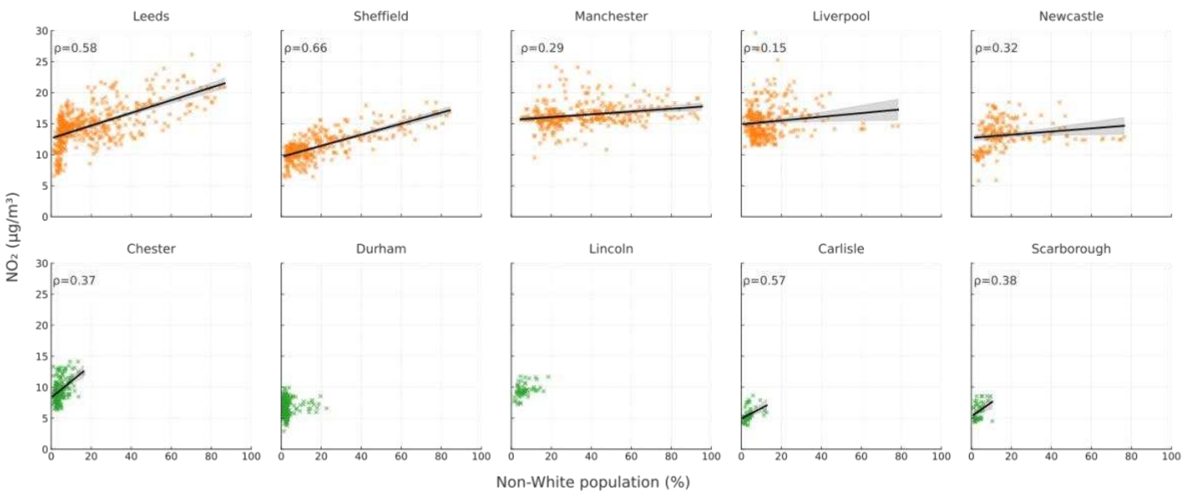

Figure S4. Correlation between mean annual NO_2 concentration and Non-White Population across 10 cities in northern England. Major urban areas are shown in orange and regional urban areas in green. A linear regression line with 95% confidence interval for the fitted mean and Spearman correlation coefficient (ρ) are displayed only for cities where the relationship is statistically significant ($p < 0.05$, two-tailed test).

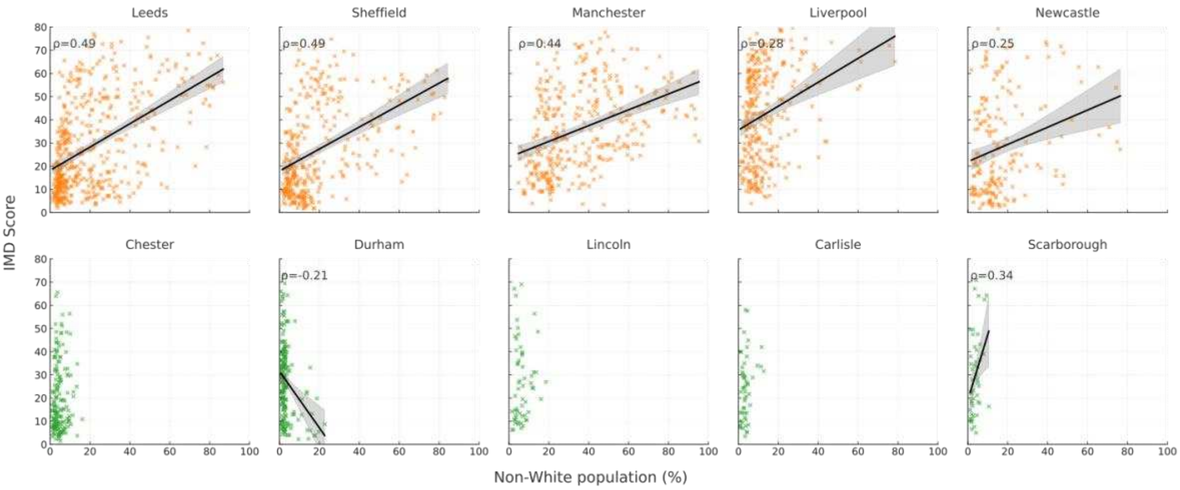

Figure S5. Correlation between IMD Score and ethnicity (% non-white population) across 10 cities in northern England. Major urban areas are shown in orange and regional urban areas in green. A linear regression line with 95% confidence interval for the fitted mean and Spearman correlation coefficient (ρ) are displayed only for cities where the relationship is statistically significant ($p < 0.05$, two-tailed test).

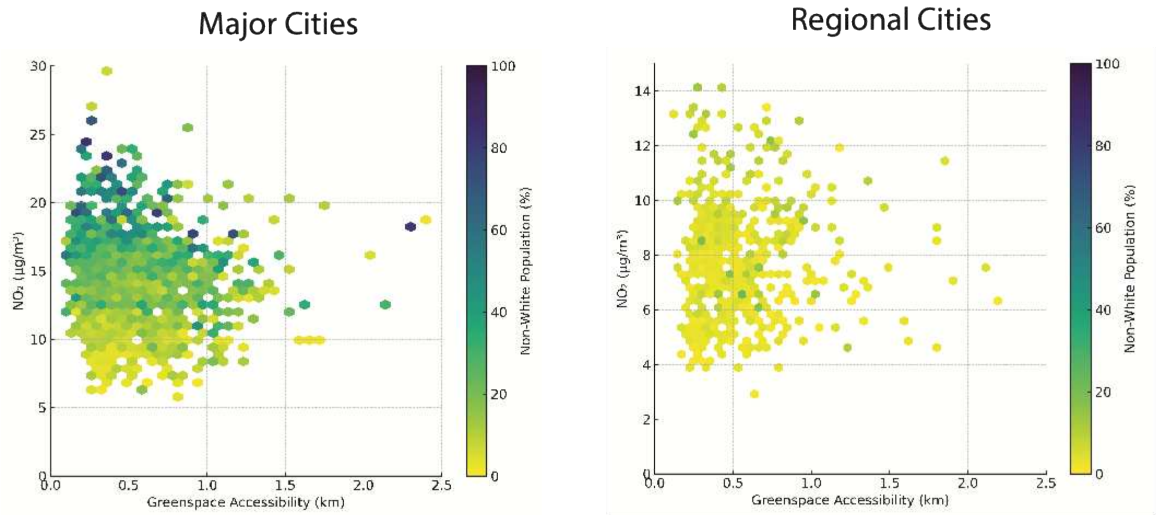

Figure S6. Relationship between annual NO_2 concentrations and greenspace accessibility (km) across urban regions in Northern England, color-coded by the percentage of Non-white population. Each hexagon represents one LSOA, with color indicating the degree of ethnic composition, for Major (right) and Regional (left) urban areas.