# Inequalities in air pollution exposure: Comparison with other cities

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# Executive Summary

## Key messages

- Whilst considerable research has been undertaken on the relationship between air quality and social deprivation, fewer studies have focused on analysis at the city-scale, and far fewer studies again have analysed the relationship over time or considered the impacts of policy actions in terms of changes to this relationship. **London has been considering this relationship for many years and is a leader in this analysis.**
- A literature search for studies that met the criteria for inclusion in this review resulted in just six suitable research papers that weren't in London.
- Comparison of results between the six studies can only be at a broad level given the differences in years analysed, the granularity of data, and the deprivation metrics.
- Of the cities analysed in the six studies found, Paris and Marseille (Padilla et al., 2014), Malmö and Lund (Flanagan et al., 2019), and Aberdeen, Edinburgh, Dundee and Glasgow (Bailey et al., 2018), found that more socially deprived deciles of populations saw larger absolute or percentage decreases in $NO_2$ and/or $PM_{2.5}$ exposure over time.
- In Beijing (Ma et al., 2019), Lyon and Lille (Padilla et al., 2014), Rome (Cesaroni et al., 2012), and North Carolina (Bravo et al., 2022) inequalities in air pollution exposure worsened over the time periods studied.
- The geographical structure of social demographics in each city was found to be an important determining factor for the nature of the change in inequality in exposure to air pollution.
- Changes in air pollutant exposure for different groups are highly specific to each city. The baselines of exposure levels are influenced by the historical trends of where jobs and low-cost housing are found. The trends over time are often related to changes in road traffic and emissions from industrial areas.
- It cannot be expected that air quality policies will necessarily reduce inequalities without this aim being intentionally built into the policy design. The reasons for existing inequalities need to be understood beforehand, so that the policy can target the underlying factors.

### Background

The links between exposure to poor air quality and adverse health outcomes are well established, with an evidence base which is both mature and extensive (COMEAP, 2022; European Environment Agency, 2022; WHO, 2021; GBD, 2020; Lelieveld et al. 2020; Causey, 2019; Defra, 2018; Walton et al., 2015). In general, London faces the greatest air quality challenges in the UK (GLA, 2020), due to both its size and density and its proximity to continental Europe.

The relationship between air pollution and deprivation, with unequal exposure to poor air quality, has a growing body of research (Horton et al., 2022; European Environment Agency, 2018a; Fairburn et al.,2019; Bailey et al., 2018). Demographic groups that already experience greater ill-health due to material deprivation and economic stress can be exposed to higher air pollution, resulting in health inequalities being exacerbated.

This report was commissioned by the Greater London Authority (GLA) as Part 2 of a larger project "Updated Analysis of Air Pollution Exposure and Equalities in London". Part 1 of the project analysed exposure to air quality ($NO_2$, $PM_{10}$ and $PM_{2.5}$) at sensitive receptors and in relation to social inequalities in London and how this has changed over time. This Part 2 report considers published evidence of how inequality in air pollution exposure has changed over time in cities other than London, and how any lessons learned can be used to help inform policy making in London to reduce inequalities further.

## Approach

A literature search was performed using DeepDyve, Google Scholar, PubMed, Connected Papers, and grey literature for studies linking air pollution/air quality with social deprivation/inequality. The search was narrowed to only studies that met criteria for this review, meaning the studies that analysed:

- The quantitative relationship between air quality and social deprivation
- How the relationship changed over time rather than assessing a single year or single cohort
- At the city scale rather than country (excluding London)
- Outdoor air pollution not indoor air pollution
- air quality concentration data
- at least one of $NO_2$, $PM_{10}$ or $PM_{2.5}$.

This reduced the number of relevant papers from over 500,000 to only six. It would have been desirable to limit the studies analysed to be within recent years, but given the limited number of studies available without any data limits, this was not possible.

The six studies of air quality and social inequality used various different metrics of social inequality, which limited direct comparison with London. All except one study included a metric related to household income in the social deprivation indicator, and all except one included a metric related to migrant status or country of birth. The spatial resolution of the air pollution and deprivation data also varied, with most using national census blocks for deprivation data, which varied from an average population size of 500 to 86,000. Not all studies could use social deprivation data that exactly matched the years of air pollution data. The London analysis in Part 1 of this project used local air quality modelling data at 20m x 20m grid squares, making it the highest resolution of air quality concentration data amongst the studies, as the other six studies used scales between 100m x 100m and 1km x 1km.

A summary of the data and scope of the six studies is presented in **Table ES1.**

*Table ES1: Summary information on the studies included in this analysis*

| Reference | City/ State | Time period | Air pollutants | | | Deprivation Indicators | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Pollutants | Scale | Model | Indicator | Source | Scale | Details |
| Bailey et al (2018) | Aberdeen, Dundee, Edinburgh and Glasgow, Scotland | 2004, 2006, 2009 and 2012 | $PM_{2.5}$ | 1 km x 1 km grid squares | Extrapolated from monitored data | Income deprivation | 2004, 2006, 2009, 2012 Scottish Index of Multiple Deprivation | Census Datazones, population between 500 - 1000 | The proportion of the population receiving low-income benefit or tax credit. |
| Cesaroni et al (2012) | Rome, Italy | 2001-2005 | $NO_2$ and $PM_{10}$ | All major roads in Rome | Local-scale dispersion modelling | Socioeconomic position; | 2001 and 2005 Municipal Registry Office | Census block, average population of 500 | Calculated using indices on:<br>• Occupation<br>• Education<br>• Housing tenure<br>• Family composition<br>• Foreign status |
| Bravo et al (2022) | North Carolina, USA | 2002-2006 | $PM_{2.5}$ and $O_3$ | Census tract centroids | US EPA "downscaler" data | Socioeconomic indices | 2010 Census | Census tract centroids, population between 1,200 – 8,000 | • Racial isolation (RI)<br>• Education isolation (EI)<br>• Neighbourhood deprivation index (NDI)<br>• Urbanicity |
| Ma et al (2019) | Beijing, China | 2000-2010 | $PM_{2.5}$ | 1 km x 1 km grid squares | Globally modelled data from the Atmospheric Composition Analysis Group | Socioeconomic indices | 2000 and 2010 Census data, | Sub-district, average population 86,000 | • Migrant status<br>• Very young children<br>• Older people<br>• Unemployment |

| Reference | City/ State | Time period | Air pollutants | | | Deprivation Indicators | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Pollutants | Scale | Model | Indicator | Source | Scale | Details |
| Padilla et al (2014) | Lille, Marseille, Paris and Lyon, France | 2002-2005, 2006-2009 | $NO_2$ | Census block | Local monitoring and various models | A composite neighbourhood deprivation index | 1999 and 2006 Census data | Census block, average population 2,000 | Using 48 different variables including:<br>• Unemployment<br>• Immigration status<br>• Job insecurity<br>• Level of education<br>• Size of residence<br>• Number of people under 25 or above 6 |
| Flanagan et al (2019) | Malmö and Lund, Sweden | 1999-2005, 2006-2009 | $NO_X$ and $PM_{2.5}$ | 100m x 100m grid squares | A dispersion model (AERMOD) | Socioeconomic indices | Statistics Sweden (year not specified) | Linked to individual records from pregnant women | • Education level<br>• Household disposal income<br>• Birth country |
| Aether (2023) | London, UK | 2013, 2016, 2019 | $NO_2$ and $PM_{2.5}$ | 20m x 20m grid squares | Mapped from the London Atmospheric Emissions Inventory (LAEI) | Index of Multiple Deprivation | 2015 and 2019 IMD data | Lower Super Output Areas, population between 1,000 – 3,000 | Multiple indicators within seven domains:<br>• Income deprivation<br>• Employment deprivation<br>• Health and disability deprivation<br>• Education, skills and training deprivation<br>• Barriers to housing and services<br>• Crime<br>• Living environment deprivation |

**Findings**

It was found that very little research has been undertaken in cities other than London into the temporal changes associated with inequality of air pollutant exposure, showing that London is leading the way in this area of work.

Whilst the results of the various studies cannot be directly compared, due to the different methodologies, different deprivation indices and spatial disaggregation of data, some broad conclusions can be made. **Table ES2** provides a summary of the findings of the studies included in this review.

In most of the studies, the baseline air quality situation started with more deprived areas in the city experiencing higher concentrations of air pollutants. The baselines of exposure levels are influenced by the historical trends of where jobs and low-cost housing are found. The trends over time are often related to changes in road traffic and emissions from industrial areas.

In general, changes in inequalities are associated with the spatial distribution of deprived communities and road networks. In some cities it is seen as desirable to live close to the city centre and therefore this area is broadly made up of higher socioeconomic groups. If this city also has high levels of traffic in the centre, then these groups can experience the larger reductions in air pollution as air quality policies often target road traffic, for example as found by Cesaroni et al (2012) in Rome.

On the other hand, in some cities, living near the centre can be seen as undesirable and so more deprived communities represent a larger proportion of residents there. In these cases, inequalities can be reduced over time as air quality policies focus on reducing pollution from vehicles, as is the case in Lille, as found by Padilla et al (2014). Alternatively, road traffic or industrial areas can be concentrated on the outskirts of the city due to pre-existing road management or development policies.

In the London analysis in Part 1 of the study, it was found that the inequality gap between the pollutant exposure of the least and most deprived deciles decreased for $NO_2$ between 2013 and 2019, and marginally decreased for $PM_{2.5}$. The most deprived decile experienced a larger reduction in pollutant exposure for both pollutants than the least deprived.

*Table ES2: Summary of conclusions from the studies analysed*

| Reference | City | Time period | Baseline | Changes over time | Reasons for change |
|---|---|---|---|---|---|
| Bailey et al (2018) | Aberdeen, Dundee, Edinburgh and Glasgow; Scotland | 2004, 2006, 2009 and 2012 | The most deprived areas experienced greater concentrations of air pollution compared with the least deprived areas. | Inequalities decreased. Air pollutant concentrations have decreased, with greater decreases in the more deprived areas. | No specific reason concluded in this study. |
| Cesaroni et al (2012) | Rome; Italy | 2001-2005 | The least deprived areas experienced greater concentrations of air pollution compared with more deprived areas. | Overall, $NO_2$ and $PM_{10}$ concentrations have declined over time, the greatest decreases were found in areas of least deprivation. | A new low emission zone policy reduced traffic emissions significantly in the centre of Rome, where the least deprived areas are found. |
| Bravo et al (2022) | North Carolina; USA | 2002-2006 | Areas of higher urbanicity experienced greater concentrations of air pollution. Areas of high racial isolation are often found in urban regions, where they experience high levels of $PM_{2.5}$, and areas of high education isolation are found in more rural regions. | Mixed results depending on deprivation metric. Despite reductions in pollutant concentrations, disparities in exposure increased for racially and educationally isolated communities. | No specific reason concluded in this study. |
| Ma et al (2019) | Beijing; China | 2000-2010 | Areas with the highest proportion of migrants, very young children and older people experienced a higher baseline of $PM_{2.5}$ concentrations (in the urban centre). Areas with the highest proportion of unemployment (in the suburbs) experienced a lower level of $PM_{2.5}$. | Mixed results depending on deprivation metric. Overall $PM_{2.5}$ concentrations have increased across Beijing. Some decreased for areas with the highest proportion of migrants, very young children and older people as they experienced relatively small increases in $PM_{2.5}$ levels. Areas of high unemployment, however, experienced greater increases in $PM_{2.5}$ levels. | Industry and its associated emissions have moved away from the urban centre and to the suburbs. Industrial jobs in the centre have been replaced with service roles. |
| Padilla et al (2014) | Lille, Marseille, Paris and Lyon; France | 2002-2005, 2006-2009 | In Lille, Marseille and Lyon, the most deprived areas experienced greater concentrations of air pollution as they are found in the urban centres. In Paris, the opposite was found, the least deprived areas were found in the centre. | Mixed results depending on location. In Paris and Marseille, the most deprived areas experienced greater decreases in air pollution. In Lille and Lyon, the opposite was found. | Likely due to changes in traffic; high volumes of in traffic in less deprived areas in Paris and Marseille and in the more deprived areas of Lille and Lyon. |
| Flanagan et al (2019) | Malmö and Lund; Sweden | 1999-2005, 2006-2009 | Mixed results across the two cities and for different air pollutants ($NO_2$ and $PM_{2.5}$) and different indicators of deprivation for pregnant women. | Inequalities decreased. Overall, $NO_2$ concentrations have declined over time, with the greatest decreases experienced by the most deprived women. $PM_{2.5}$ concentrations have remained relatively stagnant. | No specific reason for $NO_2$ exposure concluded in this study. $PM_{2.5}$ concentrations are likely to be stagnant as emissions are blown in from nearby ports. |
| Aether (2023) | London, UK | 2013, 2016, 2019 | The most deprived areas experienced greater concentrations of air pollution compared with the least deprived areas. | Inequalities decreased. Overall, $NO_2$ and $PM_{2.5}$ concentrations have declined over time, with the greatest decreases experienced by the most deprived areas. | No specific reason concluded in this study. |

## Conclusions

Whilst considerable research has been undertaken on the relationship between air quality and social deprivation, fewer studies have focused on analysis at the city-scale, and far fewer studies again have analysed the relationship over time. Of the studies that have assessed the relationship over several years, most use data that is over a decade old. Many of the studies referenced the regular analysis performed on London air quality and social deprivation as being the most recent and thorough. GLA is in a good position to share best practice of the research with other cities in the UK, Europe, and elsewhere.

It cannot be expected that air quality policies will reduce inequalities without this being intentionally built into the policy design, because it is crucial to reduce air pollution in areas of deprivation more than elsewhere in order to restore environmental equity. The reasons for existing inequalities of exposure need to be understood beforehand, so that the policy can target the underlying factors, and this will be specific to each city.

The achieved impact of air quality policies over time should be monitored and evaluated, so that the measures can be adjusted as needed to maximise the intended results. This requires high quality, granular data on air quality and deprivation indices.

# Contents

# Tables



# Figures

# Acronyms

| | |
|---|---|
| ADMS | Atmospheric Dispersion Modelling System |
| EEA | European Environment Agency |
| EI | Education Isolation |
| GLA | Greater London Authority |
| HDI | Household Disposable Income |
| IMD | Index of multiple deprivation |
| LES | London Environment Strategy |
| LEZ | Low Emission Zone |
| LSOA | Lower Super Output Area |
| $O_3$ | Ozone |
| $PM_{2.5}$ | Particulate Matter <2.5 µg in diameter |
| $PM_{10}$ | Particulate Matter <10 µg in diameter |
| NDI | Neighbourhood Deprivation Index |
| NHB | Non-Hispanic Black |
| NO | Nitric Oxide |
| $NO_X$ | Nitrogen Oxides |
| $NO_2$ | Nitrogen Dioxide |
| RI | Racial Isolation |
| SEP | Socio-Economic Position |
| WHO | World Health Organization |

# 1 Introduction

The links between exposure to poor air quality and adverse health outcomes are well established, with an evidence base which is both mature and extensive (COMEAP, 2022; European Environment Agency, 2022; WHO, 2021; GBD, 2020; Lelieveld et al. 2020; Causey, 2019; Defra, 2018; Walton et al., 2015). The UK's 2019 Clean Air Strategy marks it as the "largest environmental health risk in the UK". The World Health Organization (WHO) highlights that there is no evidence of a safe level of exposure/threshold of $PM_{2.5}$ concentrations below which no damaging health effects are seen (WHO, 2022). By improving air quality, populations experience a reduction in the burden of disease from heart disease, stroke, lung cancer, and both chronic and acute respiratory diseases, including asthma.

In general, London faces the greatest air quality challenges in the UK (GLA, 2020), due to both its size and density and its proximity to continental Europe. The current Mayor of London, Sadiq Khan, has identified air quality as a priority area for policy. The London Environment Strategy (LES), published in May 2018 (GLA, 2018), contains a range of actions to improve air quality in London over the short, medium and longer term.

## 1.1 Air pollution inequalities

The relationship between air pollution and deprivation, with unequal exposure to poor air quality, has a growing body of research (Horton et al., 2022; European Environment Agency, 2018a; Fairburn et al.,2019; Bailey et al., 2018; Mitchell et al., 2015). This can result in a "triple jeopardy" of polluted environs, health impacts and socioeconomic deprivation (Verbeek, 2019). Demographic groups that already experience greater ill-health due to material deprivation and economic stress can be exposed to higher air pollution resulting in health inequalities being exacerbated.

Research that has been undertaken at the regional or city level does not always reveal the variability of air quality and deprivation within the area. For example, a study by the European Environment Agency (2018b) used deprivation data from Urban Audit units, with Berlin, Paris and Rome each represented by a single unit. In these cases, conclusions might be misleading as they will hide the fine variability within each unit. High spatial disaggregation is needed within cities so that data are not averaged across large areas with peaks and troughs smoothed out.

The study found that within cities, the spatial distribution of groups with different socio-economic statuses was mostly influenced by the housing market and housing policies. Links were found between socio-economic status and exposure to air pollutants, but the associations were highly location and scale specific. For example, in Rome, it was found that residents with the highest economic status were exposed to higher levels of air pollutant concentrations because they lived in the centre of the city where high volumes of traffic were found.

Previous studies in London have shown a relationship between air pollution and high deprivation; populations residing in more deprived areas were on average exposed to worse air quality than their counterparts (Aether, 2017a and Aether 2017b). However, these have also shown that the difference in exposure levels between the least and most deprived areas is beginning to close.

## 1.2 This report

The analysis in this report was commissioned by the Greater London Authority (GLA) as Part 2 of a larger project "Updated Analysis of Air Pollution Exposure and Equalities in London". Part 1 of the project analysed exposure to air quality ($NO_2$, $PM_{10}$ and $PM_{2.5}$) at sensitive receptors and in relation to social inequalities in London and how this has changed over time. This Part 2 report reviews published evidence of how inequality in air pollution exposure has changed over time in other cities and how they can be compared to London.

Chapter 2 sets out the approach taken for the research and the data analysed. Chapter 3 discusses the findings of the review and the broader implications. Chapter 4 presents comparisons with London and Chapter 5, the conclusions from this research.

# 2 Method

The key research questions for this study were:

- What evidence is available of the impact of changes in air pollution exposure in relation to variations in social deprivation in cities other than London?
- What are considered to be the local influences on the relationship between air pollution and social inequalities and the reasons behind the trends over time, such as the impact of new air pollution related policies.
- How do the data presented in the literature compare to evidence related to London?

The literature review aimed to consider the evidence presented in studies that explore changes in the relationship between air pollutant exposure and social inequalities over time, on a city scale.

## 2.1 Literature review approach

While there is a substantial amount of existing scientific literature on the relationship between air quality and deprivation, there is a limited number of studies that consider the trends of these relationships over time.

A literature search was performed using Google Scholar, PubMed and DeepDyve for the combination of keywords “air pollution social inequality”, “air pollution social deprivation”, “air quality social inequality”, “air quality social deprivation”. This search yielded over 500,000 published papers. The search was narrowed with additional key words followed by manual review to target studies that analysed:

- The quantitative relationship between air quality and social deprivation
- How the relationship changed over time rather than assessing a single year or single cohort
- At the city scale rather than country (excluding London)
- Outdoor air pollution not indoor air pollution
- That used air quality concentration data
- That analysed at least one of $NO_2$, $PM_{10}$ or $PM_{2.5}$.

This reduced the number of relevant papers to only six.

The original specification from GLA requested that the review would focus on Birmingham, Manchester, Glasgow, Paris, Berlin, and Brussels, and other European cities as relevant. However, owing to the lack of studies available, the scope of the cities was not limited, nor the time periods analysed. One of the six papers (Bravo et al., 2022) covers the US State of North Carolina rather than a specific city, but is included due to the granularity of the deprivation indices. The limited selection of six studies that considered trends over time and met the criteria specific above were all evaluated as part of this report, and their methods are summarised in **Table 1**. Based on these studies, this analysis investigated trends in air quality and socio-economic indicators of deprivation in cities around the world.

The air pollutants monitored at the different cities varied as did the socioeconomic indices and the spatial resolution used. This made it difficult to perform direct comparisons between individual studies, however, overall conclusions have been drawn from the studies as a group.

*Table 1: Summary information on the studies included in this analysis*

| Reference | City/ State | Time period | Air pollutants | | | Deprivation Indicators | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Pollutants | Scale | Model | Indicator | Source | Scale | Details |
| Bailey et al (2018) | Aberdeen, Dundee, Edinburgh and Glasgow, Scotland | 2004, 2006, 2009 and 2012 | $PM_{2.5}$ | 1 km x 1 km grid squares | Extrapolated from monitored data | Income deprivation | 2004, 2006, 2009, 2012 Scottish Index of Multiple Deprivation | Census Datazones, population between 500 - 1000 | The proportion of the population receiving low-income benefit or tax credit. |
| Cesaroni et al (2012) | Rome, Italy | 2001-2005 | $NO_2$ and $PM_{10}$ | All major roads in Rome | Local-scale dispersion modelling | Socioeconomic position; | 2001 and 2005 Municipal Registry Office | Census block, average population of 500 | Calculated using indices on occupation, education, housing tenure, family composition, and foreign status. |
| Bravo et al (2022) | North Carolina, USA | 2002-2006 | $PM_{2.5}$ and $O_3$ | Census tract centroids | US EPA “downscaler” data | Socioeconomic indices | 2010 Census | Census tract centroids, population between 1,200 – 8,000 | • Racial isolation (RI)<br>• Education isolation (EI)<br>• Neighbourhood deprivation index (NDI)<br>• Urbanicity |
| Ma et al (2019) | Beijing, China | 2000-2010 | $PM_{2.5}$ | 1 km x 1 km grid squares | Globally modelled data from the Atmospheric Composition Analysis Group | Socioeconomic indices | 2000 and 2010 Census data, | Sub-district, average population 86,000 | • Migrant status<br>• Very young children<br>• Older people<br>• Unemployment |
| Padilla et al (2014) | Lille, Marseille, Paris and Lyon, France | 2002-2005, 2006-2009 | $NO_2$ | Census block | Local monitoring and various models | A composite neighbourhood deprivation index | 1999 and 2006 Census data | Census block, average population 2,000 | Using 48 different variables including % unemployment, % immigrants, job insecurity, level of education, size of residence and number of people under 25 or above 65. |
| Flanagan et al (2019) | Malmö and Lund, Sweden | 1999-2005, 2006-2009 | $NO_X$ and $PM_{2.5}$ | 100m x 100m grid squares | A dispersion model (AERMOD) | Socioeconomic indices | Statistics Sweden (year not specified) | Linked to individual records from pregnant women | • Education level<br>• Household disposal income<br>• Birth country |
| Aether (2023) | London, UK | 2013, 2016, 2019 | $NO_2$ and $PM_{2.5}$ | 20m x 20m grid squares | Mapped from the London Atmospheric Emissions Inventory (LAEI) | Index of Multiple Deprivation | 2015 and 2019 IMD data | Lower Super Output Areas, population between 1,000 – 3,000 | Multiple indicators within seven domains:<br>• Income deprivation<br>• Employment deprivation<br>• Health and disability deprivation |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | • Education, skills and training deprivation<br>• Barriers to housing and services<br>• Crime<br>• Living environment deprivation |

*Note: EPA Fused Air Quality Surface Using Downscaling ("downscaler") data. The downscaler combines modelled gridded outputs with monitoring data to produce daily point-level concentration estimates at the 2010 Census-tract centroids across the United States.*

## 2.2 Air Quality metrics

The air pollutants and the geographic resolution considered in the selected studies are listed in **Table 1**.

All of the studies use data on Nitrogen Dioxide/Nitrogen Oxides ($NO_2$/$NO_X$) and or Particulate Matter, either <10 µg or <2.5µg in diameter ($PM_{10}$/$PM_{2.5}$). Extensive research has been conducted on these air pollutants and their various health impacts (Gandini et al. 2019) and there are WHO guideline values for their long term (annual) concentrations.

Many governments have set air quality targets that are higher than the WHO air quality guideline levels. However, it is widely acknowledged that there is no safe level of exposure to air pollution, and that even the WHO air quality guidelines do not define levels of exposure that are entirely safe for the whole population (Royal College of Physicians, 2016).

The scale and model of the air quality data differs between the studies. Flanagan et al. (2019) uses 100m x 100m grid squares, whilst Ma et al. (2019) and Bailey et al. (2018) use 1km x 1km grid squares. Ma et al. (2019) in particular differs to other studies as only a few real-time air quality monitoring stations became available since 2014 in Beijing, so data from the Atmospheric Composition Analysis Group was used. This estimated global surface $PM_{2.5}$ concentrations by combining satellite observations with chemical transport model, calibrated to ground-based observations of $PM_{2.5}$ using Geographically Weighted Regression. This was validated with local Beijing data in more recent years for its applicability.

Cesaroni et al. (2012), Padilla et al (2014), Flanagan et al. (2019) use local air quality modelling data. Bravo et al. (2022) combines gridded air quality data from local, state and national air quality monitoring stations.

The finer the scale of AQ data, the less likely any important associations between AQ and deprivation will be hidden – at the larger scale these finer relationships can be smoothed over.

The London analysis in Part 1 of this study used local air quality modelling data at 20m x 20m grid squares, making it the highest resolution of air quality data amongst the studies.

## 2.3 Deprivation indicators

In the studies reviewed, each used a different method of measuring socioeconomic deprivation, as seen in **Table 1**.

Often the socioeconomic data used is from the national census, which varies from country to country according to their national circumstances. Most studies used composite indices calculated using many different socioeconomic variables, (Bravo et al., 2022; Cesaroni et al., 2012; Flanagan et al., 2019; Ma et al., 2019; Padilla et al., 2014) whereas Bailey et al. (2018) used individual statistics as measures of deprivation. All studies except Ma et al. (2019) include a metric related to household income in the deprivation indicator, and all except Bailey et al. (2018) include a metric related to migrant status or country of birth.

The granularity of this data also varied across studies. Most used national census-related blocks, which varied from an average population size of 500 (Bailey et al., 2018 and Cesaroni et al., 2012) to 86,000 (Ma et al., 2019). The larger the population block that the deprivation data covers, the more likely that heterogeneity will be lost, and relationships with AQ data hidden.

As censuses are typically not performed more often than every 5 years, applying the data from one census to multiple years of air quality data can hide social deprivation changes, and potentially affect the analysis. Half of the studies used deprivation indicator data from the same year as the air quality data (Bailey et al., 2018; Cesaroni et al., 2012; Ma et al., 2019), Bravo et al. (2022) used 2010 census data related to 2002-2006 air quality data, Padilla et al. (2014) used 1999 and 2006 census data for the two grouped years 2002-2005 and 2006-2009 respectively. Flanagan et al. (2019) did not specify the year.

This means that while each study uses measurements that are relevant and available for each city, the results cannot be directly compared with each other.

The London analysis in Part 1 of this study used the Office of National Statistics' Index of Multiple Deprivation (IMD) at the Lower Super Output Areas (LSOAs), which contain 1-3,000 residents. The IMD contains metrics on income, employment, education, health and disabilities, crime, barriers to services, and living environment deprivation.

# 3 Analysis of the relationship between air pollution and social deprivation

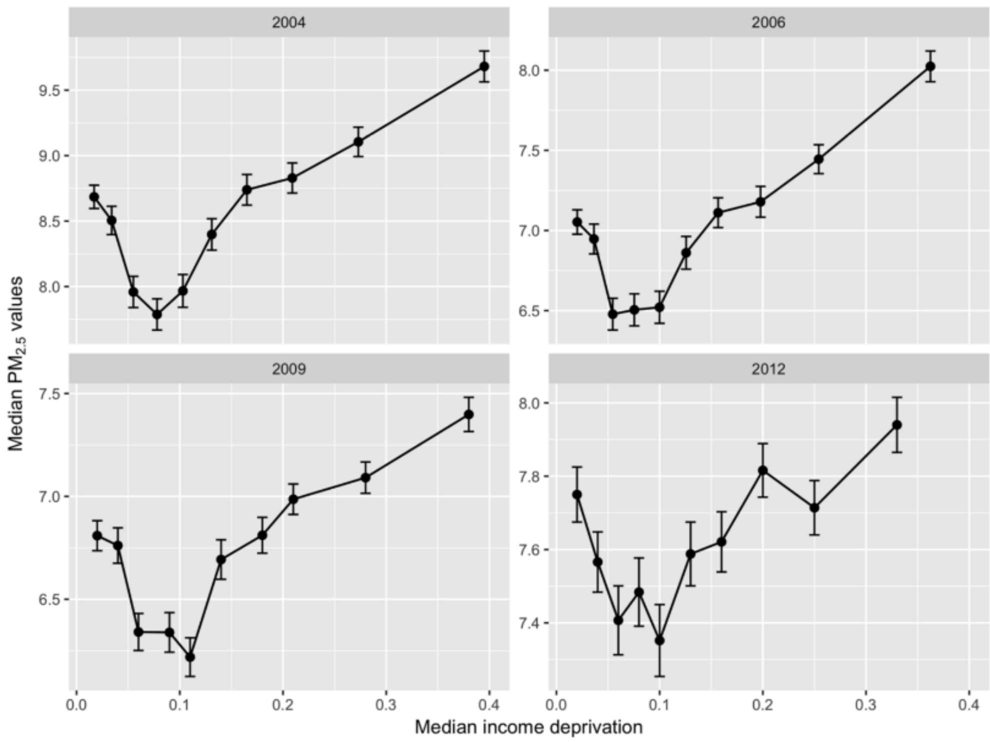
Each of the studies covered by this report is described in the following sections, to present their key results and conclusions.

## 3.1 Scotland: Aberdeen, Dundee, Edinburgh and Glasgow

A study by Bailey et al. (2018), examines the relationship between air quality and deprivation in Scotland between 2004 and 2012, focusing on four city regions; Aberdeen, Dundee, Edinburgh and Glasgow. The study uses the Scottish Index of Multiple Deprivation, which is available for four years within that period, and $PM_{2.5}$ concentration estimates that are published by Defra on a 1 km by 1 km scale.

Across the whole of Scotland, $PM_{2.5}$ concentrations were found on average to be highest in the most deprived deciles. Concentrations steadily fell with decreasing deprivation until the least deprived two deciles, where $PM_{2.5}$ concentrations began to rise again, creating a non-linear “tick” shaped relationship, as shown in **Figure 1.**

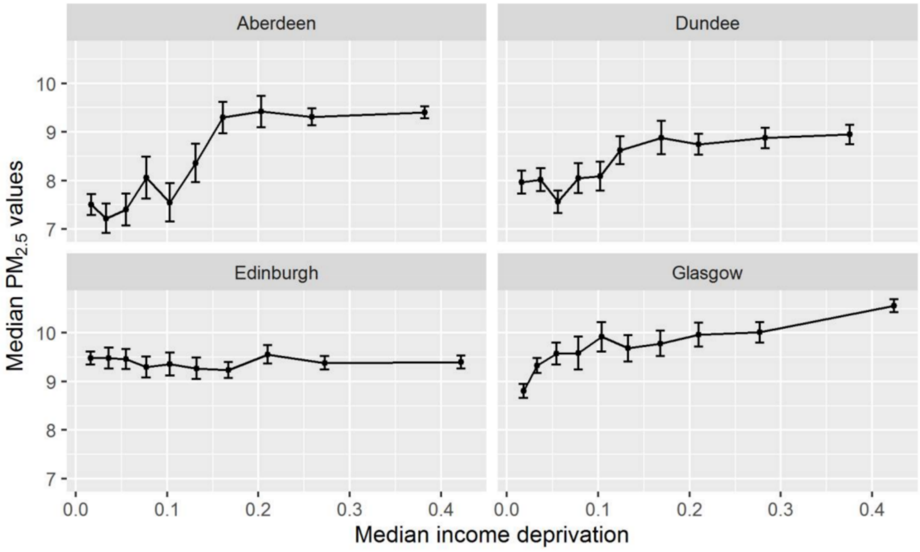
*Figure 1: Pollution - deprivation relationship for Scotland during 2004-2012*




*Source: Bailey et al. (2018)*

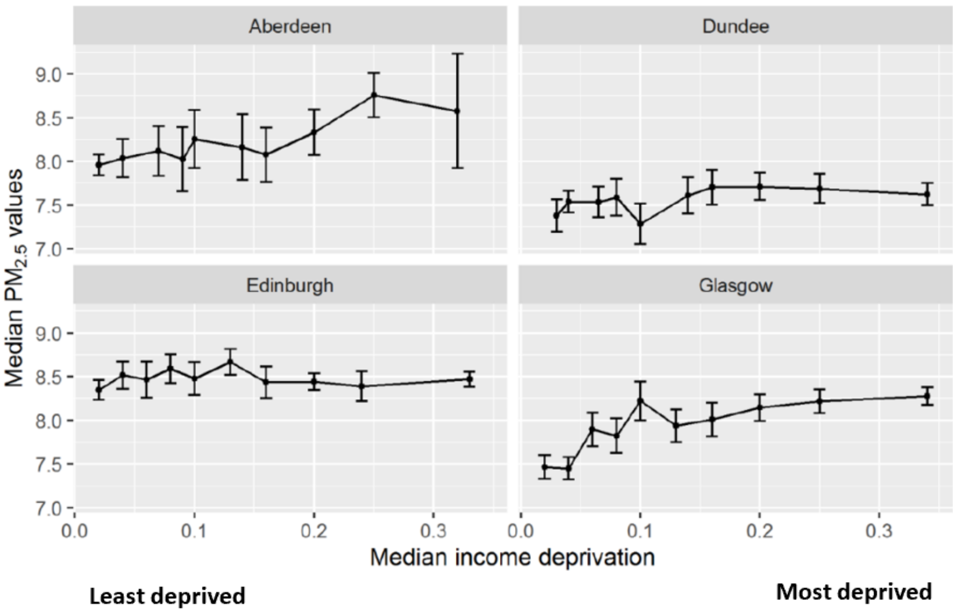
However, when air quality was studied on a city scale, the data does not reflect the national pattern, as seen in **Figure 2** and **Figure 3** Aberdeen, Dundee and Glasgow show that pollution is highest in the most deprived deciles, steadily decreasing as deprivation lowers, then sharply reducing in the least deprived decile. However, in Edinburgh, the relationship is largely flat, with no substantial difference in $PM_{2.5}$ concentrations between the least and most deprived. The study did not offer suggestions for the reason behind the different relationships.

*Figure 2: Pollution - deprivation relationship for four Scottish city-regions in 2004*




*Source: Bailey et al. (2018)*

*Figure 3: Pollution - deprivation relationship for four Scottish city-regions in 2012*




*Source: Bailey et al. (2018)*

The percentage changes in $PM_{2.5}$ concentrations in each city are shown in **Table 2**. All cities experienced a reduction in the mean $PM_{2.5}$ concentrations between 2004 and 2012, although Aberdeen saw an 8% increase in $PM_{2.5}$ concentrations for the lower quantile of deprivation (least deprived as measured by median income deprivation). For all four cities, $PM_{2.5}$ concentrations reduced more in absolute and percentage terms for the most deprived than for the least deprived.

Two key conclusions relevant to policymakers were drawn from the study. One was that the distribution of air pollution exposure by deprivation varies widely within regions and that it is therefore important to take this into account when setting national and regional targets. The second was that the results observed in Edinburgh (the relatively flat line in **Figure 2** and **Figure 3** indicate that a positive relationship between air pollution and deprivation is not inevitable and that policy intervention may lead to shifts over time.

*Table 2: The percentage change in $PM_{2.5}$ concentration between 2004 and 2012 in four Scottish cities for varying levels of deprivation*

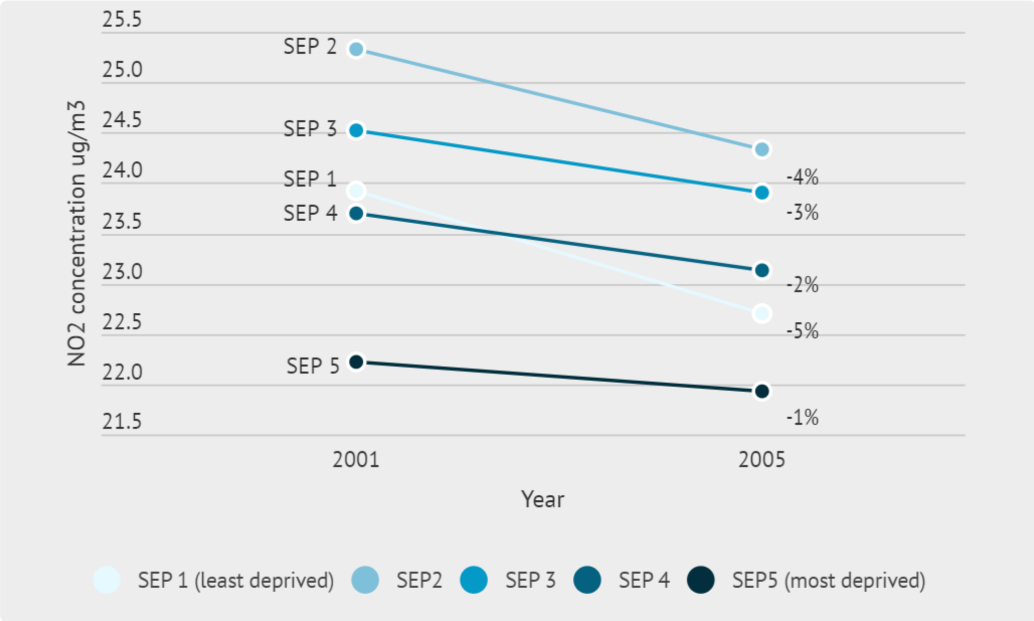
| City | Least deprived | Mean | Most deprived |
|---|---|---|---|
| **Aberdeen** | +8% | -1% | -7% |
| **Edinburgh** | -9% | -10% | -11% |
| **Dundee** | -6% | -9% | -12% |
| **Glasgow** | -17% | -19% | -21% |

## 3.2 Italy: Rome

In Rome, it was found in 2007, that road traffic accounted for 80% of $NO_2$ and 52% of $PM_{10}$ emissions in the city. In 2001, the City Council of Rome introduced two low-emission zones in the centre of the city in an effort to reduce traffic-related air pollution. Cesaroni et al. (2012) studied the impacts of these low-emission zones on air pollutant concentrations and exposure over a five year period (2001-2005). Using traffic data collected by the City Council and local-scale dispersion modelling, concentrations of $NO_2$ and $PM_{10}$ were calculated and compared against socio-economic position (SEP) index values by census block.

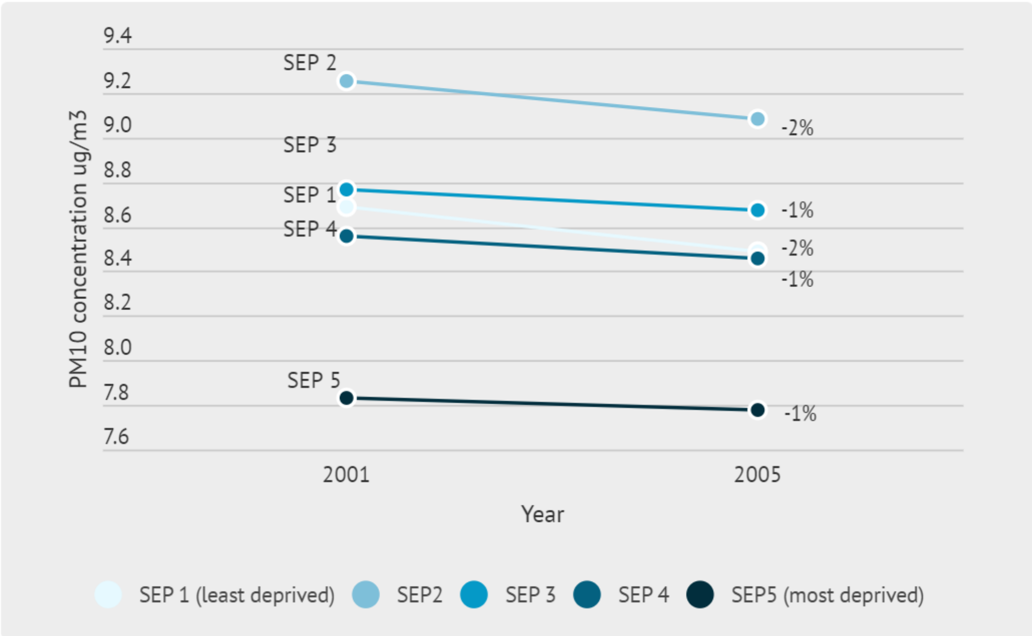
The highest SEP groups (least deprived) had a baseline of worse air quality than the most deprived, due to the desirability of living in the city centre, where there was the highest traffic congestion. The study found that the concentrations of $NO_2$ and $PM_{10}$ from cars decreased by 58% and 33% in the central low-emission zones, while city wide concentration decreases were much smaller. In Rome, the wealthiest residents are more likely to live in the city centre and therefore, across Rome, the highest SEP group experienced the greatest decrease in air pollutant exposure as a result of the policy, as illustrated by **Figure 4** and **Figure 5**.

*Figure 4: $NO_2$ concentrations in Rome before and after the introduction of low-emission zones, by SEP index*




*Source: Cesaroni et al (2012)*

*Figure 5: $PM_{10}$ concentrations in Rome before and after the introduction of low-emission zones, by SEP index*




*Source: Cesaroni et al (2012)*

### 3.3 USA: North Carolina

In North Carolina, United States, Bravo et al. (2022) compared modelled concentrations of $PM_{2.5}$ and $O_3$ across four socioeconomic indices by 2010 census tract (neighbourhoods):

- racial isolation (RI)
  - % Non-Hispanic Black (NHB) in a census tract. This is a domain of racial residential segregation long defined in the literature, and is used here in relation to adverse and disparate outcomes for racially, economically, and educationally minoritized populations
- education isolation (EI)
  - % non-college educated adults aged 25 or older in a census tract
- neighbourhood deprivation index (NDI)
  - a composite of many variables including % households in poverty and % household income <$30,000
- urbanicity
  - % of population residing in urban settings

The study found that in general concentrations of $PM_{2.5}$ and $O_3$ decreased across the study period (2002-2016). As shown in **Table 3**, statistically significant differences in exposure were found between tracts with high and low values for some indices.

In the baseline year (2002), areas with high urbanicity and high RI value had higher concentrations of $PM_{2.5}$ than areas that are less urban and have low RI. However, areas that are more educationally isolated have lower than average baseline $PM_{2.5}$ concentrations. This is unsurprising as the study found that high RI values were generally associated with urban areas, whilst high EI values were more common in rural areas.

Over the study period, air quality improved more markedly in areas that were more educationally isolated than those that were less educationally isolated. These results are also shown in **Table 3**. Similarly, very urban areas that have high baseline $PM_{2.5}$ concentrations saw a steeper decrease in concentrations than areas that are less urban. This may be because rural areas have a lower baseline of emission sources such as traffic, so there is less scope for improvement.

Communities with high RI values saw only an average decline in $PM_{2.5}$ concentrations, showing that they are not co-located with the urban areas that experienced the greatest reductions. Given that these communities already have above average levels of $PM_{2.5}$, the study suggests that racially isolated communities may experience an increased disparity in $PM_{2.5}$ exposure over time.

The patterns seen in changes of $O_3$ concentrations over time vary for RI and EI. Neither indicator was associated with higher than average baseline $O_3$ concentrations. Census tracts with higher RI values had steeper declines in $O_3$ concentrations over the study period than less racially isolated areas. Conversely, the most educationally isolated communities saw smaller drops in $O_3$ concentration than communities with low EI. Bravo et al (2022) hypothesise that although baseline $O_3$ concentrations do not vary by RI or EI, if the existing trends in $O_3$ concentrations over time for RI and EI accelerate or continue, disparities are likely to emerge in community level exposure to $O_3$.

The differing patterns observed for $PM_{2.5}$ and $O_3$ are most likely explained by the formation of the pollutants. $PM_{2.5}$ is primary pollutant emitted as a by-product of combustion in vehicles and industrial sites. On the other hand, higher $O_3$ concentrations are found in rural areas. This is mostly likely due to the presence of more nitric oxide (NO) in urban areas, for example from vehicle exhaust, which reacts rapidly to $O_3$ to form $NO_2$, leading to lower concentrations of $O_3$.

*Table 3: Differences in air pollutant exposure for neighbourhoods with high and low socioeconomic indices for North Carolina, United States*

| Pollutant | Socioeconomic index | For tracts with high index values compared with low index counterparts | |
|---|---|---|---|
| | | Baseline exposure | Exposure over time |
| $PM_{2.5}$ | High racial isolation | Higher | Average improvement |
| | High education isolation | Lower | More improvement |
| | High urbanicity | Higher | More improvement |
| $O_3$ | High racial isolation | Average | More improvement |
| | High education isolation | Average | Less improvement |
| | High neighbourhood deprivation index | Lower | Average improvement |
| | High urbanicity | Higher | Average improvement |

## 3.4 China: Beijing

Air quality in Beijing is among the worst globally, with annual mean $PM_{2.5}$ concentrations reaching 80.4 µg/m$^3$ in 2015. To study the distribution of air pollutants over time and their impacts on socially disadvantaged groups, Ma et al (2019) compared modelled $PM_{2.5}$ concentrations in Beijing with census data from 2000 and 2010. Four measures of social deprivation were used:

- Migrant status (migrants have limited access to social welfare)
- Very young children (≤ 4 years)
- Older people (≥ 65 years)
- Unemployment

Between 2000 and 2010, average annual mean concentrations of $PM_{2.5}$ increased from 53.6 µg/m$^3$ to 64.1 µg/m$^3$, an increase of around 20%. This is driven by urban growth, industrialisation and an increase in vehicle traffic. However, concentrations vary considerably across sub districts; $PM_{2.5}$ concentrations are higher in the southern areas, due to the presence of more heavy industry. Whereas the northern areas experience lower concentrations due to a prevailing northwest wind and more mountainous and vegetated terrain.

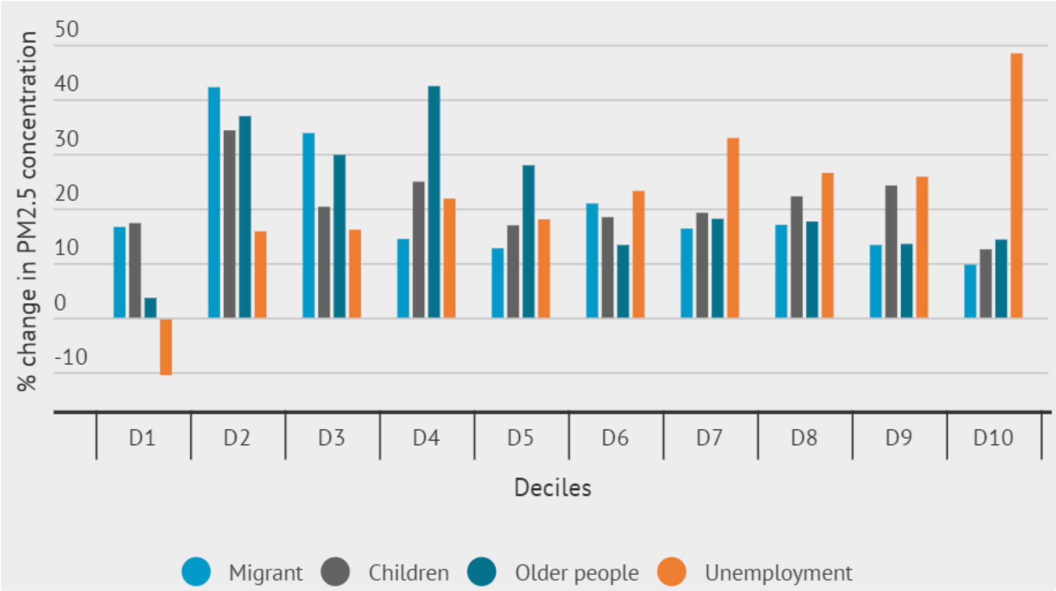
The inner-suburban zone contains sub districts with high proportions of migrants and very young children due to the presence of work opportunities and more affordable housing compared with the central urban zone. Rates of unemployment are higher in the outer suburban and city fringe zones, especially in the west.

Many sub districts experienced a significant increase in $PM_{2.5}$ concentration between 2000 and 2010, however, the those with higher proportion of migrants, very young children and older people generally experienced a higher baseline concentration and smaller increases compared with other areas. This shared pattern is likely due to grandparents living with young families and providing childcare for grandchildren, and therefore living in central areas with more job opportunities for working parents.

Sub districts with the highest unemployment were found in the north and west urban fringes, while sub districts with the lowest unemployment were found in the urban centre. In 2000, the sub districts with highest unemployment had a low baseline of air pollution compared with the polluted centre where industrial jobs were found. By 2010, these high unemployment subdistricts experience higher levels of air pollution due to the movement of industry away from the centre to the suburbs. Correspondingly, the air pollution levels in the central sub districts with lowest unemployment have decreased as industrial jobs are replaced with service roles.

**Figure 6** shows the changes in $PM_{2.5}$ concentrations for subdistricts, split by decile, starting from D1, which contains the lowest proportion of migrants, very young children, older people and unemployed people. The figure suggests that inequality in exposure to air pollution has changed over the ten year period. For example, between 2000 and 2010 the decile with the highest levels of unemployment (D10) experiences a 48% increase in $PM_{2.5}$ concentrations, whereas the group with the lowest unemployment (D1) has a 10% reduction in exposure to $PM_{2.5}$. This can be explained by the increased suburbanisation in the historically industrial centre of Beijing.

*Figure 6: Changes in $PM_{2.5}$ concentrations experienced by subdistricts split by socioeconomic indicators in Beijing between 2000 and 2010*




## 3.5 France: Lille, Marseille, Lyon and Paris

Padilla et al. (2014) conducted a study on air quality and social deprivation across four French cities: Lille, Marseille, Lyon and Paris. These cities were chosen as they show strong contrasts in socioeconomic and demographic characteristics. Two consecutive time periods (2002-2005 and 2006-2009) were examined to investigate trends in environmental inequalities.

The study used a composite neighbourhood deprivation index, calculated using 48 variables collected by the national census including % unemployment, size of residence and number of people under 25 or above 65. Air quality was modelled using local monitoring networks and deterministic models (ADMS for Lille, SIRANE for Lyon, ESMERALDA for Paris and STREET for Marseille).

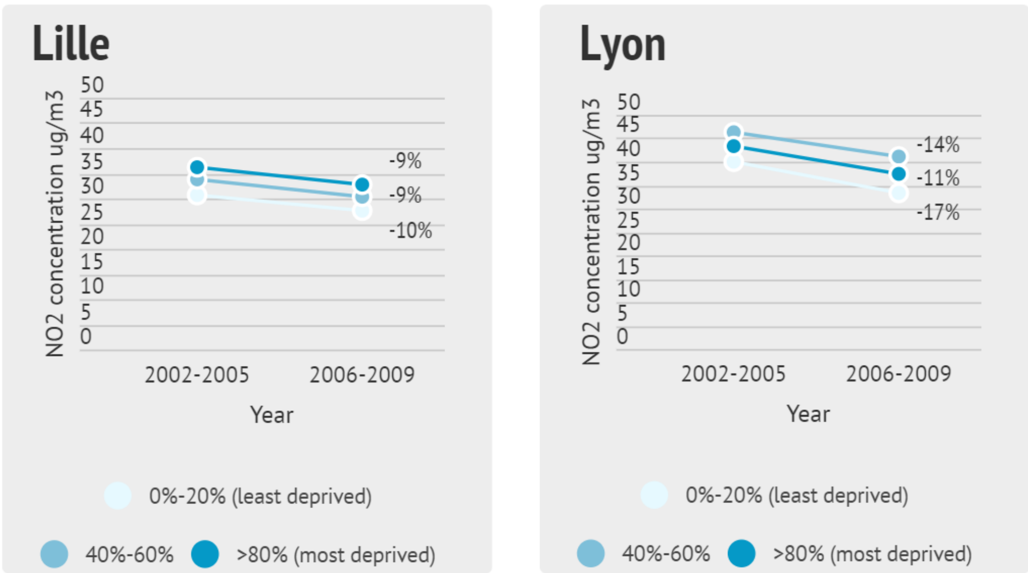
In Lille, the most deprived areas are found in the urban centre, where exposure to air pollution is highest. This is because historically, the centre has been very industrial, and workers tended to live close by. Similarly, both social deprivation and air pollution levels are highest in the urban centre of Marseille. In Lyon, the East suburb is the most deprived region; whilst the wealthiest area is in the West, in the valleys of the Saône and Rhône rivers, and experiences the lowest air pollutant exposure. However, in Lyon, the areas of medium deprivation in the centre experience the highest air pollutant concentrations.

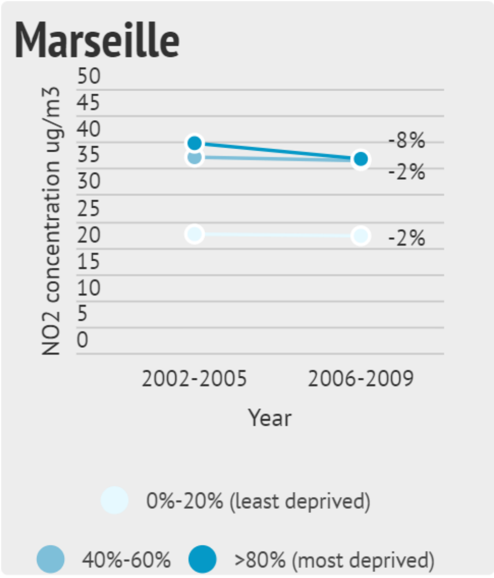
In contrast, Paris has generally more affluent areas in the centre of the city and consequently air pollution is highest in the areas with the least deprivation. Air pollution is now largely dominated by transport emissions rather than the industrial activities that have moved out of the city centre, and the poor air quality in the centre of Paris can be attributed to the high numbers of vehicles.

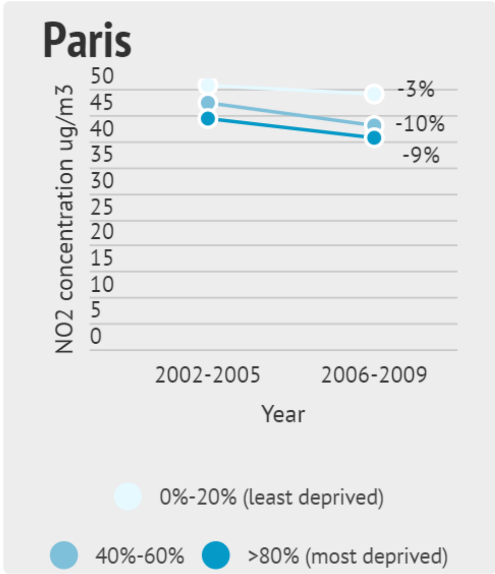
Between the two time periods, air pollutant concentrations have decreased across all cities and so air quality has improved for all levels of deprivation as seen in **Figure 7**. In Paris and Marseille, there was a bigger decrease in $NO_2$ concentrations in areas with more deprivation than in less deprived areas. Although this pattern is not fully understood, the change could be attributed to a shift in traffic density, with traffic moving away from the most deprived areas to those that are least deprived.

However, in Lyon and Lille the opposite is observed. There is a smaller decrease in $NO_2$ concentrations in areas with more deprivation than in those that are least deprived. For example, in Lyon $NO_2$ concentrations dropped by 17% in the least deprived areas, whereas the decrease was only 11% in areas with more deprivation. It is hypothesised that this is due to major traffic routes that run through these deprived areas and connect to the central metropolitan areas.

*Figure 7: Changes in $NO_2$ concentrations in areas with varying levels of social deprivation in four French cities*





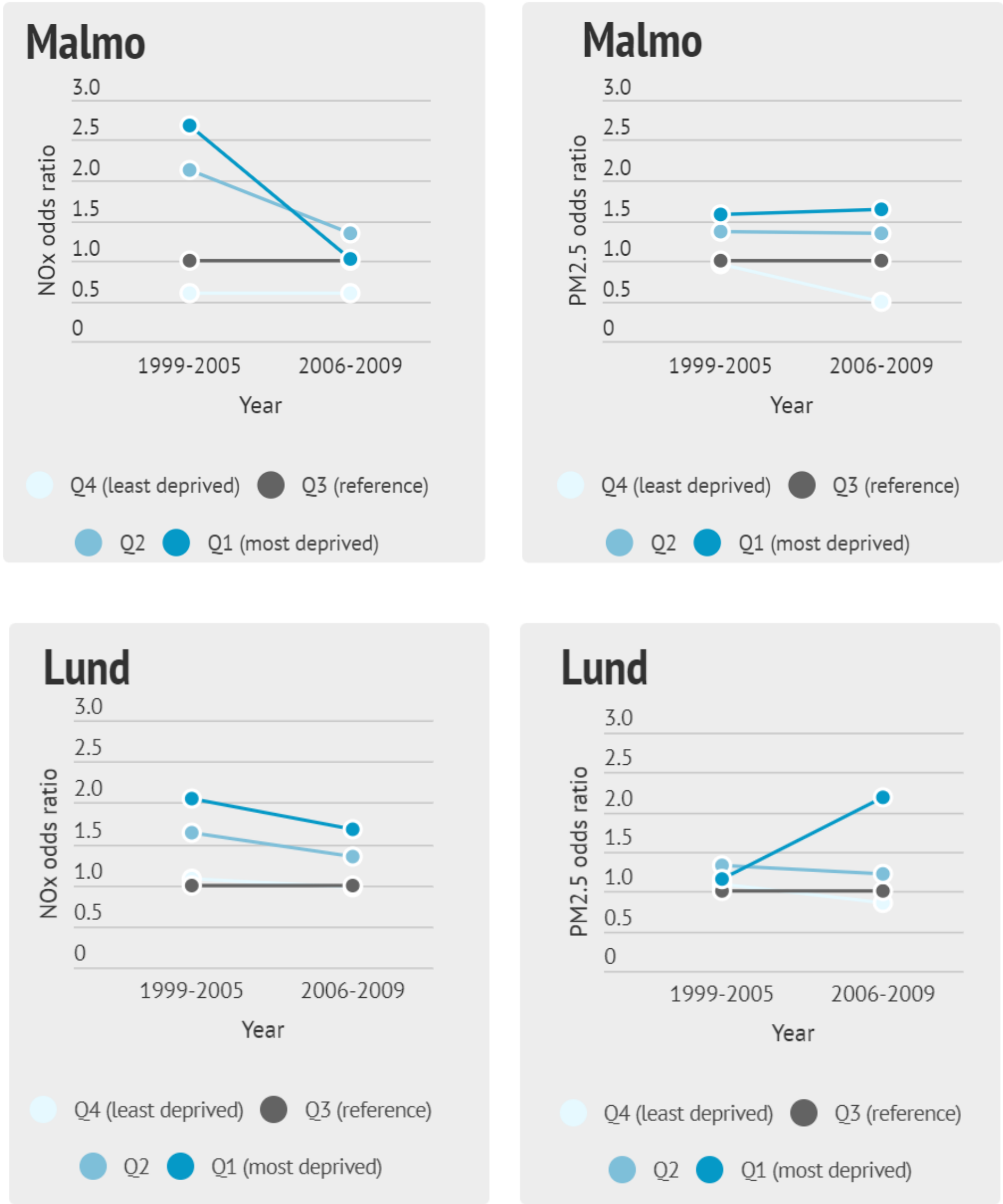

### 3.6 Sweden: Malmö and Lund

Air pollutant concentrations are relatively high in the southern region of Sweden, due to vehicles travelling through to other destinations in Sweden and to Norway. Other major pollutant sources include shipping and ferry transport at several harbours and pollutants borne on westly wind from Copenhagen and the rest of Denmark. Flanagan et al. (2019) studied data on pregnant women in the cities of Malmö and Lund in this region. The socioeconomic status of the women was assessed using separate indicators of education level, household disposable income and birth country. Air pollutant exposure to $NO_X$ and $PM_{2.5}$ was calculated using a national emissions database and an exposure model, and was presented as an air pollutant concentration in µg/m$^3$.

Over the two time periods studied (1999-2005 and 2006-2009), $NO_X$ concentrations in the study area decreased, although women from households with low disposable income, low education and those born in lower-middle income countries benefitted the most. This indicates that decreases from $NO_X$ pollution over this time period were greatest in areas with greater deprivation.

The results of the study were mixed across the cities, index and by air pollutant. This is illustrated in **Figure 8** which shows the odds of exposure to $NO_X$ and $PM_{2.5}$ concentrations above clean air objective levels compared with a reference group, split by household disposable income (HDI) level. In this figure, the reference group is the quartile with the second highest level of HDI (Q3), which is represented as a value of 1 across the chart. The other quartiles are given values (odds ratios) that represent the chance of exposure to air pollutant concentrations above the objective levels compared with the reference quartile.

*Figure 8: Odds ratio of exposure above clean air objective levels for pregnant women in Malmö and Lund, split by levels of HDI*




*Note: HDI = Household Disposable Income*

Unlike $NO_X$, Flanagan et al. observed that $PM_{2.5}$ concentrations remained relatively stagnant across the two time periods, likely due to emissions being blown in from neighbouring areas and local combustion in small residential heating devices. Odds of being highly exposed to $PM_{2.5}$ rose for the entire area, although especially amongst women from low socioeconomic backgrounds (low education, low household disposable income and born in a low-middle income country).

It is worth noting that Malmö comprises a large proportion of the total population monitored (70% of the study population) and that it is a coastal town close to shipping routes and other industrial areas, contributing to the higher levels of $PM_{2.5}$ exposure. Malmö also contains a substantial immigrant population that mostly reside on the outskirts of the city, where the five main highways converge.

## 3.7 Discussion

This review has demonstrated that very little research has been undertaken in cities other than London into the temporal changes associated with inequality of air pollutant exposure. Those that have published papers have generally used data that predates 2010. Whilst many studies have explored links between social deprivation and air quality, further research is needed in order to improve understanding of current patterns and trends in temporal variability and the factors causing these changes to occur. **Table 4** provides a summary of the findings of the studies included in this review. Generally, the baseline for each study started with more deprived areas in the city experiencing higher concentrations of air pollutants. For studies conducted in Europe and the United States, air quality improved over time. However, the improvement was not experienced equally across the cities.

In Scotland (Aberdeen, Dundee, Edinburgh and Glasgow), Paris, Marseille, Malmö, Lund inequalities in air pollution exposure decreased. Conversely, the most deprived areas experienced the smallest improvements in Lille, Lyon and Rome. In North Carolina, mixed results were found, as was the case in Beijing, where air pollutant concentrations increased over the study period. While not all the studies explored the reasons behind the changes, those that did concluded that changes were due to changes in traffic flow (including the effect of traffic policies, such as the low emission zone implemented in central Rome) and industrial activities.

*Table 4: Summary of conclusions from the studies analysed*

| Reference | City | Time period | Baseline | Changes over time | Reasons for change |
|---|---|---|---|---|---|
| Bailey et al (2018) | Aberdeen, Dundee, Edinburgh and Glasgow; Scotland | 2004, 2006, 2009 and 2012 | The most deprived areas experienced greater concentrations of air pollution compared with the least deprived areas. | Inequalities decreased. Air pollutant concentrations have decreased, with greater decreases in the more deprived areas. | No specific reason concluded in this study. |
| Cesaroni et al (2012) | Rome; Italy | 2001-2005 | The least deprived areas experienced greater concentrations of air pollution compared with more deprived areas. | Overall, $NO_2$ and $PM_{10}$ concentrations have declined over time, the greatest decreases were found in areas of least deprivation. | A new low emission zone policy reduced traffic emissions substantially in the centre of Rome, where the least deprived areas are found. |
| Bravo et al (2022) | North Carolina; USA | 2002-2006 | Areas of higher urbanicity experienced greater concentrations of air pollution. Areas of high racial isolation are often found in urban regions, where they experience high levels of $PM_{2.5}$, and areas of high education isolation are found in more rural regions. | Mixed results depending on deprivation metric. Despite reductions in pollutant concentrations, disparities in exposure increased for racially and educationally isolated communities. | No specific reason concluded in this study. |
| Ma et al (2019) | Beijing; China | 2000-2010 | Areas with the highest proportion of migrants, very young children and older people experienced a higher baseline of $PM_{2.5}$ concentrations (in the urban centre). Areas with the highest proportion of unemployment (in the suburbs) experienced lower $PM_{2.5}$ concentrations. | Mixed results depending on deprivation metric. Overall $PM_{2.5}$ concentrations have increased across Beijing. Some inequalities decreased for areas with the highest proportion of migrants, very young children and older people as they experienced relatively small increases in $PM_{2.5}$ concentrations. Areas of high unemployment, however, experienced greater increases in $PM_{2.5}$ concentrations. | Industry and its associated emissions have moved away from the urban centre and to the suburbs. Industrial jobs in the centre have been replaced with service roles. |
| Padilla et al (2014) | Lille, Marseille, Paris and Lyon; France | 2002-2005, 2006-2009 | In Lille, Marseille and Lyon, the most deprived areas experienced greater concentrations of air pollution as they are found in the urban centres. In Paris, the opposite was found, the least deprived areas were found in the centre. | Mixed results depending on location. In Paris and Marseille, the most deprived areas experienced greater decreases in air pollution. In Lille and Lyon, the opposite was found. | Likely due to changes in traffic; high volumes of in traffic in less deprived areas in Paris and Marseille and in the more deprived areas of Lille and Lyon. |
| Flanagan et al (2019) | Malmö and Lund; Sweden | 1999-2005, 2006-2009 | Mixed results across the two cities and for different air pollutants ($NO_2$ and $PM_{2.5}$) and different indicators of deprivation for pregnant women. | Inequalities decreased. Overall, $NO_2$ concentrations have declined over time, with the greatest decreases experienced by the most deprived women. $PM_{2.5}$ concentrations have remained relatively stagnant. | No specific reason for $NO_2$ exposure concluded in this study. $PM_{2.5}$ concentrations are likely to be stagnant as emissions are blown in from nearby ports. |

| Reference | City | Time period | Baseline | Changes over time | Reasons for change |
|---|---|---|---|---|---|
| Aether (2023) | London, UK | 2013, 2016, 2019 | The most deprived areas experienced greater concentrations of air pollution compared with the least deprived areas. | Inequalities decreased. Overall, $NO_2$ and $PM_{2.5}$ concentrations have declined over time, with the greatest decreases experienced by the most deprived areas. | No specific reason concluded in this study. |

In many cities, air quality is worst in the centre and along main traffic routes therefore policies are established to target these areas, for example the Low Emission Zone in Rome. This can have a varying effect on inequality which is largely dependent on the social geography of the city involved. In cities where wealthy communities live in the central areas and are exposed to the highest levels of air pollution, such policies can worsen existing inequalities. This is because the greatest benefits are experienced by the less deprived residents, and only to a lesser extent by the more deprived communities. In contrast, in cities where the city centre is home to deprived communities, for example due to lower cost housing, policies that target poor air quality in central areas are likely to result in a reduction in inequalities over time.

The trends also differ according to the air pollutant examined, for example in the Swedish cities of Malmö and Lund, while $NO_X$ concentrations decreased overall, $PM_{2.5}$ concentrations remained steady, likely due to emissions being blown in from neighbouring industrial areas and local residential combustion. In North Carolina, changes in $O_3$ concentrations did not follow those of $PM_{2.5}$, probably due to the presence of NO in urban areas which reacts rapidly to $O_3$ to form $NO_2$, leading to higher $O_3$ concentrations in rural areas.

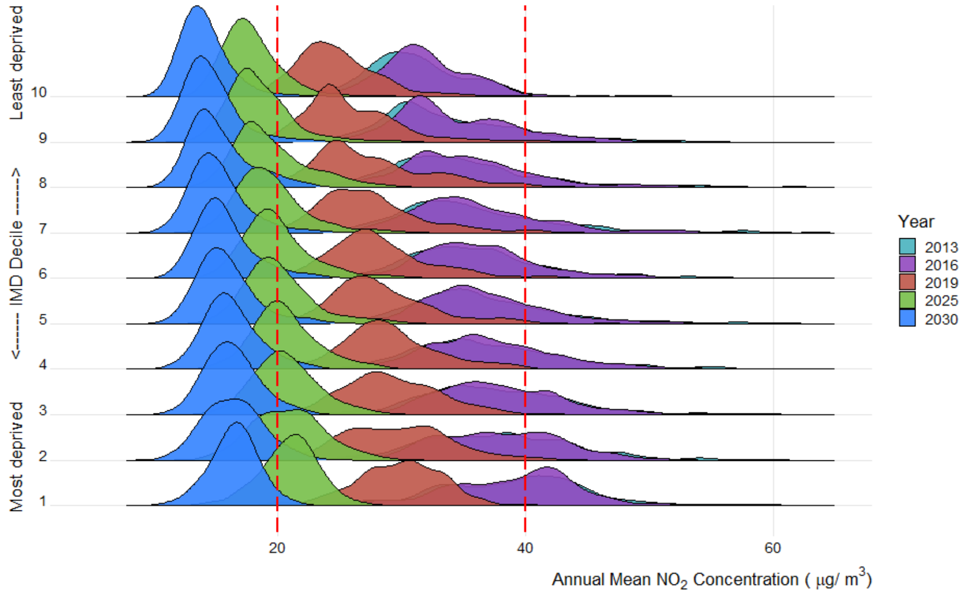
Changes in air pollutant exposure for different groups are highly specific to each city. The baselines of exposure levels are influenced by the historical trends of where jobs and low cost housing are found. The trends over time are often related to changes in road traffic and emissions from industrial areas. It is also worth noting that there are also variations in the quality of the available studies and differences in the regional scale of the data considered, the indicators used to identify social deprivation and the sources of the air quality data.

It should be noted that even if the least deprived areas have higher concentrations of air pollution compared with the most deprived areas, this does not necessarily mean that the populations are more exposed. Higher socioeconomic groups are often able to mitigate air pollution exposure to a greater extent, such as through indoor working environments rather than outdoor, private versus public transportation, and climate controlled/filtered homes.

# 4 Comparisons with London

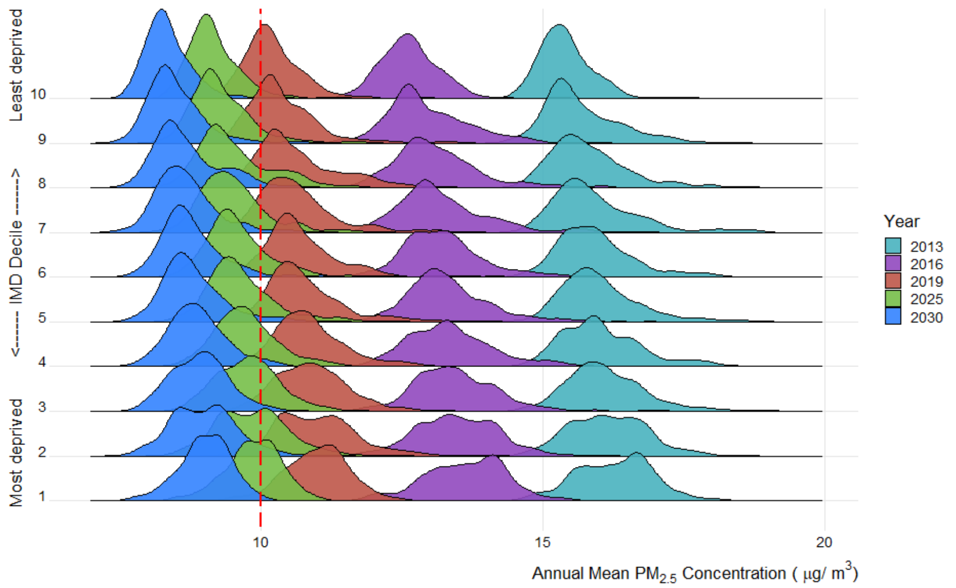
The London analysis in Part 1 of this project included an update of previous analyses of the relationship between air quality and social deprivation, undertaken by AQC (2021), Aether (2019; 2017b; 2013). Part 1 analysed the data for years 2013, 2016, 2019, and estimated future impacts based on projected air quality data for years 2025 and 2030, for pollutants $NO_2$, $PM_{10}$ and $PM_{2.5}$. The results are shown in **Figure 9** and **Figure 10** summarised in **Table 5** and **Table 6.**

*Figure 9: Average $NO_2$ exposure distributions within IMD Deciles across years.*




*Notes: Red dotted lines show current UK legal limit (40 µg/m³) and WHO interim guideline (20 µg/m³) levels. IMD = Index of Multiple Deprivation.*

*Figure 10: Average $PM_{2.5}$ exposure distributions within IMD Decile across years*



*Note: Red dotted line shows current WHO interim guideline (10 µg/m³) level. IMD = Index of Multiple Deprivation.*

*Table 5: Average $PM_{2.5}$ concentration values by deprivation decile in London*

| $PM_{2.5}$ µg/m³ | 2013 | 2016 | 2019 |
|---|---|---|---|
| **1 (most deprived)** | 16.3 | 13.6 | 11.0 |
| **2** | 16.2 | 13.5 | 11.0 |
| **3** | 16.1 | 13.5 | 10.9 |
| **4** | 16.1 | 13.4 | 10.9 |
| **5** | 16.0 | 13.3 | 10.9 |
| **6** | 15.9 | 13.2 | 10.8 |
| **7** | 15.9 | 13.2 | 10.7 |
| **8** | 15.8 | 13.1 | 10.7 |
| **9** | 15.7 | 13.0 | 10.6 |
| **10 (least deprived)** | 15.4 | 12.7 | 10.3 |

*Table 6: Average $NO_2$ concentration values by deprivation decile in London*

| $NO_2$ µg/m³ | 2013 | 2016 | 2019 |
|---|---|---|---|
| **1 (most deprived)** | 39.1 | 39.0 | 29.7 |
| **2** | 37.9 | 37.8 | 29.5 |
| **3** | 37.8 | 37.7 | 29.1 |
| **4** | 37.3 | 37.3 | 29.3 |
| **5** | 36.7 | 36.7 | 28.8 |
| **6** | 36.2 | 36.3 | 28.3 |
| **7** | 36.1 | 36.1 | 28.1 |
| **8** | 35.3 | 35.4 | 27.5 |
| **9** | 33.8 | 34.2 | 27.0 |
| **10 (least deprived)** | 31.4 | 32.0 | 25.3 |

The 2013 base year of analysis shows that in London that the most deprived deciles are on average exposed to higher $PM_{2.5}$ and $NO_2$ concentrations than the least deprived. Between 2013 and 2019, everyone saw a decrease in their average pollutant concentration exposure.

For $PM_{2.5}$, the most deprived decile saw a slightly larger absolute reduction in pollution concentrations than the least deprived, but a slightly smaller percentage reduction. However, the decreases did not vary substantially, ranging between a 5.1 µg/m³ and a 5.3 µg/m³ reduction across the deciles, or between a 32% and a 33% decrease.

For $NO_2$, the most deprived decile saw a larger absolute and percentage reduction in levels than the least deprived. This effect was more pronounced than for $PM_{2.5}$, with the most deprived decile experiencing a 9.4 $\mu g/m^3$ reduction in $NO_2$ concentrations, or 24%, between 2013 and 2019, whereas the least deprived decile saw a 6.0 $\mu g/m^3$ or 19% reduction.

The inequality gap between the pollutant exposure of the least and most deprived deciles decreased notably for $NO_2$ between 2013 and 2019, and marginally decreased for $PM_{2.5}$.

Comparison with the other six studies can only be at a broad level given the differences in years of study, granularity of data, and deprivation metrics. However, the results of the latest London analysis in Part 1 were largely similar to those of Paris and Marseille from Padilla et al. (2014), Malmö and Lund from Flanagan et al. (2019), and Aberdeen, Edinburgh, Dundee and Glasgow from Bailey et al. (2018), in that more deprived deciles of populations saw larger absolute or percentage decreases in pollutant exposure. This is the opposite of what was found in Beijing from Ma et al. (2019), Lyon and Lille from Padilla et al. (2014), Rome from Cesaroni et al. (2012), and North Carolina from Bravo et al. (2022). It is not appropriate to comment on the different rate of changes in relative exposure due to the different time periods considered in each study.

# 5 Conclusions

### Limited research has been published

Whilst considerable research has been undertaken on the relationship between air quality and social deprivation, fewer studies have focused on analysis at the city-scale, and far fewer studies again have analysed the relationship over time or considered the impacts of policy actions in terms of changes to this relationship. Of the literature that has assessed the relationship over several years, most are over a decade old. Many reference the research previously done on the unequal exposure to poor air quality in London, showing that London is leading the way in this area of work.

### Research is not directly comparable

Cities in different countries have different metrics of measuring deprivation and different air quality measurement strategies. Air pollutant concentrations are available at different levels of spatial granularity, and if data is only available as an average for a relatively large area it can hide the detail/nuance of the association with deprivation.

Different deprivation indices without a consistent definition and measurement of deprivation means that studies are not analysing exactly the same elements. Whilst high level conclusions can be drawn by grouping the research within the broad category of deprivation, specific metrics of deprivation will likely have different relationships with air quality than others, potentially leading to different results and outcomes of the studies. However, we assume that each study will have considered the best available data on deprivation relevant for the locations of study, so this is not considered a significant drawback.

### Factors behind the change in relationship

The geographical structure of social demographics in each city was found to be an important determining factor for the nature of the change in inequality in exposure to air pollution.

Frequently, air pollution is worse around high levels of road traffic, which can be in congested city centres or large trunk routes and junctions on the periphery. Since 2000, improvements in technology and tighter vehicle emissions standards have resulted in substantial reductions in road transport emissions. Coupled with the fact that air quality policies often target road traffic, the result is that the largest changes in air pollution are found in the areas around previously high-traffic routes. In some cities e.g. Rome, living close to the city centre was seen as desirable and therefore is broadly made up of higher socioeconomic groups. In this situation inequalities tend to increase as the higher socioeconomic groups benefit from larger reductions in air pollution.

In other cities e.g. Paris, living near the centre was seen as undesirable. This can result in a decrease in inequalities where the more deprived groups live close to high traffic flows, and these areas are targeted by air quality policies and so see a greater reduction in air pollution.

In the London analysis in Part 1 of the study, it was found that the inequality gap between the pollutant exposure of the least and most deprived deciles decreased slightly for $PM_{2.5}$ and substantially for $NO_2$ between 2013 and 2019. The most deprived decile experienced a larger reduction in pollutant exposure for both pollutants than the least deprived.

### Implications for policy making

It cannot be expected that air quality policies will necessarily reduce inequalities without this aim being intentionally built into the policy design. The reasons for existing inequalities need to be understood beforehand, so that the policy can target the underlying factors. The reasons will vary from city to city. The impact of policies should be monitored over time so the policy's metrics of success can be evaluated, and adjusted as needed. This requires high quality, granular data on air quality and deprivation indices.

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