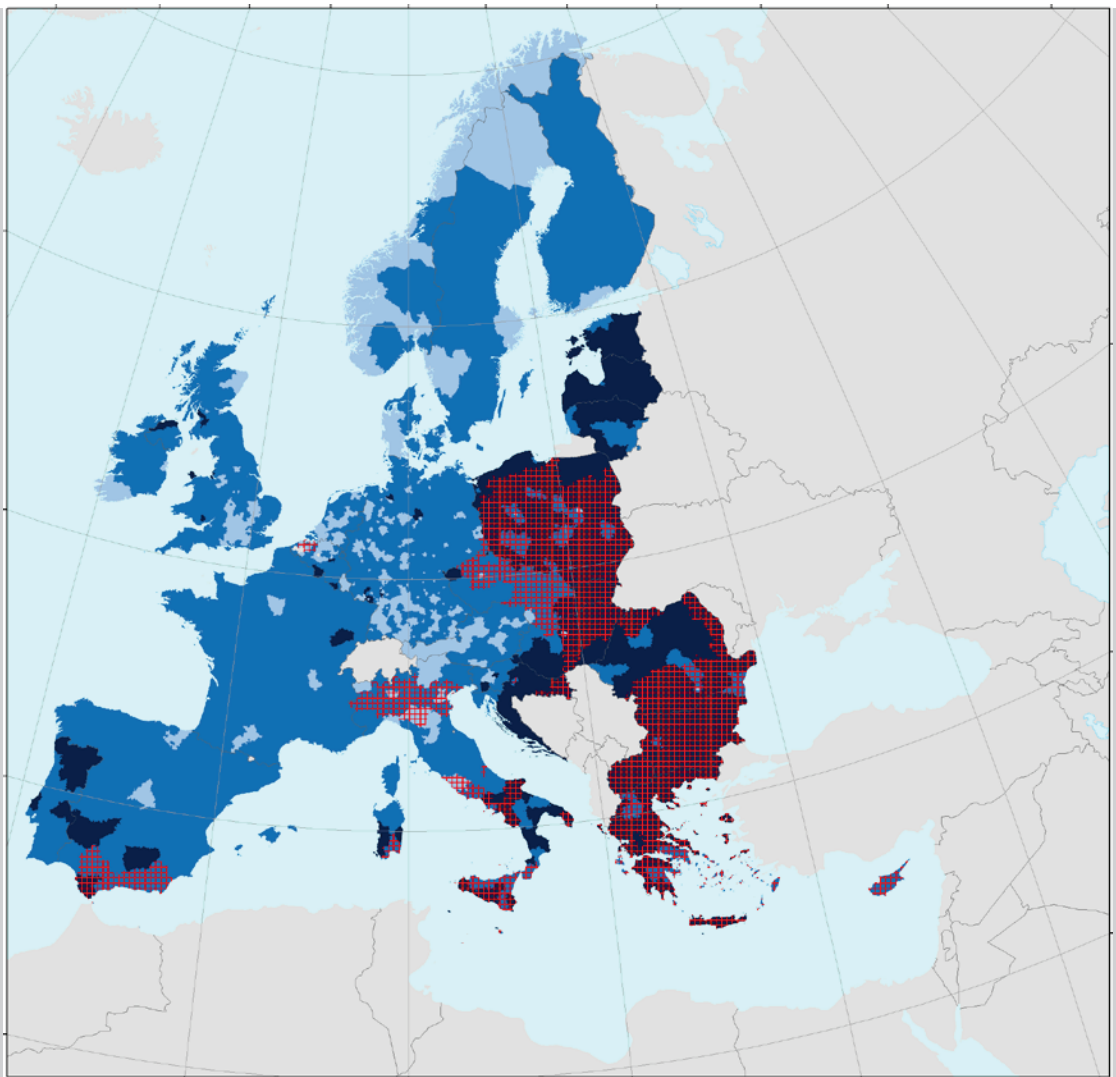
Eionet Report - ETC/ACM 2018/7

Analysis of Air Pollution and Noise and Social Deprivation

October 2018



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Cover photo – Geographic co-occurrence of exposure to PM10 pollution and GDP per capita deprivation across NUTS 3 regions. Red hatching represents regions in the top 20% for exposure to PM10 pollution, and the three grades of blue shading represent the least deprived 20%, middle 60% and most deprived 20% of regions going from lightest to darkest. Adapted from figure 5.2 in the report.

More information on the European Union is available on the Internet (http://europa.eu).

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1 Introduction

1.1 Background

The links between exposure to poor air quality and adverse health outcomes are well established, underscored by an evidence base which is both mature and extensive as described in the recent EEA report on Air Pollution in Europe (EEA, 2017). The links between ambient noise exposure and adverse health outcomes are less clearly defined but the evidence base is still strong. Effects here range from sleep disturbance to hypertension and links to cardiovascular impacts (ETC/ACM, 2016a).

What is less well understood is the role which exposure to noise and air quality plays in health inequality. It has been shown that those in society who are more deprived, socially and economically, are also likely to suffer from poor health. It is also the case that those in poor health, as well as the very old or the very young, are more likely to be susceptible to the health impacts of poor air quality. Therefore, if those in a more deprived situation, or in populations where the proportion of very old or young people are higher than average, are also exposed to higher levels of air pollution or ambient noise, it could be said that poor air quality and high ambient noise levels are exacerbating health inequalities.

The Centre for Research on Environment Society and Health (CRESH) published a report in 2013 (CRESH, 2013) examining the relationship between socio-economic inequality and exposure to air pollution in Europe. The study compared per capita Gross Domestic Product (GDP), as a proxy for social deprivation, with population-weighted concentration of PM_{10} and ozone within geographical units (NUTS 3 and NUTS 2 regions) across 27 EU countries, in 2006 and 2010. The main conclusion of the study was that:

"Whilst there is encouraging evidence demonstrating reductions in overall levels of air pollution across the EU the findings reveal that these advances have not been shared equally across all regions. Regional air pollution inequalities in the EU have narrowed slightly for short- and long-term PM_{10}, remained constant for short-term ozone, and widened for long-term ozone between 2006 and 2010. We found evidence of socioeconomic inequalities in pollution – mean PM_{10} concentrations and long-term ozone concentrations were higher in the most disadvantaged areas compared to the least disadvantaged areas. This unequal burden may partially account for the well-established social gradient in health across areas and social groups in the EU".

1.2 Aims of this report

This report was commissioned to update and extend the 2013 CRESH study, and in particular:

- Extend the measure of social deprivation to include other indicators of wellbeing and vulnerability, such as demography, education and labour market;
- Consider further air pollutants;
- Consider noise pollution as an additional environmental variable;
- Undertake analyses with cities as the spatial unit, to enable comparison of relationships across a broader range of spatial resolutions;
- Investigate whether relationships vary over time and between different parts of Europe.

The research questions which this report addresses are:

1. How does exposure to air and noise pollution vary across NUTS 3 regions of Europe, and how has the degree of variation in air pollution[1] exposure changed over time?
2. What is the relationship between per-capita GDP and exposure to air and noise pollution across NUTS 3 regions of Europe, and how has the relationship with air pollution changed over time?
3. What is the relationship between the proportion of the population that is vulnerable to air pollution (<5 years and >75 years) and exposure to air and noise pollution across NUTS 2 regions of Europe, and how has the relationship with air pollution changed over time?
4. What is the relationship between measures of social deprivation and exposure to air and noise pollution across NUTS 2 regions of Europe, and for air pollution how has this relationship changed over time?
5. What is the relationship between measures of social deprivation and exposure to air and noise pollution across different cities in Europe?
6. Concerning measures of social deprivation for which data are available at multiple levels of spatial aggregation, how do the observed relationships with air pollution differ according to the level of spatial aggregation used in analysis?
7. How do the relationships analysed above vary between different parts of Europe, or different clusters of cities and regions?

The key constraint in undertaking the analysis was the availability and compatibility of data. Member States across the EU collect and hold a variety of data on social and economic conditions, which can be used to construct standard indicators of deprivation. However, such information varies between countries in terms of its geographical coverage (i.e. all or just selected regions), time or spatial resolution, or parameter definition. This leaves a relatively limited dataset from which to construct the analysis and ensure comparisons between regions are valid.

1.3 Methods summary

This study combined population-weighted air pollution data and population exposure to noise with social indicators, to assess the extent to which these variables correlate spatially across Europe. Where the data are available the changes in patterns over time has been considered. This section provides a short summary of the methodology, a more detailed description of which is provided in **Annex 1**.

1.3.1 Air and noise pollution data aggregation

The air quality pollutants analysed in the study were nitrogen dioxide (NO_2), particulate matter (PM_{10} and $PM_{2.5}$) and ozone (O_3), based on interpolated 1 km by 1 km concentration grids. These pollutants are those that currently pose a bigger risk to human health in Europe. To combine these data with social indicators, the pollution grids were combined with population data to calculate population-weighted average concentrations for each geographical unit. This gives a concentration value representing typical exposure for a person living in that area. Air pollution data are available for various years across the study timeframe (2005 -2014), and the years vary depending on the pollutant. Population-weighted pollutant concentrations were combined to calculate averages across short periods, to be combined with social indicators representing the same time periods. A table showing the years available and used in this study is included in **Annex 1**. For brevity, hereafter population-weighted concentration is also referred to as “exposure” (or “pollution”), although it is recognised that a range of other factors affect the true exposure of any given individual.

1 Noise exposure data are only available for one year

The noise indicators used in this study were the proportion of people exposed to 24-hour average road noise levels of 55dB or more (L_{den} ≥55dB) and the proportion of people exposed to night-time average road noise levels of 50dB or more (L_{night} ≥50dB). Two different datasets were used to compile this data for NUTS regions and cities: (1) estimates of the number of people exposed to noise from roads within urban areas containing 100 000 people or more ("agglomerations") reported under the Environmental Noise Directive (END); and (2) an interpolated road noise map covering areas outside of agglomerations at 1x1 km resolution. The second dataset has greater uncertainty than the first, as it extends the coverage to areas for which no data has been reported by Member States. This analysis uses only the road noise data reported under the END in 2012, which relates to the situation in 2011. When comparing noise exposure to social indicators, the calendar year is taken to be 2011.

1.3.2 Geographic scope and breakdown

The analysis encompasses several levels of spatial granularity: two levels of administrative areas across Europe at different scales (NUTS3 regions and NUTS2 regions) and also for cities covered by the Urban Audit database (Eurostat, 2018a). This allows the consideration of a wide range of social indicators (see below), but also the comparison of results among different levels of granularity.
The main analysis in this study focus on patterns seen across the whole of Europe (subject to data availability in individual cases). However, in order to investigate possible regional differences, the analysis was also repeated for smaller groupings of countries following the United Nations Statistics Division (UNSD) classification of European countries into Northern, Eastern, Southern and Western Europe (UNSD, 2018).

1.3.3 Choice of social indicators

Social indicator datasets were obtained from Eurostat (Eurostat, 2018a), and different indicators are available at each geographical scale. Only GDP per capita data is available at NUTS 3 level to reflect social deprivation, whereas many other more relevant datasets are available at NUTS 2. Cities have been included as a third scale because additional indicators are available at that scale, and because cities are areas where exposure to environmental stressors and deprivation tend to coincide. The indicators chosen for the full analysis are listed in **Table 1.1** below, with more details available on each in the **Annex 1**. Some other datasets were considered but either there were more salient results using similar alternative indicators or the data coverage was not good enough to include in the results.

In order to make the results simpler to interpret, some indicators were converted so that high values always represent higher deprivation or vulnerability. For example, the percentage of population with higher education was converted to the percentage without higher education to represent higher education deprivation.

Where possible we considered how patterns in the data and relationships have changed over time, between 2005 and 2014.

Table 1.1 Summary of social indicator datasets

Spatial scale	Theme	Indicator definition	Indicator short name used in tabulated results
NUTS 3	**Economy**	Per capita GDP, Purchasing Power Standard (PPS)	GDP per capita deprivation
NUTS 2	**Economy**	Per capita household income after social transfers, Purchasing Power Standard (PPCS)	Household income deprivation
	Demography	Percentage of population aged < 5 years	Proportion under 5 years
		Percentage of population aged >= 75 years	Proportion 75 years and over
	Labour market	Long-term unemployment (12 months or more) rate, % of economically active population	Long-term unemployment
	Education	Percentage of people aged 25-64 with ISCED level 5-8 as the highest level of education	Higher education deprivation
Cities	**Demography**	Percentage of population aged < 5 years	Proportion under 5 years
		Percentage of population aged >=75 years	Proportion 75 years and over
	Labour market	Unemployment rate (% of economically active population)	Unemployment
	Education	Percentage of people aged 25-64 with ISCED level 5-8 as the highest level of education	Higher education deprivation
	Health	Death rate per year under 65 years due to diseases of the circulatory or respiratory systems	Respiratory disease death rate
	Landscape	Population without green urban areas in their neighbourhood (% of total population).	Green space deprivation

Note: Detailed information regarding the definitions and sources of the social indicators is available in **Annex 1**.

1.3.4 Analysis methods

In order to analyse the degree of variation in pollution exposure and the association between pollution exposure and social deprivation or vulnerability, a combination of data visualisation and numerical summary statistics was used. The charts and maps provide a rich source of information to facilitate interpretation of patterns, but objective comparisons among pollutants or over time are difficult. In contrast, numerical summary statistics are more abstract, but are well suited to objective comparisons.

To analyse the degree of geographic variation in pollution exposure and change over time, choropleth maps of pollution exposure and rank-value plots showing the spread of exposure values at each time point were created to visualise geographic variation. The absolute and relative difference in pollution exposure between the most and least polluted 20% of regions or cities was also calculated, to summarise geographic variation numerically. Statistics on pollutant exposure in isolation are only presented for NUTS 3 regions, because this spatial scale represents the best balance between geographic coverage and detail.

To analyse associations between air pollution or noise exposure and social indicators, the Spearman’s rank correlation coefficient and the absolute and relative difference in pollution exposure levels between the most and least deprived/vulnerable quintile (20% of regions/cities) were calculated. To display associations visually, box and whisker plots were used to show pollution levels in each deprivation/vulnerability quintile, and overlap maps were created to illustrate the spatial co-occurrence of pollution and deprivation/vulnerability.

More information about these summary statistics and visualisations are provided in the next section.

1.4 How to interpret the figures, charts and maps in this report

This section describes how the various charts, maps and summary statistics used throughout this report should be interpreted.

1.4.1 Spearman's rank correlation coefficient

In this report, correlation coefficients are used to quantify the degree of spatial association between a measure of deprivation/vulnerability and pollution exposure. Spearman's rank correlation is a variant which first converts values to ranks, thereby decreasing the influence of extreme values. Correlation can range between -1 and 1.

- Positive numbers indicate that areas with higher deprivation/vulnerability tend to have higher pollution exposure, with 1 being the strongest association possible
- Negative numbers indicate that areas with higher deprivation/vulnerability tend to have lower pollution exposure, with -1 being the strongest association possible
- Values close to zero indicate that there is little association between deprivation/vulnerability and pollution exposure.

Note that the correlation coefficients presented here are purely descriptive statistics, with no implication for causal relationships and no statistical significance level attached. Statistical significance levels were not reported because the data used in this study does not satisfy the necessary assumptions. The data used either represents a whole population (or in some cases a non-random subsample where data is missing), rather than a random sample which is required for the significance level to be meaningful.

1.4.2 Pollution levels by pollution or deprivation quintile

The second main type of statistic reported in this study is the comparison of mean pollution levels in the most polluted or deprived 20% (quintile) and least polluted or deprived 20% of regions/cities, in order to quantify “inequality”.

Both the absolute difference and relative difference (ratio) are presented. Measures of relative difference, such as the ratio of the top and bottom quintiles or the Gini index (provided in **Annex 2**) are commonly used measures of inequality in the literature (e.g. CRESH 2013), particularly when considering measures of wealth. However, when considering physical exposure to pollution, the absolute difference (in units of pollutant concentration or proportion of population exposed to noise) may better represent the difference in health impacts.

Comparison of pollution levels across quintiles is used to summarise two different types of inequality:

- When describing the overall variation in pollution exposure, independently of any other variable, the absolute difference and ratio of the mean pollution levels in the **most polluted 20%** (5th quintile, Q5) and **least polluted 20%** (1st quintile, Q1) of regions is reported. Higher numbers indicates a greater range of pollution levels across Europe

- When describing the association between pollution exposure and a measure of deprivation or vulnerability, the absolute difference and ratio of mean pollution levels in the **most deprived or vulnerable 20%** (5th deprivation quintile, DQ5) and **least deprived or vulnerable 20%** (1st deprivation quintile, DQ1).

- An absolute difference of 0 or ratio of 1 means that there is no difference in pollution exposure between regions with different levels of deprivation/vulnerability. Positive absolute differences and ratios > 1 indicate the most deprived 20% of regions have higher pollution levels than the least deprived 20%. Negative absolute differences and ratios < 1 mean the opposite.

1.4.3 Colour-coding in tables

A blue-white-red colour scale is used in this report to facilitate the interpretation of tables reporting the association between pollution exposure and measures of deprivation or vulnerability (e.g. **Table 3.2**). Red colours correspond to cases where higher pollution exposure is found in **more** deprived/vulnerable areas, and blue colours to cases where higher pollution exposure is found in **less** deprived/vulnerable areas. Increasing intensity of colours indicates increasing strength of association or inequality, with white signifying no association or inequality.

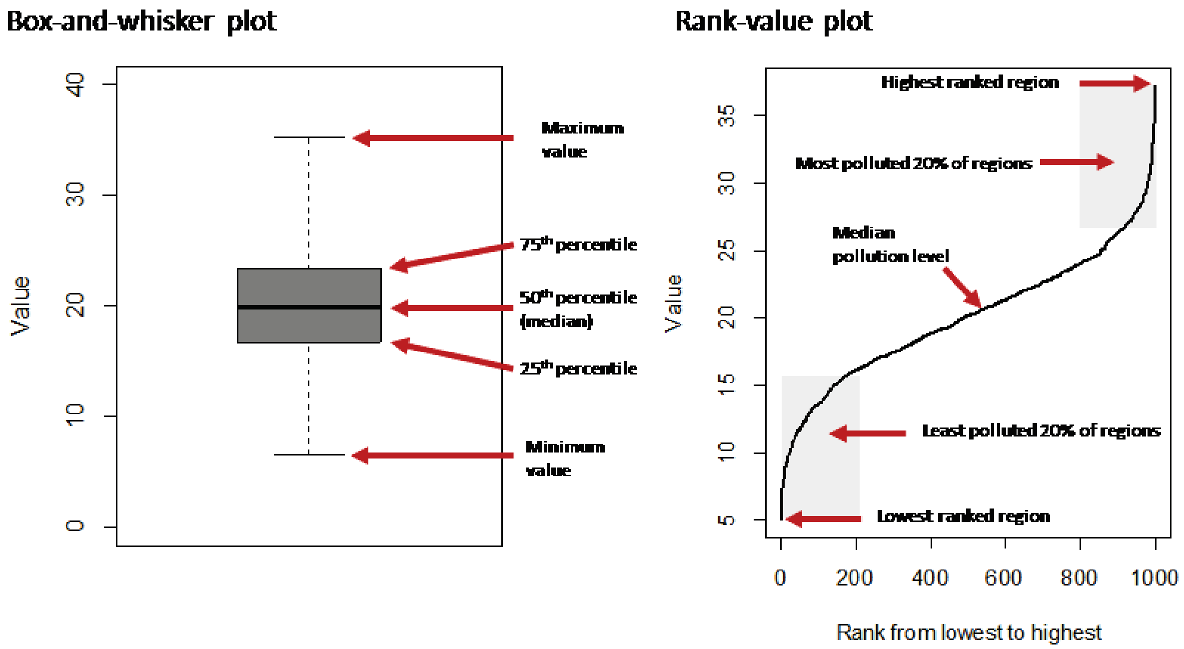
The colour-coding aims to help visualise changes in a given measure of association or inequality over time, and differences between different combinations of pollutant and social indicator. However, the colour scales are **not comparable between the different kinds of statistic**; i.e. the colour-scale used for the Spearman's rank correlation coefficient should not be compared to that used for the ratio or absolute difference between most and least deprived quintiles.

1.4.4 Box-and-whisker plots and rank-value charts

Box-and-whisker plots are a way to illustrate the spread of values of a variable, where each part of the box and whiskers represent a different percentile of the distribution. The interpretation of the box-and whisker plots in this report is given in the left-hand side of **Figure 1.1** below.

Rank-value plots are a more detailed way of showing the spread of values of a variable, used in this report to show the spread of pollution exposure at different time-points. Rank-value plots simply show the pollution exposure in every NUTS 3 region on the y-axis, when NUTS 3 regions are ordered from lowest to highest pollution exposure along the x-axis (i.e. the x-axis scale is the pollution exposure ranking). A flatter line indicates less variation among regions, and a steeper line more variation.

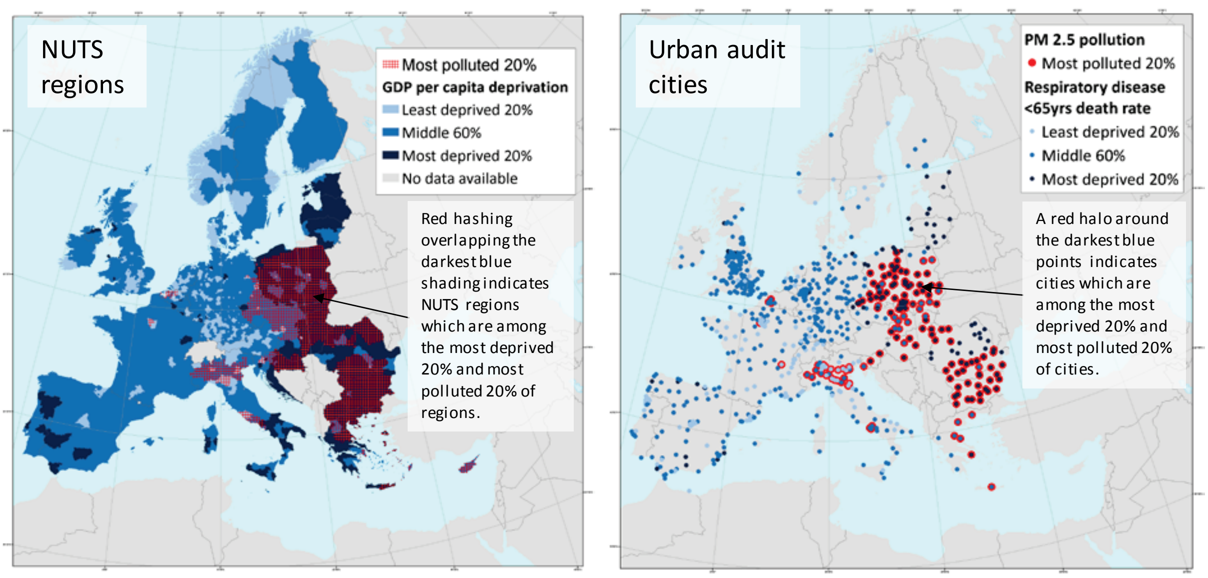
Figure 1.1 **Schematic charts illustrating how to interpret box-and-whisker plots (left) and rank-value plots (right)**



1.4.5 Overlap maps

In this report, overlap maps are used to illustrate the location of areas of Europe where high pollution and high deprivation levels co-occur (**Map 1.1**).

Map 1.1 **Examples of overlap maps used in the report for assessing the geographic co-occurrence of pollution exposure and deprivation or age-related vulnerability, for NUTS 2 or 3 regions (left) and for Urban Audit Cities (right)**



In each map, the relative degree of deprivation or vulnerability of a NUTS region or city with respect to a specific social indicator is represented by varying shades of blue. The least deprived or vulnerable 20% of regions or cities have the lightest blue shading, the middle 60% have a medium blue shading, and the most deprived or vulnerable 20% have the darkest blue shading. In parallel, the most polluted 20% of regions with respect to a specific pollutant are shaded red; red hashing for NUTS 2 or 3 regions, and a red halo around points for Urban Audit Cities.

Therefore, regions or points where the darkest blue shading and red hashing or a red halo coincide are those belonging to both the most polluted 20% and most deprived or vulnerable 20% of regions, with respect to the specific social indicators and pollutants in question.

2 Key Findings

The statistical analysis undertaken for this report has sought to identify some of the relationships between indicators of deprivation or vulnerability and exposure to either air pollution or ambient noise. The picture revealed in the report is complex, and the datasets are not necessarily complete, especially at the city scale; some of the data issues are discussed below and in **Section 8**.

The patterns and correlations identified vary between the different pollutants, across the different indicators and between European regions. These variations are examined in later sections looking at each pollutant individually. However, **the overall finding is that there is, in general, a positive correlation between exposure to higher levels of air pollution, and ambient noise, and social deprivation, at the scales analysed**. That is, those in socially or economically deprived situations are more likely to be exposed to higher levels of the pollutant in question. **These findings support those reported in the 2013 CRESH study**.

However, **the general finding is that exposures to air pollution[2] have reduced over time and that those in socially or economically deprived situations have generally benefited at least as much as those in the least deprived communities**. In this analysis we have considered both relative and absolute differences in pollution exposure as measures of inequality, and found that by both measures the level of inequality has remained similar over the period studied.

Summary findings are presented below and presented in detail in the chapters that follow. A brief response to the research questions is also provided in Annex 3. Note that for all of the indicators analysed, the higher the value, the greater the level of deprivation, vulnerability or exposure. For example, a correlation between high values for pollutant exposure and high values for long-term unemployment indicates that the population in areas of higher long-term unemployment will also tend to be exposed to higher levels of pollution.

2.1 Associations between pollution exposure and deprivation or vulnerability

Considering the data for the latest years covered in this study, the association between exposure to air or noise pollution and levels of deprivation or vulnerability varied substantially, depending on the pollutant and measure of deprivation in question. **Table 2.1** illustrates this by showing the Spearman's rank correlation between each pair of social indicator and pollutant, in the latest year available. Specifically:

- Exposure to NO_2 tended to be higher in **less** deprived regions for most social indicators (negative, blue-shaded values); a pattern observed at both NUTS 2 and NUTS 3 scales. The association was strongest for economic measures of deprivation (GDP per capita and household income).
- In contrast, for the other three air pollutants ($PM_{2.5}$, PM_{10} and ozone), pollution exposure tended to be higher in **more** deprived areas, for the majority of measures of deprivation considered in this study (positive, red-shaded values).
- The strongest associations between economic deprivation and pollution exposure were seen for PM_{10}, with regions both relatively deprived and polluted occurring in **Eastern and South-Eastern parts of Europe**.

[2] Only one year of data on noise exposures is available and so a comparison over time is not possible.

- For ozone exposure, the strongest associations were found with long-term unemployment and higher-education deprivation, where regions relatively deprived and polluted occurred in **Southern parts of Europe**.
- Of the air pollutants, ozone is the only one with a relatively strong association with age-related vulnerability, with higher exposure in NUTS 2 regions and cities with a greater proportion of elderly (>=75 years), and lower exposure in regions with a greater proportion of infants (< 5 years).
- In general, there was less association between noise exposure and measures of deprivation than was found for air pollutants. This may relate to noise exposure varying predominantly at the local scale, which could not be detected in this analysis. However, when interpreting the results for noise exposure, it must be noted that there is greater uncertainty and potential inconsistency among countries in estimation of noise exposure, in comparison to air pollution.
- At the NUTS 2 and NUTS 3 levels, the different social indicators chosen to represent deprivation tended to all have the same qualitative association with air pollution exposure. For example, Spearman's rank correlations between NO_2 and all deprivation-related indicators (i.e. not included age-related vulnerability) were all negative, whereas they were all positive for $PM_{2.5}$, PM_{10}, and ozone (**Table 2.1**). No such consistency was found at the Urban Audit city level., or for noise exposure.

Table 2.1 Spearman's rank correlation coefficients illustrating the strength and direction of associations between exposure to air and noise pollutants and indicators of deprivation and vulnerability

Spatial scale	Social indicator	Spearman's rank correlation					
		NO_2	$PM_{2.5}$	PM_{10}	O_3	L_{den} ≥55dB	L_{night} ≥50dB
NUTS 3	GDP per capita deprivation	-0.49	0.22	0.33	0.16	-0.09	-0.04
NUTS 2	Higher education deprivation	-0.21	0.46	0.49	0.51	0.03	0.06
	Household income deprivation	-0.44	0.31	0.47	0.12	0.21	0.22
	Long-term unemployment	-0.22	0.28	0.49	0.50	0.04	0.08
	Proportion 75 years or over	-0.14	-0.16	-0.13	0.31	-0.10	-0.09
	Proportion under 5 years	0.06	-0.25	-0.24	-0.46	-0.04	-0.04
Urban Audit Cities	Higher education deprivation	0.04	0.17	0.22	0.12	0.07	0.04
	Unemployment	-0.29	-0.10	0.27	0.37	0.26	0.30
	Proportion 75 years or over	-0.05	-0.07	-0.12	0.32	0.02	0.05
	Proportion under 5 years	0.20	-0.23	-0.20	-0.42	0.01	0.02
	Respiratory disease death rate	-0.27	0.28	0.17	-0.19	0.06	0.02
	Green space deprivation	-0.13	0.13	0.16	0.08	0.11	0.13

Note: All correlations are reported for the latest year considered (2013-14 for air pollutants at NUTS 2 and 3 scales, 2011 for noise pollution, 2010-12 at Urban Audit city scale).

The differences observed between pollutants in their relationship with deprivation can to a certain extent be explained by their rather different spatial patterns across Europe. Exposure to NO2 follows a relatively fine-grained urban to rural patterning, so is associated with other variables which follow the same gradient (such as GDP per capita). In contrast, exposure to particulate matter and ozone follow large-scale East-West and South-North gradients respectively, so they seem to be associated with social indicators which follow these same large -scale gradients (such as long-term unemployment in Southern Europe). See also **Section 8** for consideration of the limitations of the data.

2.1.1 Comparison across spatial scales

Where similar social indicators were available at more than one level of spatial aggregation, a comparison across scales is possible. The findings were mixed:

- The associations between GDP per capita deprivation and air pollution exposure at the NUTS 3 level showed the same qualitative pattern as for household income deprivation at the NUTS 2 level.
- The same was true for the associations between the share of old and young people in the population and air pollution exposure at the NUTS 2 and Urban Audit city scales.
- In contrast, the direction of the association between higher education deprivation and NO_2 exposure at the NUTS 2 level differed to that seen at the Urban Audit city level. The same was true of the association between long-term unemployment and $PM_{2.5}$ exposure.

Where relationships are similar across scales, this may indicate that regional and national level variations in both social indicators and pollution exposure are being detected at all scales. Where they differ between NUTS 2 and Urban Audit city scales, this could be partly due to incomplete coverage for some indicators at the Urban Audit city scale, but also due to urban-rural gradients in some variables. The NUTS 2 level of aggregation combines together many urban areas with more rural surroundings, whereas the Urban Audit city scale exclude most rural areas from the analysis.

2.1.2 Comparison between country-groupings

Separate analyses were undertaken to investigate the association between pollution exposure and social indicators within smaller groups of countries, defined by the UN Statistics Division groupings of Northern, Southern, Eastern and Western Europe. Differences in the associations were found between the different groupings for all pollutant and social indicator combinations. However, due to the slightly arbitrary nature of the grouping it is difficult to interpret these differences.

Nonetheless, a key finding from the country-grouping analysis was that for $PM_{2.5}$, PM_{10} and ozone, the associations with social indicators within individual country groups tended to be weaker than the association across the whole of Europe. This is likely due to the dominance of large-scale variation in PM and ozone pollution levels, meaning that pollution varies much more between country groups than within country groups. This result underlines the crucial role of the geographic extent in determining the results obtained from correlational studies such as this.

2.2 Change over time in inequality in pollution exposure between more and less deprived regions

The extent to which relative and absolute inequality in pollution exposure, between the most and least deprived areas of Europe, has reduced or increased over the period studied depends on the pollutant and measure of deprivation in question.

Generally, the ratio of least to most deprived - i.e. relative inequality - is considered the most relevant measure of inequality, often used to quantify inequalities in wealth. In contrast, the health effects of air pollution are often associated with the absolute exposure and for pollutants where the dose response relationship is linear (as is suggested for $PM_{2.5}$), the health benefit is derived from the absolute reduction in exposure concentration regardless of the initial concentration level. Therefore, in this study both the relative and absolute inequality in pollution exposure are considered.

Table 2.2 shows the change in the ratio and absolute difference in pollution exposure in the most and least deprived 20% of NUTS regions, between the first time-point studied and 2013-14. An increase in the ratio (red shaded cells) indicates an increase in pollution exposure for the most deprived 20% of regions relative to the least deprived 20% of regions. A decrease in the ratio (green shaded cells) indicates the opposite trend. Negative changes (green text) in the absolute difference indicate that pollution exposure in the least deprived quintile of regions reduced more than in the most deprived quintile, and positive changes (red text) indicate the opposite.

Table 2.2 Change over time in the ratio and absolute difference in pollution exposure for the most deprived or vulnerable 20% and least deprived or vulnerable 20% of regions, between the first time-point and 2013-2014

Spatial scale	Social indicator	Change in DQ5/DQ1 pollution ratio				Change in DQ5-DQ1 pollution difference			
		NO_2	$PM_{2.5}$	PM_{10}	O_3	NO_2 (μg/m³)	$PM_{2.5}$ (μg/m³)	PM_{10} (μg/m³)	O_3 (μg/m³·days)
NUTS 3	GDP per capita deprivation	-0.02	0.02	0.14	0.08	1.2	-0.2	0.5	46
NUTS 2	Higher education deprivation	-0.10	0.01	0.07	0.03	-1.8	-0.6	-1.6	-675
	Household income deprivation	-0.03	0.08	0.15	0.16	0.9	0.5	0.1	530
	Long-term unemployment	-0.11	-0.11	0.16	0.31	-1.6	-1.8	0.3	665
	Proportion 75 years or over	-0.14	0.01	0.08	0.34	-2.5	0.5	3.4	883
	Proportion under 5 years	0.01	0.06	0.10	-0.03	-0.2	1.4	4.2	407

Note: First time-points were NO_2 = 2007, $PM_{2.5}$ = 2007-8, PM_{10} and O_3 = 2005-6. Positive numbers (red) signify that relatively more deprived areas are becoming relatively more polluted over time, and negative numbers (green) indicate the opposite.

Changes in the absolute difference (DQ5 – DQ1) generally followed the same direction as changes in the ratio (DQ5 / DQ1). One exception to this is for particulate matter and ozone exposure across levels of higher education deprivation, where although the ratio of exposure increased slightly, the absolute difference in exposure decreased.

It is clear from **Table 2.2** that for PM_{10} and ozone exposure especially, both relative and absolute inequality by some measures of deprivation and vulnerability has become worse over time. For example, in 2005-6, the 20% of NUTS 2 regions with the highest long-term unemployment rate had 1.44 times the ozone exposure than those 20% with the lowest rate, but in 2013-14 this ratio had increased to 1.74 (that is why a red value of 0.3 appears in the table).

However, these changes must be put into the context of the general decline in pollution exposure seen for all deprivation quintiles over the time period studied. With some exceptions (such as ozone exposure and long-term unemployment), in general even where the most deprived 20% of regions have become **relatively** more exposed (compared to the least deprived 20%), the **actual level of** pollution exposure in the most deprived 20% of regions has nonetheless fallen.

In contrast to PM_{10} and ozone, relative and absolute measures of inequality in $PM_{2.5}$ and NO_2 exposure across deprivation levels has remained similar over time, or even changed in favour of the most deprived regions. In the case of NO_2 this was manifested in an increasingly strong tendency for the **least** deprived regions to experience higher exposure than the more deprived regions. While technically this is also an increase in inequality, the main concern for this study is greater pollution in more deprived areas.

Note that change in inequality over time could not be investigated for measures of noise exposure, or for Urban Audit city-level indicators, because data was only available for a single time-point in these cases.
Summaries of the answers to the specific research questions posed in section 1.2 can be found in Annex 3.

2.3 Data and methodological issues

This section summarises the key issues with regard to the availability and quality of data, the scales at which the data were available and the impact that has on the findings set out above. These issues are discussed in greater detail in **Section 8**. It is important to note that the analysis is dependent on the availability of data and, crucially, the geographical resolution of those data. In particular:

- **Spatial scale**: there is a significant variation in correlations depending on geographic resolution of the analysis. For example, a NUTS 3 area could be identified as an area of lower deprivation but still contain areas of relatively high deprivation which this analysis cannot identify. For example, analysis undertaken on behalf of the Greater London Authority (Aether, 2017) showed a positive correlation between deprivation and concentrations of NO_2, whereas this analysis indicates a negative correlation. This is because, at the scale of this analysis, London is shown as relatively wealthy, with high levels of employment and high educational indicators. However, the average for London is skewed by some areas of very high wealth, which outweigh those areas with high levels of deprivation relative to the rest of the UK.

- **Air pollution data**: ambient concentrations of air pollutants vary according to meteorology as well as long term emission trends. Where possible 2-3 year averages have been used to smooth out meteorological variation but this will remain within the data and will impact on both the correlations shown and their trends. In addition, data have been sourced from measurements complemented with modelling results which do not always replicate accurately the fine spatial variation in concentrations, especially for reactive pollutants such as NO_2. Finally, population weighted concentrations have been used as a proxy for average personal exposure when, in fact, the individual exposure tends to be far more complex and variable.

- **Noise exposure data**: the main source of noise exposure data is that which has been reported by Member States under the Environmental Noise Directive (2002/49/EC). The methods for estimating such data vary between Member States and, in any case, generally only address noise from transport sources. Moreover, it has been assumed that exposure is uniformly distributed within agglomerations. In reality, there are many more sources of noise and ambient levels will vary considerably across short distances. This may account for the relatively weak correlations seen for noise when compared to “urban” air pollutants such as NO_2.

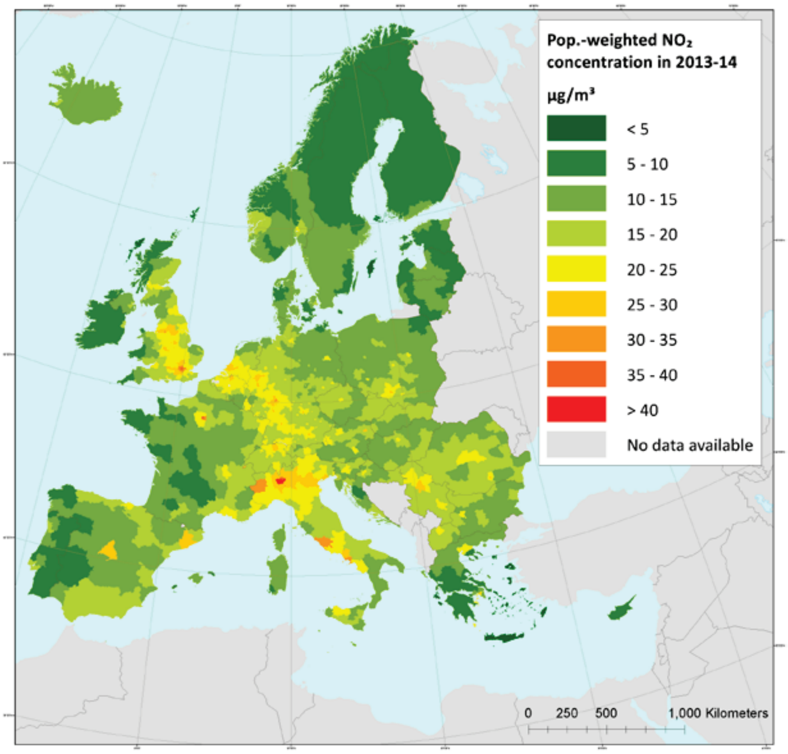
- **Social indicators**: Social indicator data was obtained predominantly from Eurostat (Eurostat, 2018a). The main data quality issue encountered was the poor geographic and temporal coverage of some of the indicators available. To a large extent this issue was solved by excluding indicators with poor coverage from the analysis. However, even for indicators where a high proportion of NUTS regions and/or Urban Audit cities have data, if data for key countries (i.e. countries which may have a large impact on the observed association) is missing this could strongly affect the association found.

- **Regional analysis**: the country groupings used for this analysis to represent European regions were aligned with United Nations classifications of Northern, Southern, Eastern and Western Europe. In terms of this study, these groupings are relatively arbitrary and place apparently similar states in different groups. Moreover, it was not possible to undertake an analysis based on urban and rural areas, despite this appearing to be an important variable. Future studies of this nature would benefit from a more rational grouping system and more data classified by urban and rural areas.

3 Nitrogen dioxide

3.1 Geographic variation in NO_2 exposure and change over time

Map 3.1 NO_2 exposure in NUTS 3 regions, 2013-2014



In 2013-14, the level of NO_2 exposure in NUTS 3 regions varied between concentrations of 1 and 43 µg/m^3. Higher values seem to be associated with more urban units, and lower values with more rural areas throughout Europe. There is no large-scale North-South or East-West patterning of concentration values, but more densely populated regions of Europe seem to have generally higher values (**Map 3.1**).

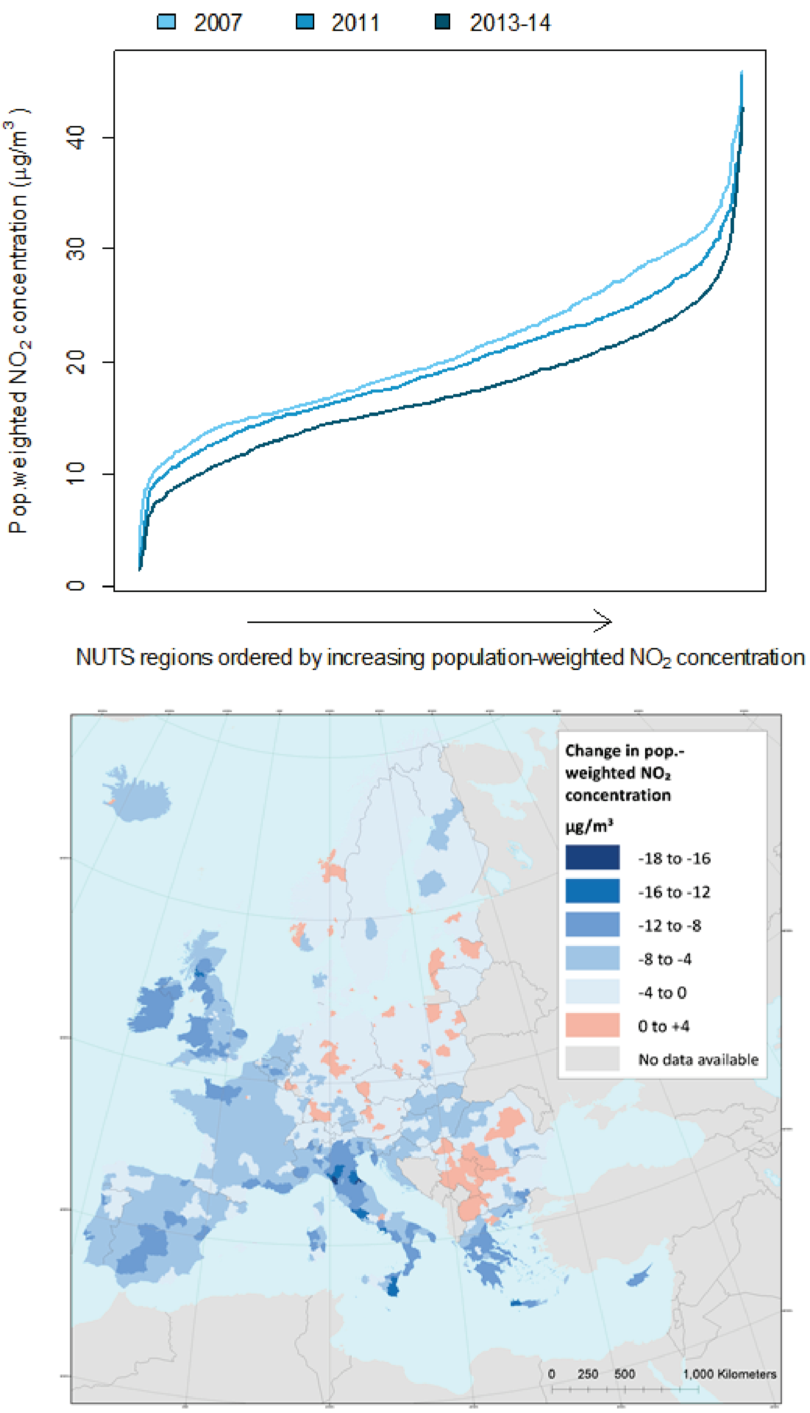
Table 3.1 NO_2 exposure in the most and least polluted 20% of regions, and change over time

NO_2	Mean population-weighted concentration (µg/m^3)						
Year	Least polluted 20% (Q1)	Q2	Q3	Q4	Most polluted 20% (Q5)	Ratio of Q5/Q1	Absolute difference (Q5-Q1)
2007	12.7	16.7	20.1	24.5	31.5	2.47	18.8
2011	11.5	16.1	19.2	22.8	28.7	2.49	17.1
2013-14	9.6	14.2	16.7	19.8	25.7	2.67	16.1

In 2013-14, NO_2 exposure in the most polluted 20% of NUTS 3 regions was on average 2.67 times that in the least polluted 20% of NUTS 3 regions, with concentrations of 26 and 10 µg/m^3 respectively (**Table 3.1**).

Between 2007 and 2013-14, most regions saw a decrease in NO_2 exposure, with parts of Italy seeing the largest decreases and only a few regions seeing small increases (**Figure 3.1**). Moreover, average NO_2 exposure in the most polluted 20% of regions (Q5) reduced to a greater extent than in the least polluted 20% of regions (Q1), leading to a decrease in the absolute difference in NO_2 exposure between Q5 and Q1, from 19 to 16 µg/m^3. However, the ratio of Q5/Q1 did not decline, increasing slightly from 2.47 in 2007 and 2.67 in 2013-14 (**Table 3.1**).

Figure 3.1 **Top: Rank-value chart showing the distribution of NO_2 exposure in 2007, 2011 and 2013-14. Bottom: Map showing the absolute change in NO_2 exposure in each NUTS 3 region, between 2007 and 2013-2014**



3.2 Relationship with deprivation-related variables, and change over time

Overall, NO_2 exposure was lower in more deprived areas and higher in less deprived areas across the time period in question, for most of the indicators of deprivation or vulnerability considered in this study. This is reflected in the predominance of negative correlations and pollution ratios below seen in **Table 3.2**.

Specific findings:

- More deprived regions tended to have lower NO_2 exposure than less deprived areas according to GDP per capita at NUTS 3, and household income, higher education and long-term unemployment at NUTS 2
- For GDP per capita at NUTS 3, the wealthiest 20% of regions in 2013-14 were exposed to NO_2 concentrations around 8 µg/m^3 higher – around 1.6 times the concentration – than the poorest 20% of regions
- Age-related vulnerability (% of people <5 or > 75) did not strongly correlate with NO_2 exposure at the NUTS2 or city scale
- Unemployment and the death rate of people under 65 from respiratory diseases in Urban Audit cities in 2011-12 was lower in those cities having higher levels of NO_2 exposure

  The associations found have been fairly stable across the time period considered (2007 - 2013-14), though have become slightly more pronounced at the NUTS 2 scale for higher education deprivation, long-term unemployment, and the proportion of people over 75 years in the population. This equates to an increase in inequality of NO_2 exposure across levels of deprivation over time, but increasingly in favour of more deprived areas.

Table 3.2 Association of NO_2 exposure with social indicators at the NUTS3, NUTS 2 and City scales, and change over time

Spatial scale	Social indicator	Spearman's correlation			Pollution ratio DQ5/DQ1			Pollution difference DQ5-DQ1 (µg/m^3)		
		2007	2011	2013-2014	2007	2011	2013-2014	2007	2011	2013-2014
NUTS 3	GDP per capita deprivation	-0.45	-0.41	-0.49	0.64	0.69	0.63	-9.3	-7.4	-8.1
NUTS 2	Higher education deprivation	-0.17	-0.17	-0.21	0.93	0.89	0.83	-1.6	-2.4	-3.4
	Household income deprivation	-0.45	-0.41	-0.44	0.67	0.72	0.65	-8.5	-6.7	-7.6
	Long-term unemployment	-0.13	-0.18	-0.22	0.93	0.86	0.82	-1.5	-2.9	-3.1
	Proportion 75 years or over	-0.01	-0.11	-0.14	0.96	0.87	0.82	-0.9	-2.5	-3.3
	Proportion under 5 years	0.15	0.04	0.06	1.11	1.04	1.12	2.3	0.8	2.1
			2011-2012			2011-2012			2011-2012	
Urban Audit Cities	Higher education deprivation		0.04			0.99			-0.3	
	Unemployment		-0.29			0.85			-3.7	
	Proportion 75 years or over		-0.05			0.96			-0.9	
	Proportion under 5 years		0.20			1.18			4.0	
	Respiratory disease death rate		-0.27			0.80			-4.9	
	Green space deprivation		-0.13			0.90			-2.2	

Note: See section 1.4 for interpretation of Spearman's correlation, and pollution ratio and pollution difference between Q5 and Q1.

Perhaps surprisingly, given the link between NO_2 pollution and urban areas, the association between NO_2 exposure and both economic and unemployment measures seem to be similar across the three different levels of aggregation (NUTS3, NUTS 2 and Urban Audit cities) where indicators are comparable. In particular, GDP per capita deprivation at NUTS 3 level and household income deprivation at NUTS 2 level, and the unemployment indicators at NUTS 2 and Urban Audit city level all show a negative correlation with NO_2 exposure. If urban-rural gradients dominate variation in NO_2 exposure, one might expect little variation in NO_2 exposure between different Urban Audit cities across Europe. However, it seems that the cities with the highest NO_2 exposure tend to be clustered in particular parts of Europe, which have lower levels of unemployment and respiratory disease (see e.g. **Figure 3.4**).

In contrast, while NO_2 exposure was higher for areas with lower higher education deprivation when considered at the NUTS 2 scale, there was very little difference when considered at the Urban Audit city scale. This may be partly because some variation in higher educational attainment is correlated with the level of urbanisation of NUTS 2 regions, which cannot be detected for Urban Audit cities as rural areas are not included in that geographical classification.

The results presented here contrast with smaller scale studies from individual cities finding the opposite association (NO_2 exposure was higher in more deprived areas). This discrepancy is likely due to the coarse-grained and large geographical extent of analysis, which is unable to detect the fine scale variation of social indicators and NO_2 exposure within towns and cities, but instead encompasses various parts of Europe with differing levels of urbanisation and social conditions.

The result that the death rate of people under 65 from respiratory diseases in Urban Audit cities in 2011-12 was lower in those cities having higher levels of NO_2 exposure is superficially surprising, given the recognised effect of NO_2 exposure on respiratory health. This highlights that statistical associations where one factor is considered in isolation can easily be obscured if other, collectively stronger influences on respiratory health (including other air pollutants) do not follow the same geographic patterns. In contrast to NO_2 exposure, $PM_{2.5}$ exposure is positively correlated with respiratory disease death rates (see section 4.2.3).

No comparison of the results presented above and those from the CRESH study (CRESH, 2013) is possible, as the CRESH study did not consider NO_2 in the analysis.

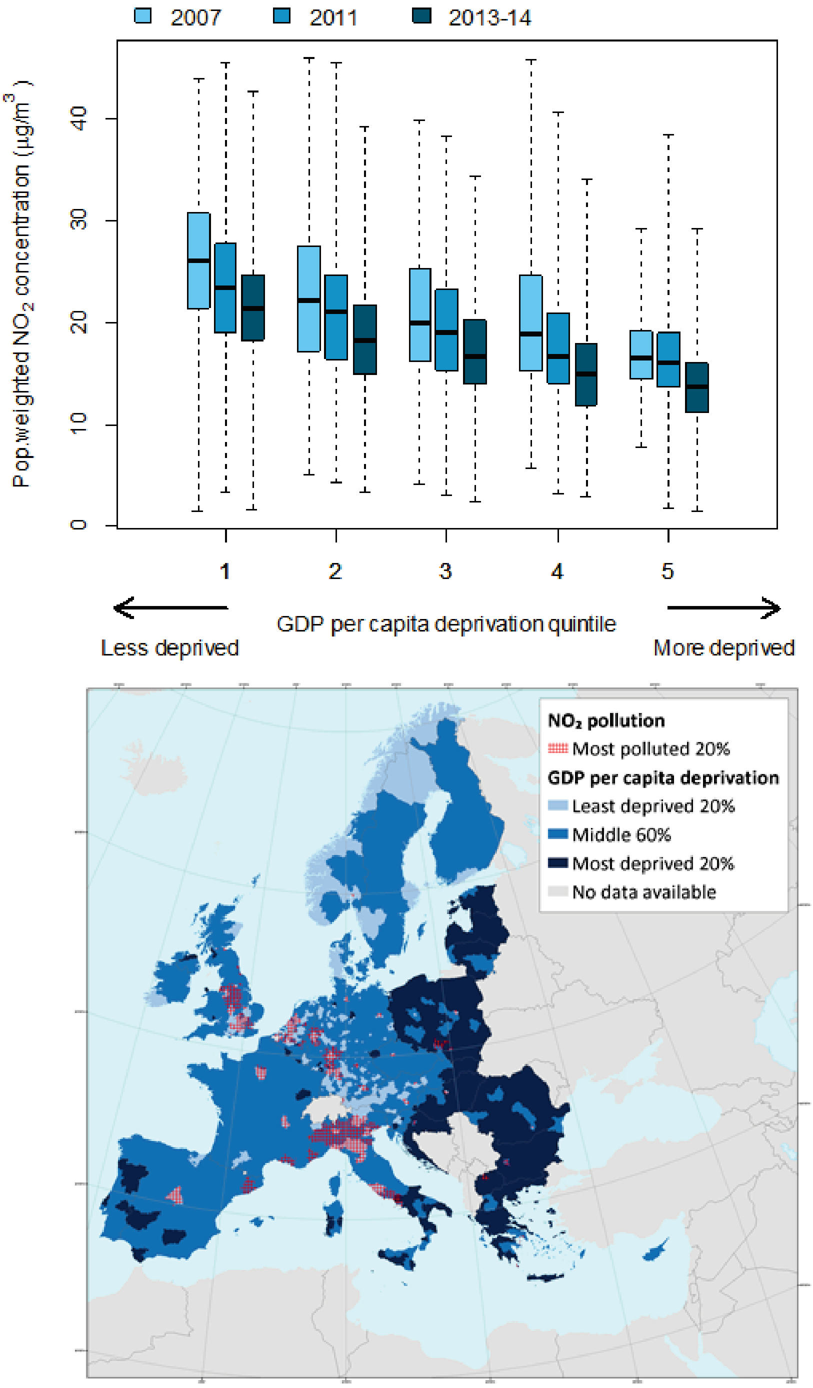
Some of the stronger associations emerging from these results are examined in more detail below.

3.2.1 NO_2 exposure and GDP per capita deprivation at NUTS 3 level

For all time-points considered, wealthier NUTS 3 regions (by GDP per capita) had on average higher NO_2 exposure than less wealthy areas. For instance, in 2013-14, people in the poorest 20% of NUTS 3 regions were exposed on average to concentrations of 14 µg/m^3 NO_2, compared to 22 µg/m^3 in the wealthiest 20%; around 1.6 times as high (**Figure 3.2**, top). This is reflected also by the rarity of NUTS 3 regions which were both among the top 20% most polluted and in the poorest 20% in 2013-14 (**Figure 3.2,** bottom). The most polluted areas tend to be located in densely populated regions of Europe such as Northern Italy, Western Germany and the UK, whereas the poorest areas tend to be in less densely-populated parts of Europe.

NO_2 exposure reduced between 2007 and 2013-14 for NUTS 3 regions in all quintiles of GDP per capita deprivation (**Figure 3.2**, top). However, the relative and absolute difference in exposure across GDP per capita deprivation levels remained similar (**Table 3.2**).

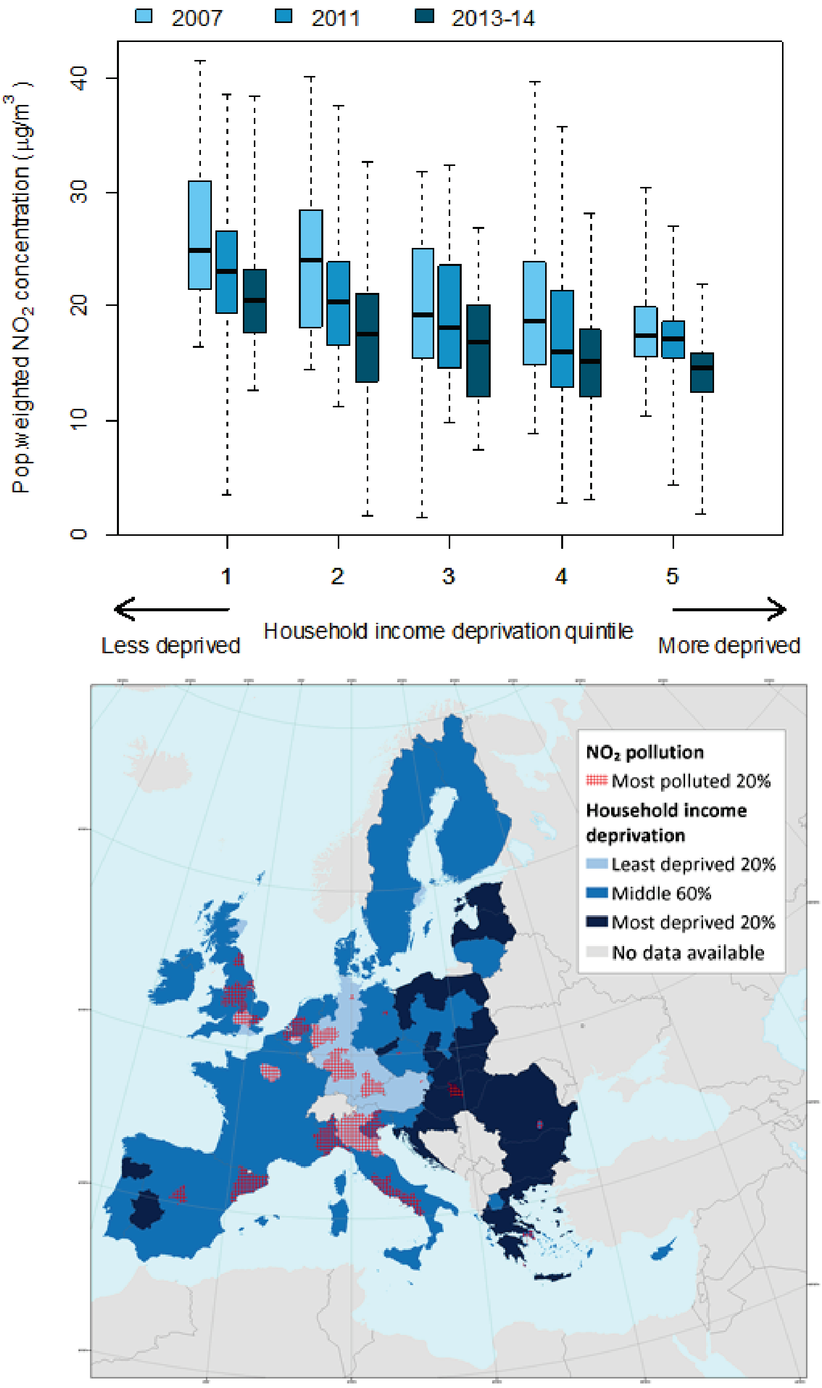
Figure 3.2 **Association between NO_2 exposure and GDP per capita across NUTS 3 regions, over time (top), and in 2013-14 (map, bottom)**



3.2.2 NO_2 exposure and household income deprivation at NUTS 2 level

Household income is a more appropriate measure of deprivation than is GDP per capita, as it more directly quantifies the means at the disposal of people living within each region. Nevertheless, the association between household income deprivation and NO2 exposure at NUTS 2 level shows a similar pattern, with people in the least deprived 20% of regions (by household income) being exposed on average to 1.5 times the NO2 concentration of the most deprived 20% in 2013-14, at 21 and 14 µg/m3 respectively (Figure 3.3, top).

Figure 3.3 **Association between NO_2 exposure and household income deprivation across NUTS 2 regions, over time (top), and in 2013-14 (map, bottom)**



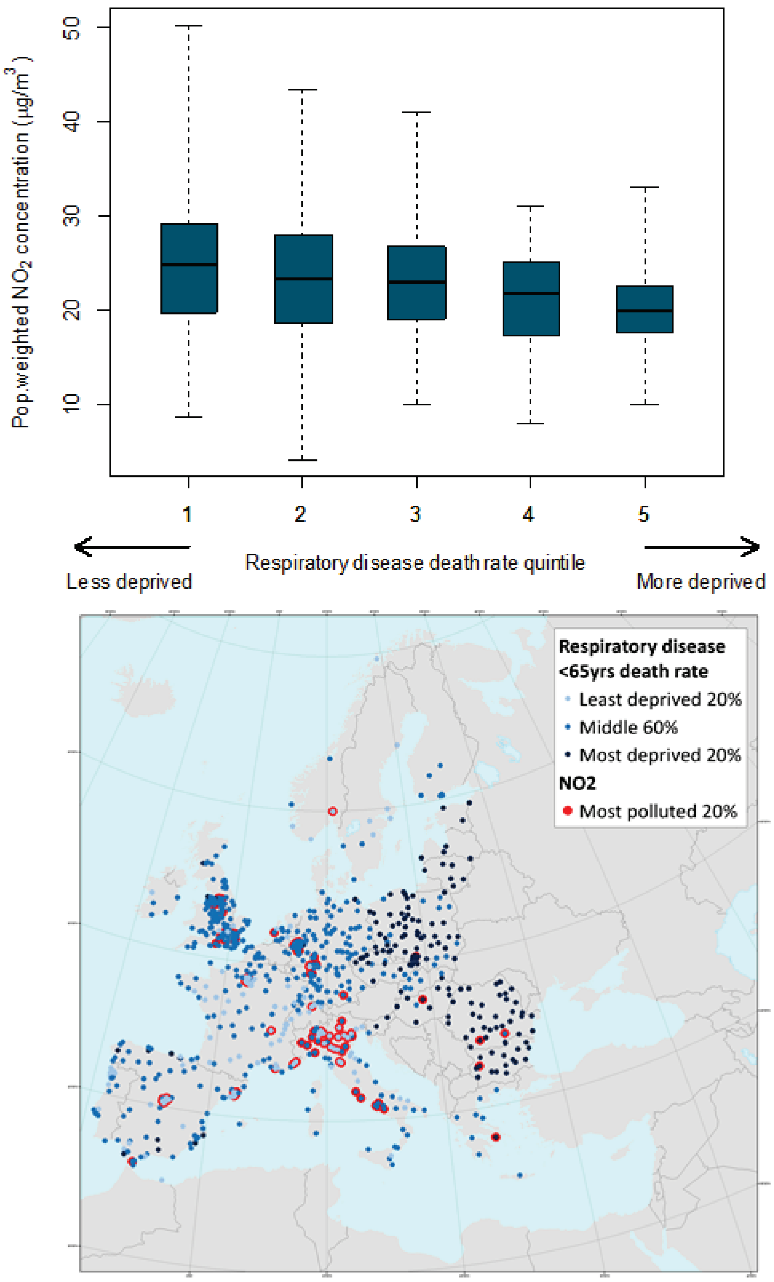
Once again, there were very few regions which were both among the top 20% most polluted and in the poorest 20% in 2013-14 (**Figure 3.3**; red hashing over dark blue).

As for GDP per capita at NUTS 3 level, NO_2 exposure reduced between 2007 and 2013-14 for NUTS 2 regions in all quintiles of household income deprivation, but the absolute and relative difference in pollution across household income deprivation levels remained similar over time (**Table 3.2**).

3.2.2 NO_2 exposure and respiratory disease in Urban Audit cities

Across Urban Audit cities in 2011-12, NO_2 exposure tended to be slightly higher in those cities with lower respiratory disease death rates among people under 65. In the 20% of cities with the lowest respiratory disease death rates among people under 65, people were exposed to an average NO_2 concentration 5 µg/m³ higher than in the 20% of cities with the highest rates, at 25 and 20 µg/m³ respectively (**Figure 3.4**, top).

Figure 3.4 Association between NO_2 exposure and the death rate from respiratory diseases among under 65s in Urban Audit cities in 2011-12



This result is somewhat surprising, given the link between NO_2 exposure and respiratory health. However, there are many factors influencing rates of respiratory illness (including other air

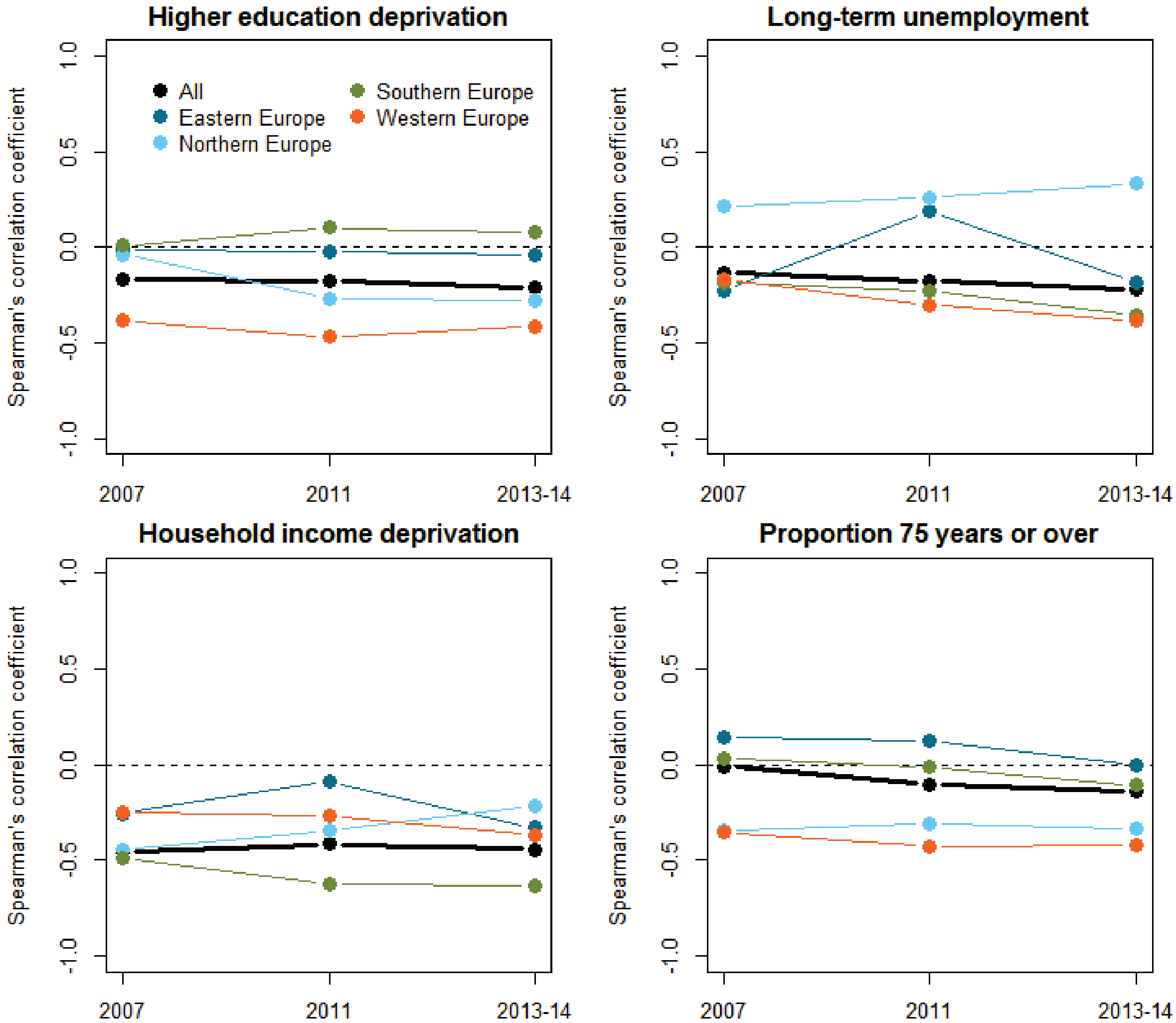
pollutants) which may not follow the same geographic patterns as NO_2 exposure, obscuring any statistical association when NO_2 is considered in isolation.
Considering the geographic distribution, the 20% of cities with the highest NO_2 exposure were mostly concentrated in urbanised parts of central Europe and the UK, whereas the 20% of cities with the highest respiratory disease death rates among under 65s levels were predominantly in Eastern Europe.

3.3 Differences within and across European country groups

Patterns are broadly consistent across all of the four groups of countries and consistent with the whole Europe analysis, indicating that similar associations exist within groups of countries as well as between them (**Figure 3.5**).

- For higher education deprivation, all regions show a negative correlation with NO_2 exposure except for Southern Europe, where the association is weakly positive
- For long term unemployment, all regions show a negative correlation with NO_2 exposure apart from Northern Europe, where there is weak positive correlation
- All regions show a clear negative association between NO_2 exposure and household income deprivation.

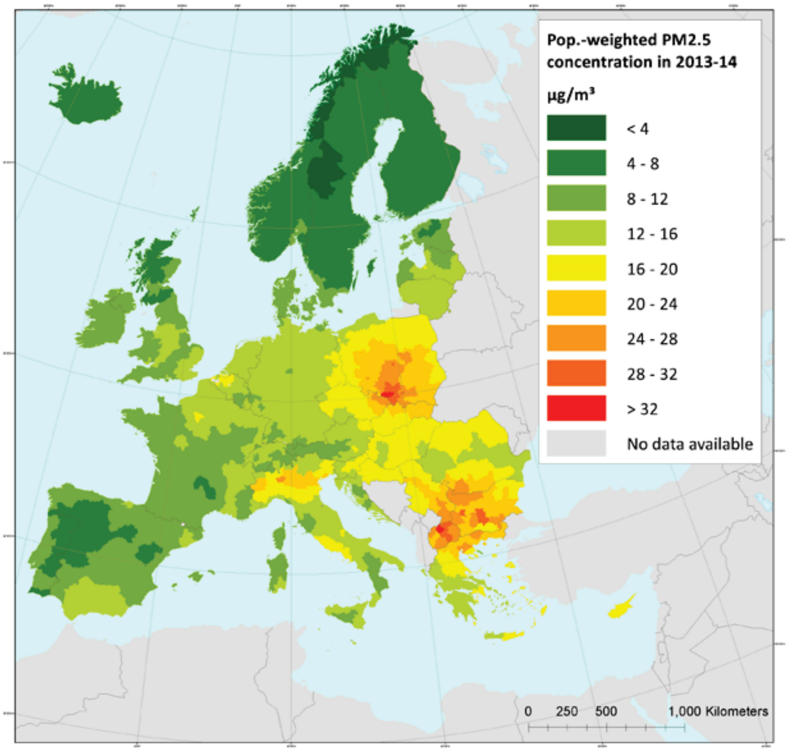
Figure 3.5 Spearman's rank correlation between NO_2 exposure and selected deprivation indicators at NUTS 2 level, split by UNSD country grouping



4 Particulate matter ≤ 2.5 µm ($PM_{2.5}$)

4.1 Geographic variation in PM2.5 exposure and change over time

Map 4.1 $PM_{2.5}$ exposure in NUTS 3 regions, 2013-2014



In 2013-14, the level of $PM_{2.5}$ exposure in NUTS 3 regions varied between concentrations of just under 4 and 34 µg/m^3. Large-scale patterns seem to dominate the variation seen across Europe, with higher values seen in Northern Italy, Poland and the Balkans, and lower values in other parts of Europe (**Map 4.1**).

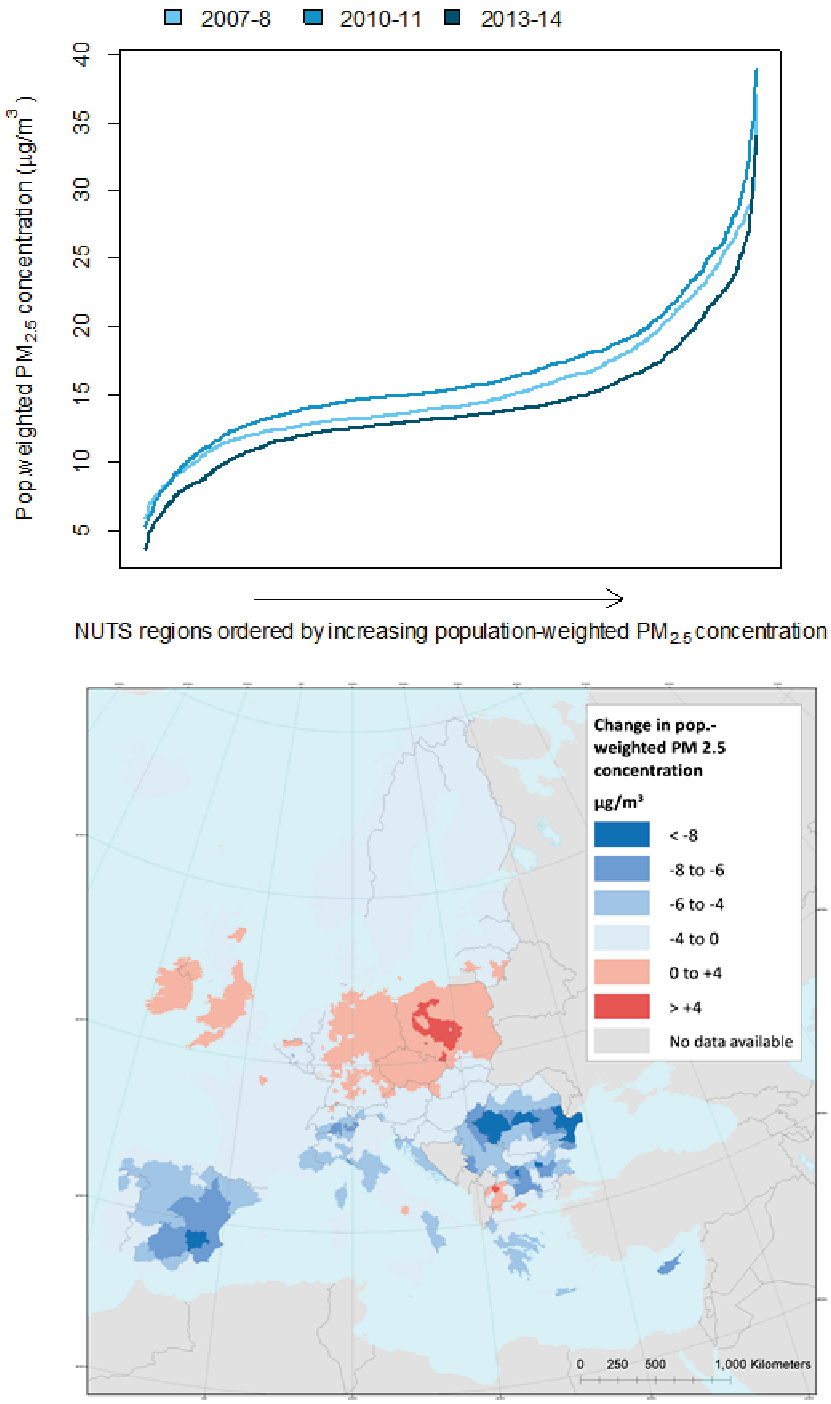
Table 4.1 $PM_{2.5}$ exposure in the most and least polluted 20% of regions, and change over time

$PM_{2.5}$	Mean population-weighted concentration (µg/m^3)						
Year	Least polluted 20% (Q1)	Q2	Q3	Q4	Most polluted 20% (Q5)	Ratio of Q5/Q1	Absolute difference (Q5-Q1)
2007-8	10.3	13.0	14.1	16.5	23.1	2.25	12.8
2010-11	10.6	14.2	15.4	17.7	24.5	2.30	13.8
2013-14	8.8	12.3	13.3	14.9	20.8	2.37	12.0

In 2013-14, exposure to $PM_{2.5}$ in the most polluted 20% of NUTS 3 regions was on average 2.4 times higher than in the least polluted 20% of NUTS 3 regions, with concentrations of 21 and 9 µg/m^3 respectively (**Table 4.1**).

Between 2007-8 and 2013-14, most NUTS 3 regions saw a slight decrease in $PM_{2.5}$ exposure, although larger decreases were observed in Spain and the Eastern Balkans; and increases occurred in large parts of the UK, Germany, the Czech Republic, the Republic of Ireland and Poland, among other countries (**Figure 4.1**; bottom). $PM_{2.5}$ concentrations actually increased between 2007-8 and 2010-11, then declined again to 2013-14 (**Figure 4.1**; top).

Figure 4.1 Top: Rank-value chart showing the distribution of $PM_{2.5}$ exposure in 2007-8, 2010-11 and 2013-14. Bottom: Map showing the absolute change in $PM_{2.5}$ exposure in each NUTS 3 region, between 2007-8 and 2013-2014



Both the relative and absolute difference in exposure between the most polluted 20% (Q5) and least polluted 20% (Q1) of NUTS 3 regions remained relatively similar over the time period studied (**Table**

4.1), with the Q5/Q1 pollution ratio rising slightly from 2.25 in 2007-8 to 2.37 in 2013-14, and the absolute difference falling slightly from 13 to 12 µg/m^3.

4.2 Relationship of $PM_{2.5}$ exposure with deprivation-related variables, and change over time

$PM_{2.5}$ exposure tended to be higher in more deprived areas and lower in less deprived areas for most of the indicators of deprivation considered in this study. This is illustrated by the positive correlations and pollution ratios above 1 seen in **Table 4.2**. This is the opposite pattern to that seen for NO_2.

Specific findings:

- More deprived regions tend to have higher $PM_{2.5}$ exposure than less deprived areas according to GDP per capita at NUTS 3, and higher education, household income and long-term unemployment at NUTS 2.
- In contrast, $PM_{2.5}$ exposure tended to be lower in areas with a higher proportion of very young (<5 yrs) or elderly (>= 75 yrs) people.
- At the city level, there was a tendency for cities having higher $PM_{2.5}$ exposure to also have higher death rates among people under 65 from respiratory diseases, in 2010-12 (**Table 4.2**; Respiratory disease death rate).
- Most associations have remained relatively consistent over the period studied, except that the association between long-term unemployment and $PM_{2.5}$ exposure at the NUTS 2 level has weakened over time. This resulted in reduced unemployment-related inequality in $PM_{2.5}$ exposure in both relative and absolute terms across NUTS 2 regions.

Table 4.2 Association of $PM_{2.5}$ exposure with social indicators at the NUTS3, NUTS 2 and City scales, and change over time

Spatial scale	Social indicator	Spearman's correlation			Pollution ratio DQ5/DQ1			Pollution difference DQ5-DQ1 (µg/m^3)		
		2007-2008	2010-2011	2013-2014	2007-2008	2010-2011	2013-2014	2007-2008	2010-2011	2013-2014
NUTS 3	GDP per capita deprivation	0.24	0.20	0.22	1.31	1.30	1.33	4.6	4.7	4.3
NUTS 2	Higher education deprivation	0.52	0.44	0.46	1.45	1.36	1.46	5.8	5.0	5.2
	Household income deprivation	0.27	0.27	0.31	1.29	1.39	1.37	4.5	6.1	5.0
	Long-term unemployment	0.41	0.23	0.28	1.39	1.24	1.29	5.1	3.3	3.3
	Proportion 75 years or over	-0.22	-0.19	-0.16	0.87	0.87	0.88	-2.4	-2.4	-1.9
	Proportion under 5 years	-0.28	-0.25	-0.25	0.80	0.87	0.86	-3.3	-2.1	-1.9
			2010-2012			2010-2012			2010-2012	
Urban Audit Cities	Higher education deprivation		0.17			1.20			2.9	
	Unemployment		-0.10			1.01			0.1	
	Proportion 75 years or over		-0.07			0.91			-1.7	
	Proportion under 5 years		-0.23			0.87			-2.1	
	Respiratory disease death rate		0.28			1.47			7.4	
	Green space deprivation		0.13			1.14			2.2	

Note: see section 1.4 for interpretation of Spearman's correlation, and pollution ratio and pollution difference between Q5 and Q1.

Comparing patterns across spatial scales, GDP per capita variation at NUTS 3 level and household income deprivation at NUTS 2 level were both positively correlated with $PM_{2.5}$ exposure. Comparing associations at the NUTS 2 and Urban Audit city level, the proportion of vulnerable age groups was negatively associated with $PM_{2.5}$ exposure at both scales, and higher education deprivation positively associated with $PM_{2.5}$ exposure at both scales. However, long-term unemployment at NUTS 2 level was positively associated with $PM_{2.5}$ exposure, whereas there was little or no association between $PM_{2.5}$ exposure and unemployment across Urban Audit cities. This discrepancy may be due to missing data for Urban Audit cities in Greece and Romania, which both have relatively high levels of $PM_{2.5}$ exposure and unemployment so may play a large part in driving the positive correlation seen at the NUTS 2 level.

Some of the associations emerging from these results are examined in more detail below.

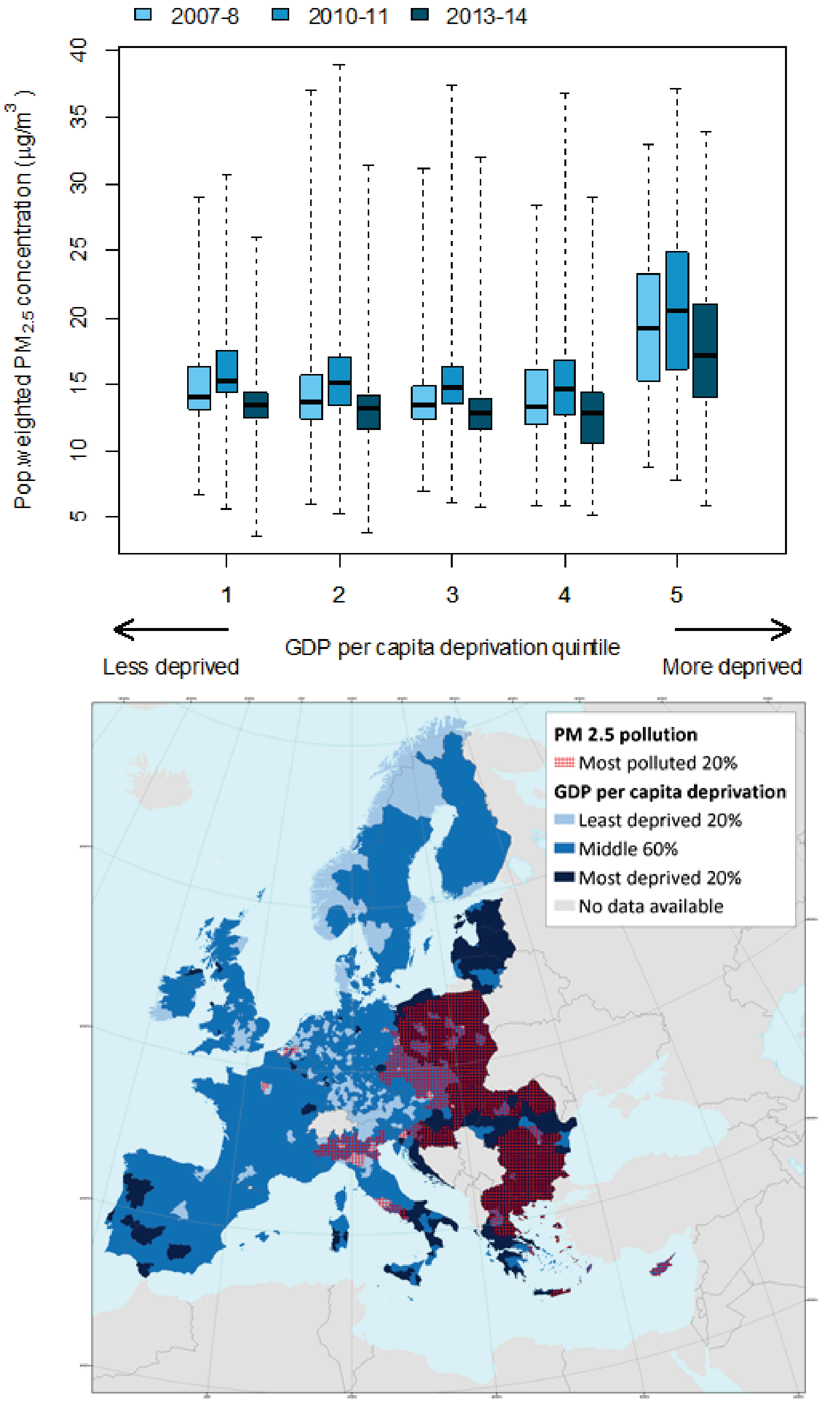
4.2.1 $PM_{2.5}$ concentration and GDP per capita deprivation at NUTS 3 level

For all time points considered, people in the most deprived 20% of NUTS 3 regions (by GDP per capita) were exposed to higher $PM_{2.5}$ concentrations than more wealthy NUTS 3 regions. However, the association was not linear across the quintiles; in 2013-14 NUTS 3 regions lying in the wealthiest four quintiles by GDP per capita all had very similar $PM_{2.5}$ exposure of around 13 $\mu g/m^3$, compared with 18 $\mu g/m^3$ for the most deprived quintile (**Figure 4.2**, top).

NUTS 3 regions which were both among the highest 20% for $PM_{2.5}$ exposure and the most deprived 20% by GDP per capita in 2013-14 were found in the most Eastern part considered, from Poland to the North of Greece (**Figure 4.2**, bottom).

$PM_{2.5}$ exposure reduced between 2007-8 and 2013-14 overall in NUTS 3 regions across all quintiles of GDP per capita deprivation (Figure 4.2, top). However, the relative and absolute difference in exposure between the most and least deprived 20% of NUTS 3 regions by GDP per capita remained similar (**Table 4.2**).

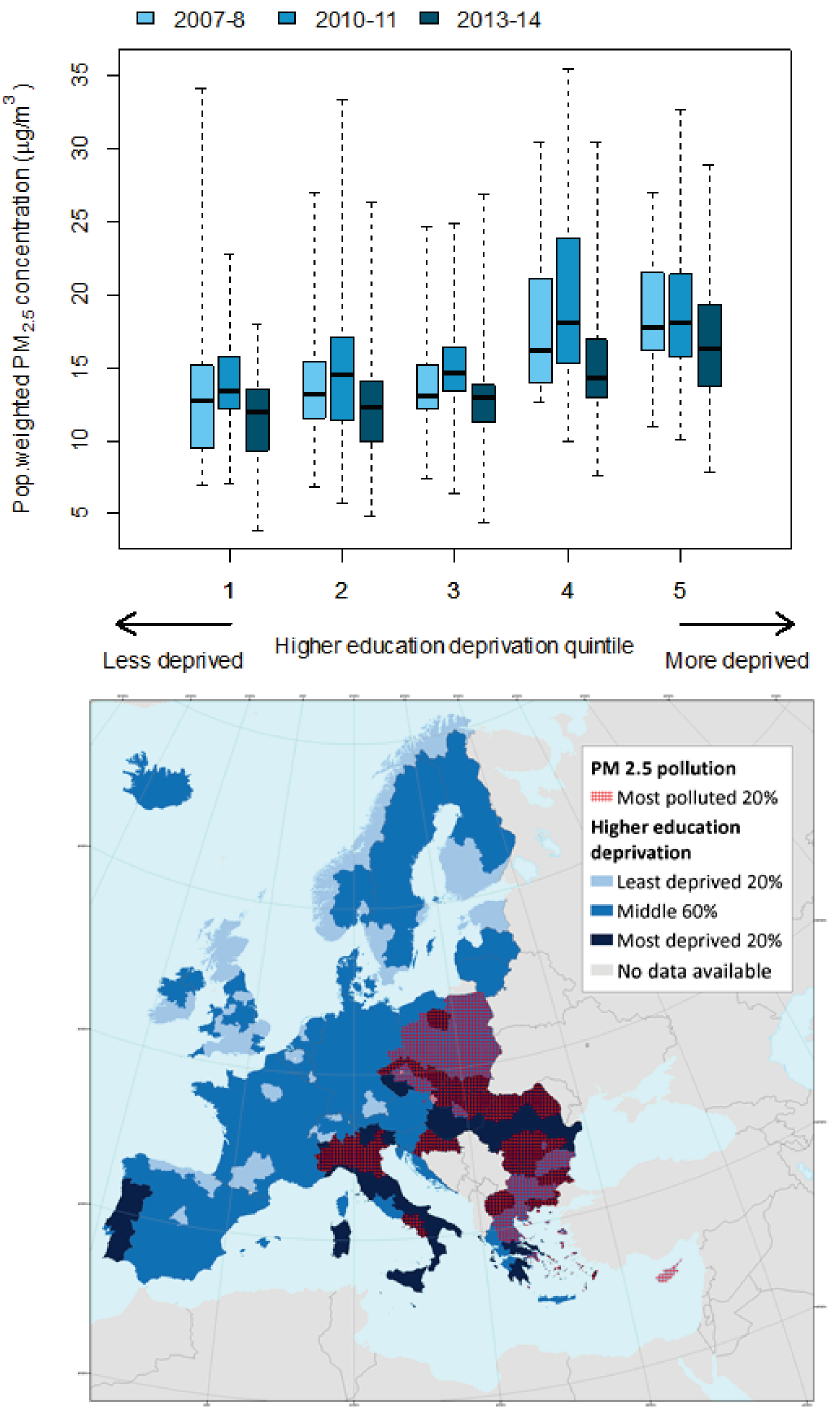
Figure 4.2 **Association between $PM_{2.5}$ exposure and GDP per capita deprivation across NUTS 3 regions, over time (top), and in 2013-14 (map, bottom)**



4.2.2 *$PM_{2.5}$ exposure and higher education deprivation at NUTS 2 level*

Across the time period studied, people in NUTS 2 regions with a higher proportion of higher education deprivation (i.e. less qualified) tended to have higher exposure to $PM_{2.5}$. For instance, in 2013-14, people in the most deprived 20% of NUTS 2 regions (by higher education qualifications) were exposed to average $PM_{2.5}$ concentrations of 17 $\mu g/m^3$, compared with 11 $\mu g/m^3$ in the least deprived 20% (**Figure 4.3**, top). The map below (**Figure 4.3**, bottom) also illustrates this, showing that extensive areas of Italy and South-Eastern parts of Europe are both in the top 20% of regions by $PM_{2.5}$ exposure, and in the most deprived 20% of regions by higher education qualifications (red-hashing over dark blue areas in the map).

Figure 4.3 **Association between $PM_{2.5}$ exposure and higher education deprivation across NUTS 2 regions, over time (top), and in 2013-14 (map, bottom)**

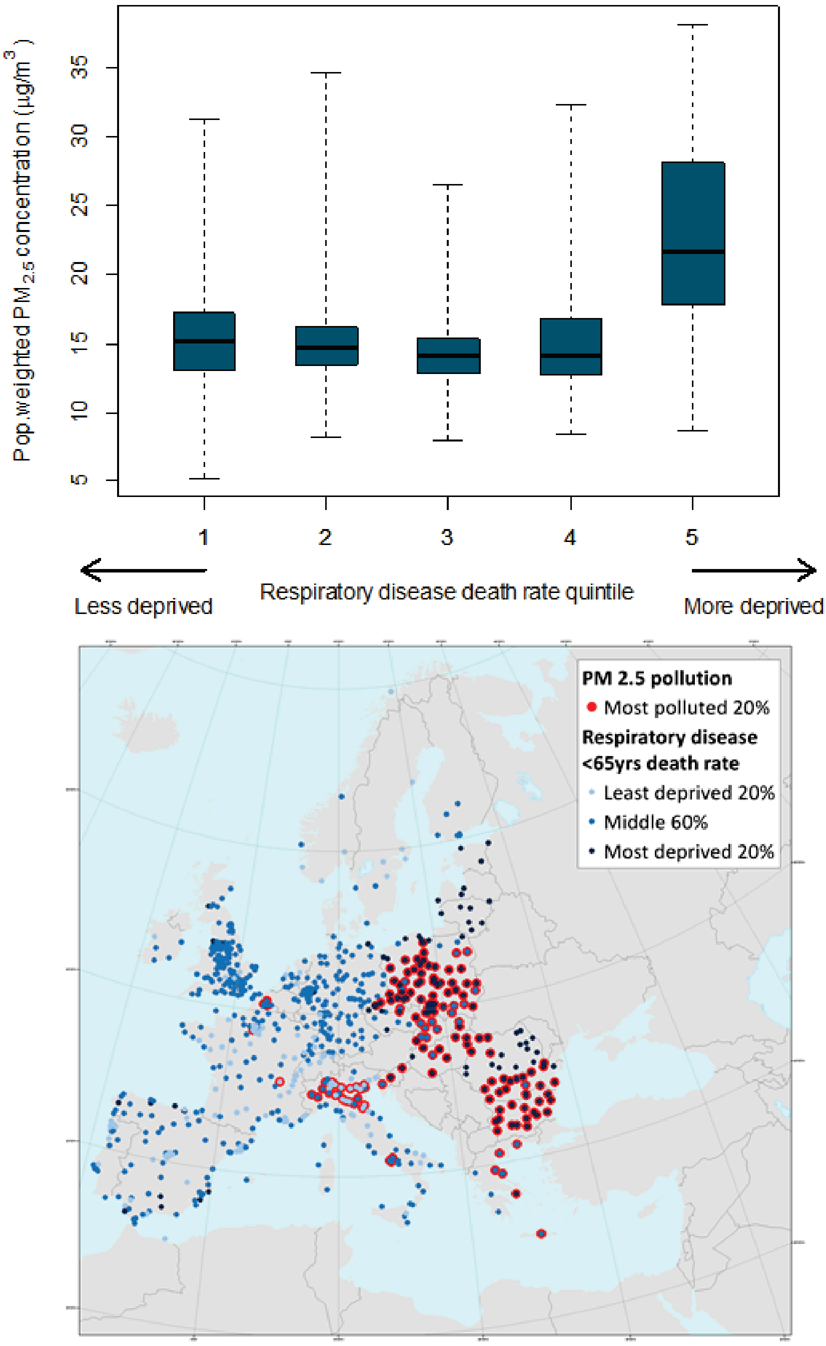


After rising between 2007-8 and 2010-11, $PM_{2.5}$ exposure reduced overall for NUTS 2 regions across all quintiles of higher education deprivation (**Figure 4.3**, top), but there was no evidence for reduced inequality in $PM_{2.5}$ exposure between the most and least deprived regions across the period studied (**Table 4.2**).

4.2.3 $PM_{2.5}$ exposure and respiratory disease death rate at the city level

At the urban audit city level, the strongest association found for the period 2010-2012 was the tendency for exposure to PM2.5 to be higher in cities having a higher death rate of people under 65 from respiratory disease.

Figure 4.4 Association between $PM_{2.5}$ exposure and death rate among people under 65 from respiratory disease across Urban Audit cities in 2011



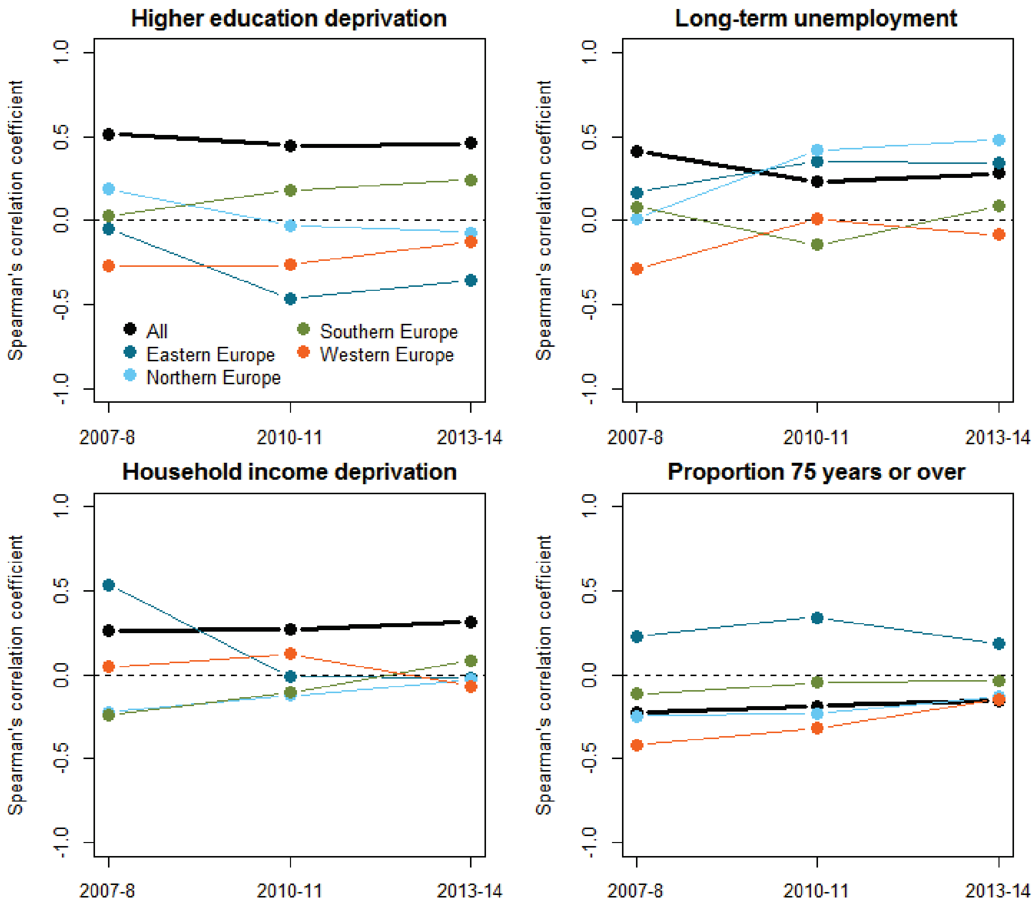
In this case, the association is not linear across different levels of deprivation; in 2011-12, people in the least deprived 80% of cities by respiratory disease death among people under 65 rate all had fairly similar $PM_{2.5}$ exposure at 14-16 μg/m^3, but the exposure in the most deprived 20% was around 1.5 times higher at 23 μg/m^3 (**Figure 4.4**, top).

The locations of cities which experienced the highest respiratory disease death rates among people under 65 and also suffered the highest levels of $PM_{2.5}$ exposure are predominantly in Poland, Romania, Hungary and Bulgaria (**Figure 4.4**, bottom).

4.2.4 Differences among sub-regions of Europe

The major result of looking at associations between $PM_{2.5}$ exposure and deprivation within individual groups of countries defined by the UNSD classification, is that they tend to be weaker than at the whole-Europe scale (Figure 4.5). This is because the spatial variation in $PM_{2.5}$ detectable in this analysis is dominated by large-scale patterns, with most of the countries having the highest exposure levels being part of the "Eastern" Europe grouping. Any individual group of countries (North, East, South or West) does not contain as wide a range of variation in $PM_{2.5}$ exposure as when considering the whole of Europe.

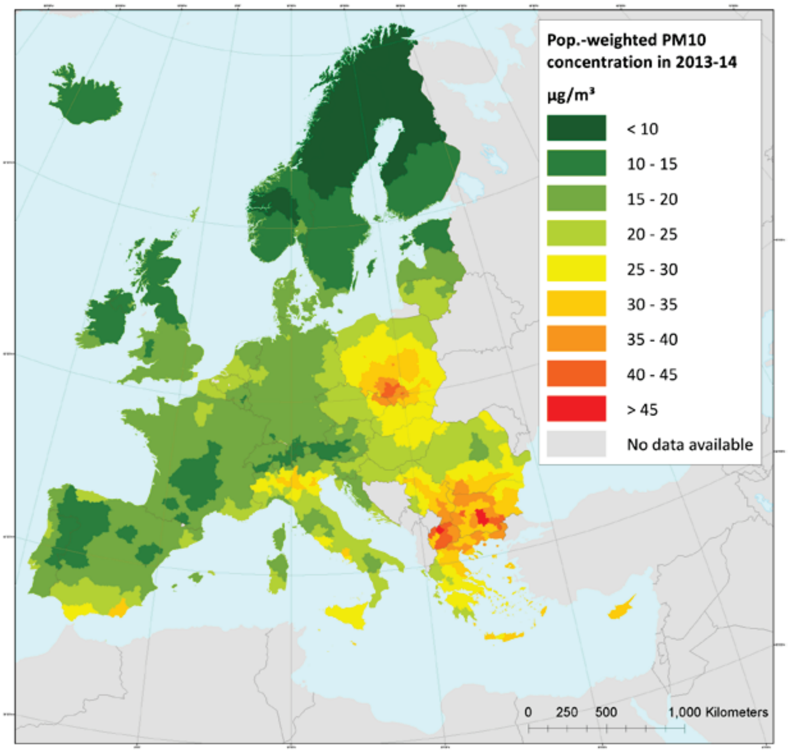
Figure 4.5 Spearman's rank correlation between $PM_{2.5}$ exposure and selected deprivation indicators at NUTS 2 level, split by UNSD country grouping



5 Particulate matter ≤ 10 µm (PM_{10})

5.1 Geographic variation in PM_{10} exposure and change over time

Map 5.1 PM_{10} exposure in NUTS 3 regions, 2013-2014



In 2013-14, PM_{10} exposure in NUTS 3 regions varied between concentrations of 8 and 48 µg/m^3. In general, the spatial pattern of PM_{10} concentration mirrors that for $PM_{2.5}$; i.e. large-scale variation with the highest in parts of Poland and the Balkans (**Map 5.1**). This similarity is to some extent to be expected, as $PM_{2.5}$ makes up a considerable fraction of PM_{10}.

Table 5.1 PM_{10} exposure in the most and least polluted 20% of regions, and change over time

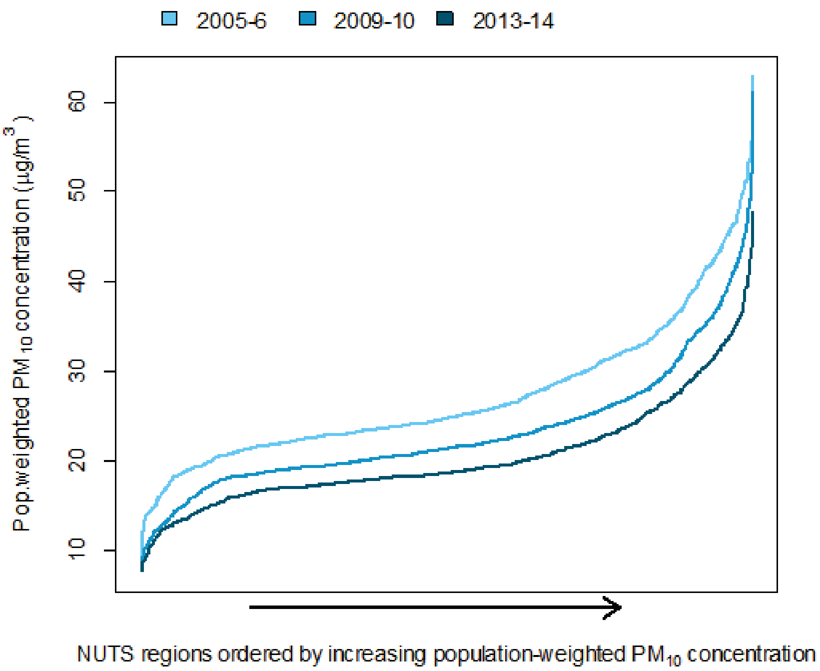
PM_{10}	Mean population-weighted concentration (µg/m^3)						
Year	Least polluted 20% (Q1)	Q2	Q3	Q4	Most polluted 20% (Q5)	Ratio of Q5/Q1	Absolute difference (Q5-Q1)
2005-6	19.0	22.8	24.9	29.4	40.0	2.10	21.0
2009-10	15.9	19.6	21.4	24.6	34.6	2.18	18.7
2013-14	14.2	17.4	18.8	21.6	30.1	2.12	15.9

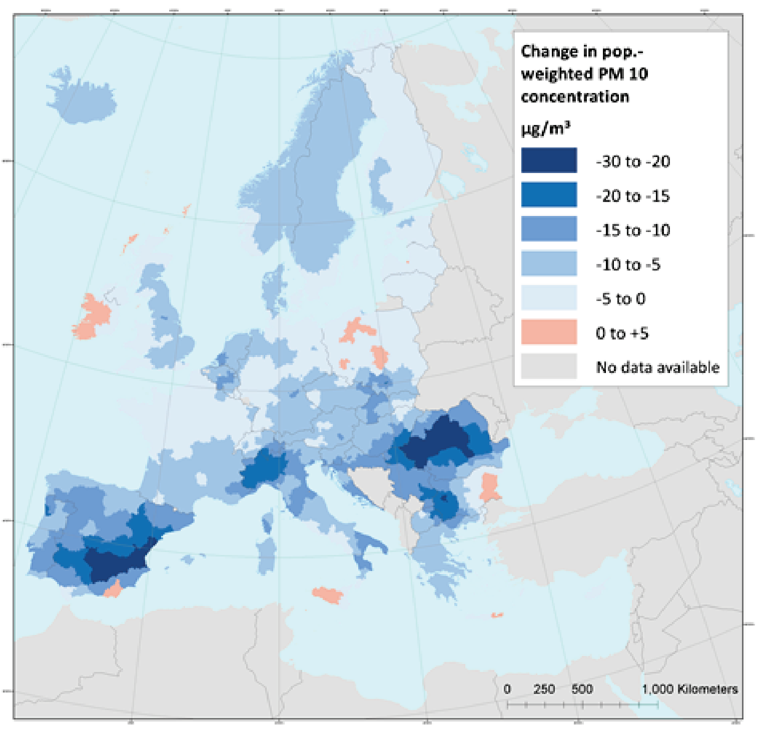
In 2013-14, people in the most polluted 20% of NUTS 3 regions across Europe were exposed on average to a PM_{10} concentration 2.1 times higher than in the least polluted 20% of NUTS 3 regions, at 30 and 14 µg/m^3 respectively (**Table 5.1**). As for $PM_{2.5}$ however, the spread of pollution within Eastern Europe and Western Europe individually was lower, with the most polluted regions having only 1.4 and 1.7 times the exposure of the least polluted regions respectively (see Annex 2).

Between 2005-6 and 2013-14, most NUTS 3 regions saw decreases in PM_{10} exposure, with only a few regions seeing small increases (**Figure 5.1**, bottom). Overall, PM_{10} exposure fell steadily across the three time-points, in contrast to $PM_{2.5}$ where exposure rose between 2007-8 and 2010-11.

Average PM_{10} exposure in the most polluted 20% of NUTS 3 regions (Q5) fell around twice as much as in the least polluted 20% (Q1), by 10 and 5 µg/m^3 respectively, between 2005-6 and 2013-14. Accordingly, the absolute difference in PM_{10} exposure between Q5 and Q1 fell over the period, from 21 to 16 µg/m^3. However, the relative inequality (Q5/Q1) remained similar over the time period (**Table 5.1**).

Figure 5.1 **Top: Rank-value chart showing the distribution of PM_{10} exposure in 2005-6, 2009-10 and 2013-14. Bottom: Map showing the absolute change in PM_{10} exposure in each NUTS 3 region, between 2005-6 and 2013-2014**





It is worth noting that some of the differences in trend over time between $PM_{2.5}$ and PM_{10} exposure may be due to the different year-groupings used for the two pollutants (2005-6, 2009-10 and 2013-14 for PM_{10}; 2007-8, 2010-11 and 2013-14 for $PM_{2.5}$), which were dictated by data availability.

5.2 Relationship of PM_{10} exposure with deprivation-related variables and change over time

As seen for $PM_{2.5}$, PM_{10} exposure tended to be higher in more deprived areas and lower in less deprived areas, for most of the indicators of deprivation considered in this study (**Table 5.2**).

Specific findings:

- More deprived regions tended to have higher PM_{10} exposure than less deprived areas according to GDP per capita at NUTS 3, and higher education, household income, and long-term unemployment at NUTS 2. These associations were generally stronger for PM_{10} than for $PM_{2.5}$.
- At the city level, there was also association between PM_{10} exposure and death rates among people under 65 from respiratory diseases, although it was less strong in comparison to $PM_{2.5}$
- In cities and NUTS 2 regions having a high share of vulnerable age groups (<5yrs and >=75yrs) in the population, people were in general exposed to lower PM_{10} concentrations than in cities and NUTS 2 regions having a lower share of vulnerable age groups.
- Relative inequality in PM_{10} exposure across deprivation levels increased slightly between 2005-6 and 2013-14, for GDP per capita deprivation at NUTS 3 level, and higher education deprivation, household income deprivation and long-term unemployment at NUTS 2. This is reflected in stronger positive correlations and higher DQ5/DQ1 pollution ratios between the most and least deprived 20% of regions. However, the absolute difference in average exposure for the most and least deprived 20% of regions (DQ5-DQ1) for these same variables has changed little over the period (having even decreased for higher education deprivation), indicating a similar absolute reduction in PM_{10} exposure across all levels of deprivation.

Table 5.2 Association of PM_{10} exposure with social indicators at the NUTS3, NUTS 2 and City scales, and change over time

Spatial scale	Social indicator	Spearman's correlation			Pollution ratio DQ5/DQ1			Pollution difference DQ5-DQ1 (µg/m^3)		
		2005-2006	2009-2010	2013-2014	2005-2006	2009-2010	2013-2014	2005-2006	2009-2010	2013-2014
NUTS 3	GDP per capita deprivation	0.28	0.26	0.33	1.27	1.30	1.41	7.2	6.7	7.6
NUTS 2	Higher education deprivation	0.47	0.48	0.49	1.37	1.35	1.44	9.2	7.1	7.6
	Household income deprivation	0.35	0.36	0.47	1.32	1.37	1.47	8.6	8.0	8.7
	Long-term unemployment	0.33	0.40	0.49	1.30	1.36	1.46	7.4	7.1	7.7
	Proportion 75 years or over	-0.24	-0.12	-0.13	0.83	0.96	0.91	-5.4	-1.1	-2.1
	Proportion under 5 years	-0.31	-0.20	-0.24	0.79	0.91	0.90	-6.2	-2.0	-2.1
			2010-2012			2010-2012			2010-2012	
Urban Audit Cities	Higher education deprivation		0.22			1.19			4.1	
	Unemployment		0.27			1.19			3.9	
	Proportion 75 years or over		-0.12			0.90			-2.7	
	Proportion under 5 years		-0.20			0.89			-2.6	
	Respiratory disease death rate		0.17			1.35			8.3	
	Green space deprivation		0.16			1.18			4.1	

Note: see section 1.4 for interpretation of Spearman's correlation, and pollution ratio and pollution difference between Q5 and Q1.

Comparing patterns across spatial scales, as was the case for $PM_{2.5}$, GDP per capita variation at NUTS 3 level and household income deprivation at NUTS 2 level were also both positively correlated with PM_{10} exposure. Considering associations at the NUTS 2 and Urban Audit city level, areas with a higher share of vulnerable age groups tended to have lower PM_{10} exposure at both scales, and those areas with greater unemployment and higher education deprivation tended to be exposed to higher PM_{10} concentrations at both scales. The consistency of the associations between PM_{10} exposure and social indicators across scales may be related to the dominance of large-scale gradients (see **Map 5.1**) in PM_{10} exposure over short-range urban-rural ones when dealing with the fairly coarse resolution data used in this study. In this case, the lack of data on rural areas at the Urban Audit city scale would not greatly weaken the associations observed.

Some of the associations emerging from these results are examined in more detail below.

5.2.1 PM_{10} exposure and GDP per capita deprivation at NUTS 3 level

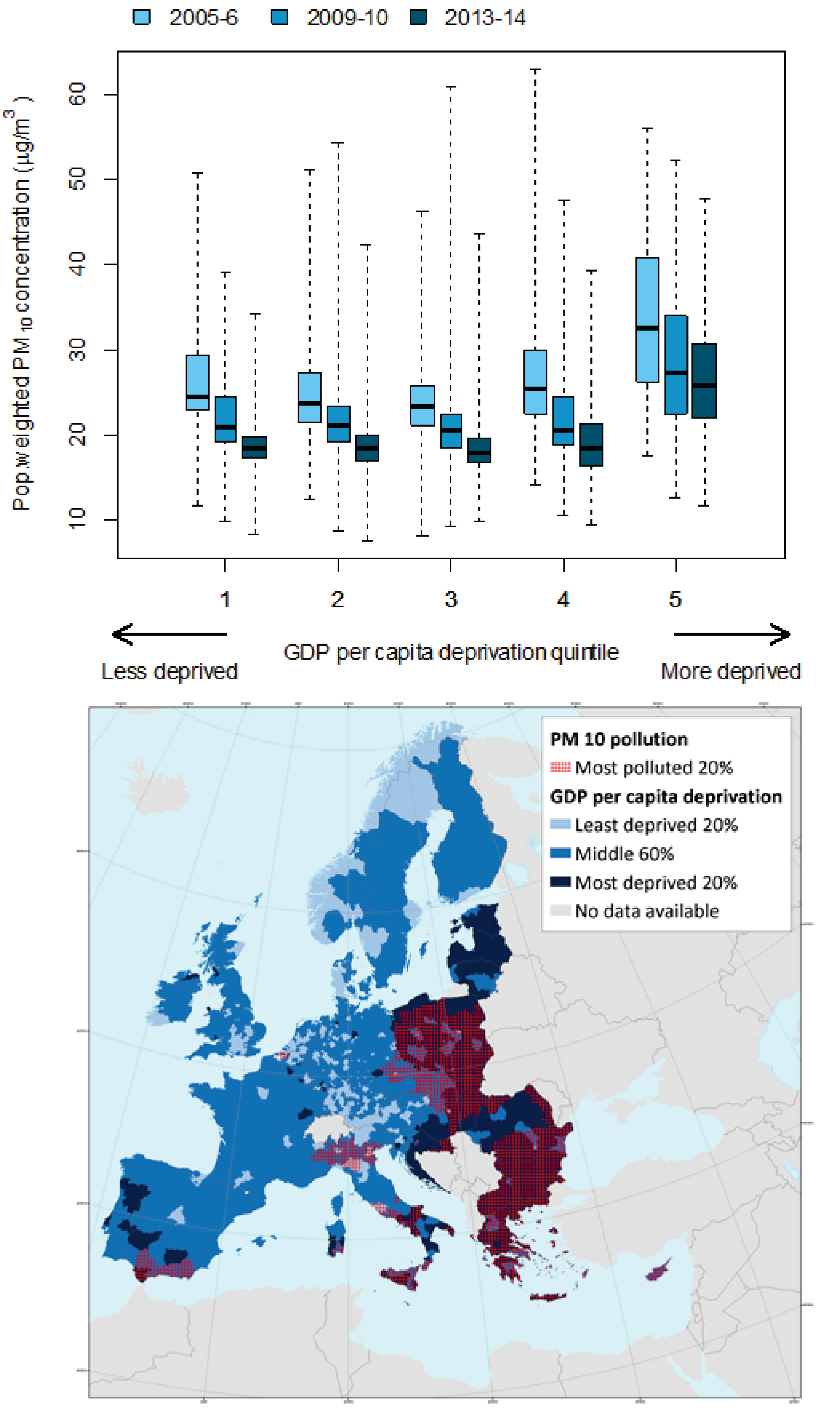
Across all three time-points considered, people in the most deprived 20% of NUTS 3 regions (by GDP per capita) were exposed on average to higher PM_{10} concentrations than people in more wealthy NUTS 3 regions. As was the case for $PM_{2.5}$ exposure, the association was not smooth; in 2013-14 people in the wealthiest four quintiles of NUTS 3 regions by GDP per capita were exposed to PM_{10} concentrations of around 19 µg/m^3, compared with around 26 µg/m^3 (1.4 times the exposure) in the most deprived quintile (**Figure 5.2**, top).

The map below (**Figure 5.2**, bottom) shows the NUTS 3 regions which were both among the highest 20% for PM_{10} exposure and the most deprived 20% by GDP per capita in 2013-14.

PM_{10} exposure reduced between 2005-6 and 2013-14 overall for NUTS 3 regions across all quintiles of GDP per capita deprivation (**Figure 5.2**, top), with similar decreases in the most and least deprived quintiles (of 7 and 8 µg/m^3 respectively). This resulted in the absolute difference in exposure between the most and least deprived quintiles remaining similar, but the relative difference (DQ5/DQ1) increasing to a greater extent from 1.27 to 1.41 (**Table 5.2**).

The CRESH study (CRESH, 2013) also considered the association between PM_{10} exposure and GDP per capita at the NUTS 3 level across Europe. This study found a similar qualitative pattern; i.e. that PM_{10} exposure remains higher in more deprived NUTS 3 regions than in less deprived ones. However, the CRESH study showed a decrease in relative inequality (DQ5/DQ1 ratio) in average pollution exposure between the most and least deprived quintiles between 2005-6 and 2009-10 (from 1.2 to 1.1), whereas in this analysis we have found generally higher relative inequalities, as well as an increase in the DQ5/DQ1 ratio (from 1.27 to 1.41) over time between 2005-6 and 2013-14. Clearly, the addition of a third, more recent time point in this analysis can account for some of the difference in inequality trends. The remaining discrepancy in levels of inequality may be due to the slightly larger geographic coverage of this analysis, as well as revisions to air pollution concentration data and interpolation methodology.

Figure 5.2 Association between PM_{10} exposure and GDP per capita deprivation across NUTS 3 regions, over time (top), and in 2013-14 (map, bottom)

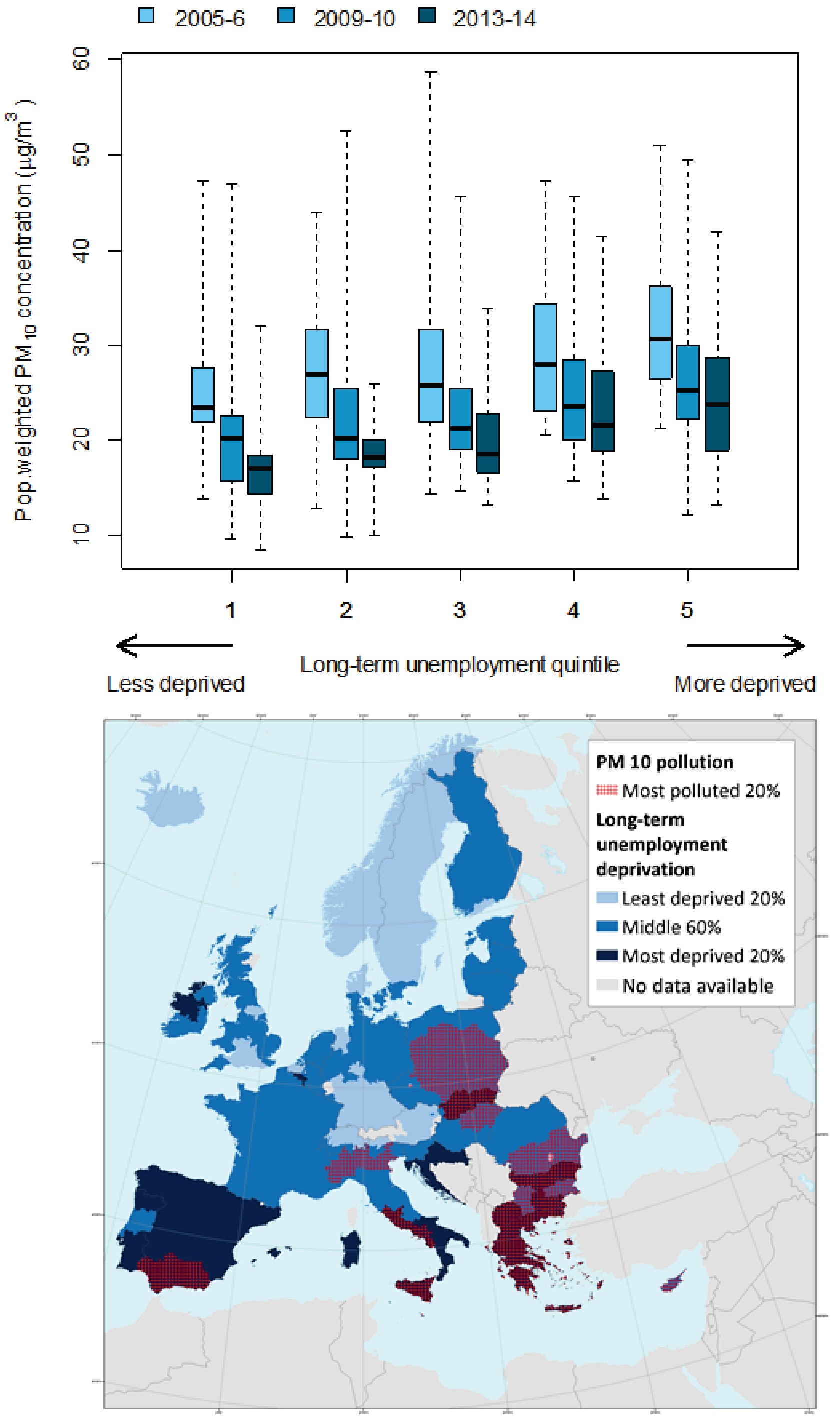


5.2.2 PM_{10} exposure and long-term unemployment at NUTS 2 level

In 2013-14, people in the most deprived 20% of NUTS 2 regions by long-term unemployment rate were exposed to about 1.5 times the concentration of PM_{10} as the least deprived 20% (**Table 5.2**), at 24 and 17 µg/m^3 respectively (Figure 5.3, top). Most of the regions both in the top 20% of PM_{10} exposure, and in the most deprived 20% by long-term unemployment are found in parts of Spain, Greece, Italy Bulgaria and Slovakia (**Figure 5.3**, bottom).

Average PM_{10} exposure reduced between 2005-6 and 2013-14 overall for people in NUTS 2 regions across all quintiles of long-term-unemployment by between 6 and 8 µg/m^3. Correspondingly, there was little change in the absolute difference in exposure between the most and least deprived quintiles, but a slight increase in the relative difference (DQ5/DQ1 ratio), from 1.3 to 1.5 (**Table 5.2**)

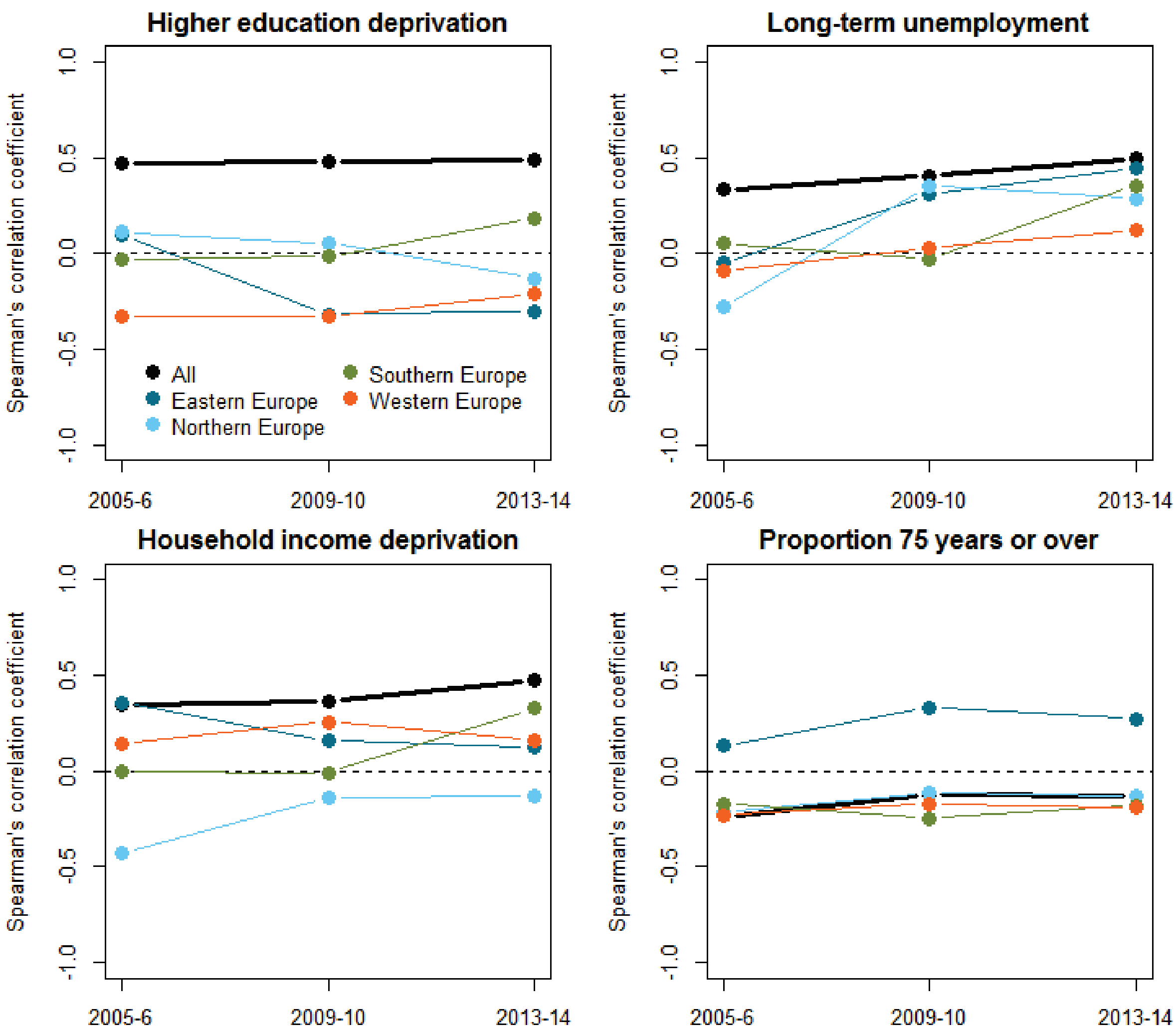
Figure 5.3 Association between PM_{10} exposure and long-term unemployment across NUTS 2 regions, over time (top), and in 2013-14 (map, bottom)



5.2.3 Differences among sub-regions of Europe

As was seen for PM2.5, the dominance of large-scale spatial patterns in PM10 exposure resulted in associations between PM10 exposure and deprivation within individual country groups being weaker than at the whole-Europe scale. For some deprivation indicators, even the direction of the association with PM_{10} exposure differed at the whole-Europe and country group scales; for example, in 2013-14 across the whole of Europe there was a relatively strong tendency for more deprived regions by higher education attainment to have higher PM_{10} exposure, but when considering individual country groups, a weak tendency in the opposite direction was observed (**Figure 5.4**).

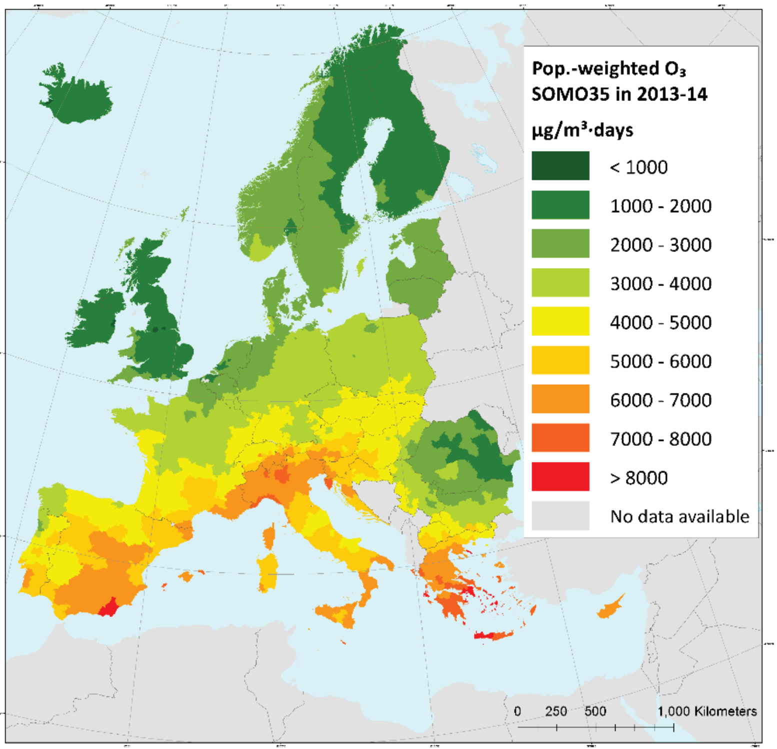
Figure 5.4 Spearman's rank correlation between PM_{10} exposure and selected deprivation indicators at NUTS 2 level, split by region



6 Ozone

6.2 Geographic variation in Ozone exposure and change over time

Map 6.1 Ozone exposure in NUTS 3 regions, 2013-2014



In 2013-14, ozone exposure (SOMO35; accumulated 8-hour concentrations above 70 µg/m^3 [= 35 ppb]) in NUTS 3 regions varied between 693 and 8786 µg/m^3·days. As for particulate matter, spatial variation in ozone exposure across Europe was dominated by a large-scale gradient, with the highest values found in Southern Europe and lower values further north (**Map 6.1**). This pattern reflects the major influence of solar radiation intensity on ozone concentrations.

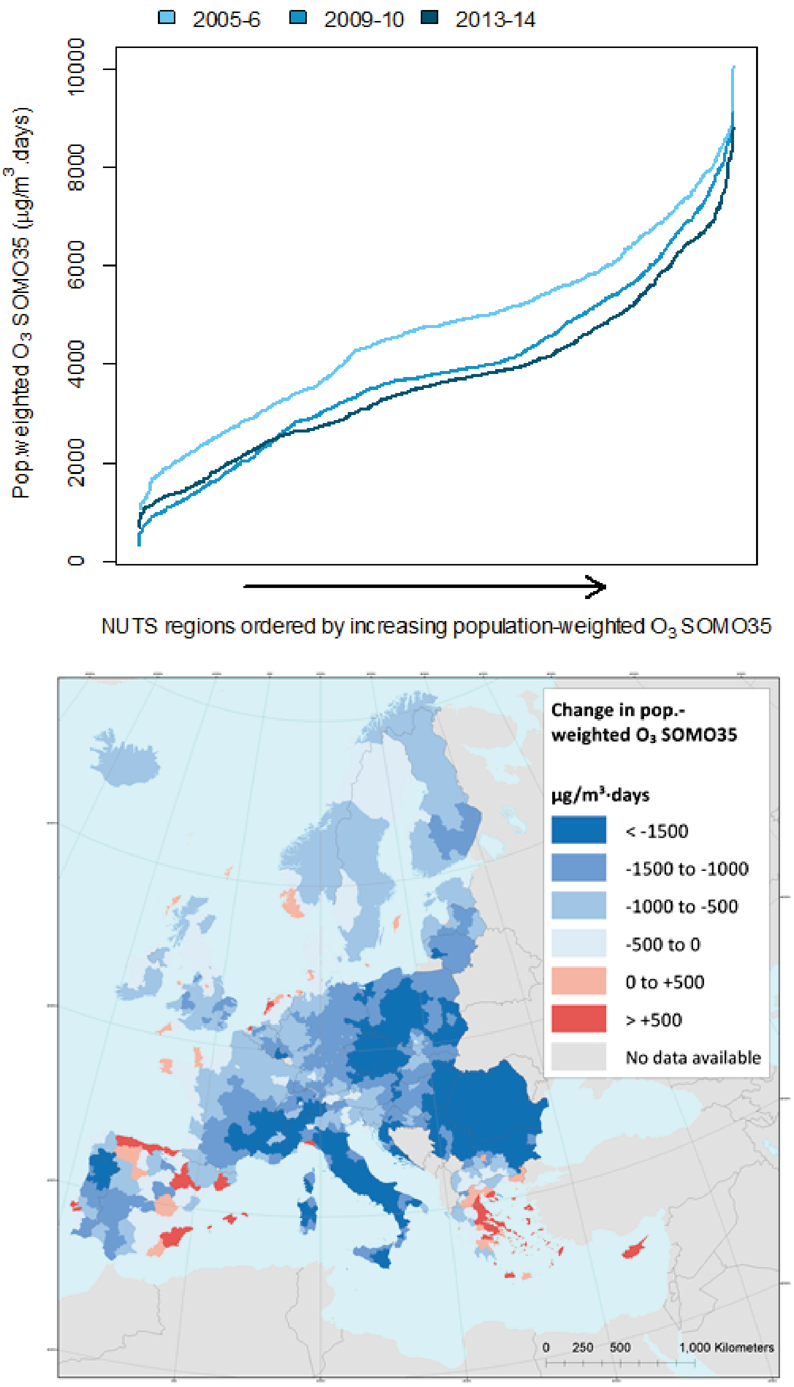
Table 6.1 Ozone exposure in the most and least polluted 20% of regions, and change over time

O_3	Mean population-weighted SOMO35 (µg/m^3·days)						
Year	**Least polluted 20% (Q1)**	**Q2**	**Q3**	**Q4**	**Most polluted 20% (Q5)**	**Ratio of Q5/Q1**	**Absolute difference (Q5-Q1)**
2005-6	2269	3695	4776	5524	7254	3.20	4985
2009-10	1456	2971	3803	4673	6678	4.59	5222
2013-14	1652	2764	3586	4305	6186	3.74	4534

In 2013-14 the degree of spatial variation in ozone exposure was greater than for NO_2 and particulate matter, with the most polluted 20% of NUTS 3 regions having around 3.7 times the SOMO35 value as the least polluted 20%, at 6186 and 1652 µg/m^3·days respectively (**Table 6.1**).

A general decrease in ozone exposure occurred in most regions between 2005-6 and 2013-14 (**Figure 6.1**), although inequality (as measured by exposure in most polluted 20% / least polluted 20%) has increased slightly over time from 3.2 to 3.7, being highest in 2009-10 at 4.6. This seems to be due to larger decreases (in percentage terms) in ozone exposure in the lowest pollution quintile than in the highest pollution quintile. Between 2005-6 and 2013-14, exposure fell by 28% in the lowest quintile, compared to only 15% in the highest quintile.

Figure 6.1 Top: Rank-value chart showing the distribution of ozone exposure in 2005-6, 2009-10 and 2013-14. Bottom: Map showing the absolute change in ozone exposure in each NUTS 3 regions, between 2005-6 and 2013-2014



6.2 Relationship of ozone exposure with deprivation-related variables and change over time

As seen for particulate matter, more deprived regions of Europe tended to have higher exposure to ozone across the time period studied for most indicators of deprivation. However, compared with particulate matter there were some important differences in both the strength of the associations for each indicator, and in the regions of Europe experiencing both high pollution and high deprivation (**Table 6.2**).

Specific findings:

- GDP per capita deprivation (NUTS 3) and household income deprivation (NUTS 2) are only weakly associated with ozone exposure.
- The strongest associations are found for higher education deprivation (NUTS 2 regions), unemployment (at both NUTS 2 and city scale) and proportion of the population >= 75, where more deprived (or vulnerable) NUTS 2 regions and cities have higher ozone exposure.
- In contrast, NUTS2 regions and cities with higher ozone exposure tend to have a lower proportion of the population under 5 years old.
- Inequality in ozone exposure across deprivation/vulnerability levels has grown between 2005-6 and 2013-14 when considering long-term unemployment and proportion of people >= 75 at the NUTS 2 level. However, for other measures of deprivation, inequality in ozone exposure has remained similar or reduced slightly over the same period.

Table 6.2 Association of ozone exposure with social indicators at the NUTS3, NUTS 2 and City scales, across the years studied

Spatial scale	Social indicator	Spearman's correlation			Pollution ratio DQ5/DQ1			Pollution difference DQ5-DQ1 (µg/m^3·days)		
		2005-2006	2009-2010	2013-2014	2005-2006	2009-2010	2013-2014	2005-2006	2009-2010	2013-2014
NUTS 3	GDP per capita deprivation	0.24	0.20	0.16	1.21	1.25	1.29	890	896	936
NUTS 2	Higher education deprivation	0.61	0.61	0.51	1.92	2.21	1.95	3060	3075	2385
	Household income deprivation	0.10	0.14	0.12	1.02	1.06	1.17	86	230	616
	Long-term unemployment	0.32	0.42	0.50	1.44	1.76	1.74	1630	2175	2295
	Proportion 75 years or over	0.10	0.23	0.31	1.13	1.43	1.47	608	1531	1491
	Proportion under 5 years	-0.42	-0.45	-0.46	0.62	0.59	0.59	-2077	-1828	-1670
			2010-2012			2010-2012			2010-2012	
Urban Audit Cities	Higher education deprivation		0.12			1.28			859	
	Unemployment		0.37			1.81			2357	
	Proportion 75 years or over		0.32			1.59			1805	
	Proportion under 5 years		-0.42			0.49			-2219	
	Respiratory disease death rate		-0.19			0.78			-1006	
	Green space deprivation		0.08			1.13			464	

Note: see section 1.4 for interpretation of Spearman's correlation, and pollution ratio and pollution difference between Q5 and Q1.

The associations between ozone exposure and deprivation/vulnerability are relatively consistent between the NUTS 2 and Urban Audit city scales for unemployment and age-related vulnerability.

However, the positive correlation between higher education deprivation and ozone exposure is much stronger at the NUTS 2 level than at the Urban audit city level. One plausible explanation for this may be an urban-rural gradient in access to higher education in the parts of Europe with the highest ozone exposure and lowest average higher education. This would mean that the Urban Audit cities in these regions have a greater share of people with higher education than the NUTS 2 regions to which they belong, weakening the association between this and ozone exposure.

Some of the associations emerging from these results are examined in more detail below.

6.2.1 Ozone exposure and GDP per capita deprivation at NUTS 3 level

In 2013-14, more deprived NUTS 3 regions (by GDP per capita) experienced on average slightly higher ozone exposure than more wealthy NUTS 3 regions. However, the association of ozone exposure with GDP per capita deprivation was the weakest of all of the pollutants, with NUTS 3 regions in the most deprived quintile exposed on average to 1.29 times the ozone exposure than those in the least deprived quintile (**Table 6.2**).

The map below (Figure **6.2,** bottom) shows that the NUTS 3 regions which were both among the highest 20% for ozone exposure and the most deprived 20% by GDP per capita in 2013-14 were primarily located in Greece, Croatia, Italy and Spain.

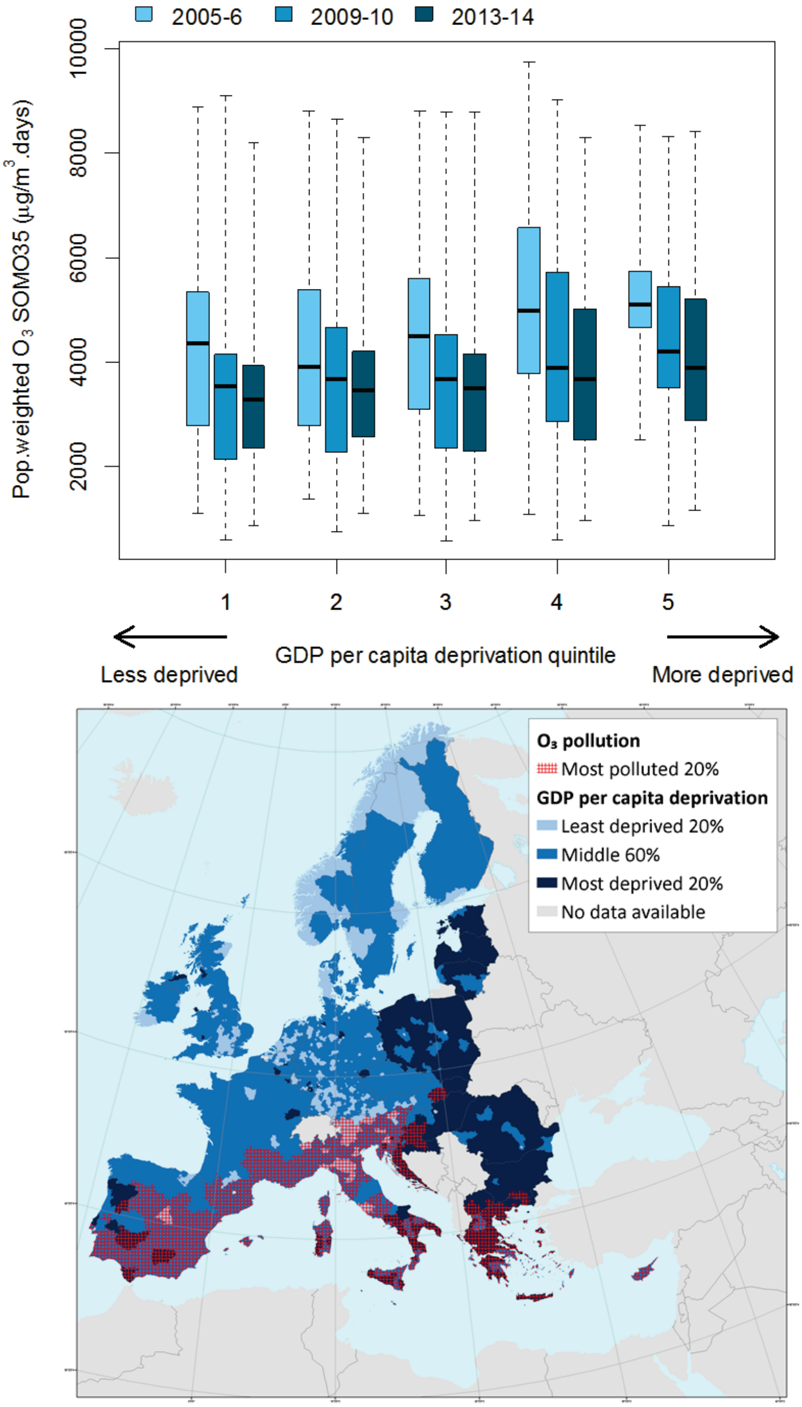
Average ozone exposure reduced between 2005-6 and 2013-14 overall for NUTS 3 regions in all quintiles of GDP per capita deprivation (**Figure 6.2**, top). A similar decrease of around 1000 $\mu g/m^3 \cdot$days was observed in both the top and bottom quintiles, which caused the absolute difference in exposure between the most and least deprived quintiles to remain similar at around 900 $\mu g/m^3 \cdot$days. The relative difference (DQ5/DQ1 ratio) also remained fairly similar, increasing slightly from 1.21 to 1.29 (**Table 6.2**).

The CRESH study (CRESH, 2013) found that ozone exposure was higher in more deprived NUTS 3 (by GDP per capita) regions than in less deprived ones in both 2005-6 and 2009-10. As for PM_{10} the CRESH study showed a slight decrease in relative inequality (DQ5/DQ1 ratio) in ozone exposure between the most and least deprived quintiles between 2005-6 and 2009-10, declining from 1.4 to 1.3. This study has also found that ozone exposure was higher in more deprived NUTS 3 regions than in less deprived ones across all three time-points. However, it has not found an overall decrease in relative inequality. As cited for PM_{10}, the differences in geographic coverage and air pollution interpolation methodology between the two studies hinder direct comparisons of the results.

6.2.2 Ozone exposure and higher education deprivation at NUTS 2 level

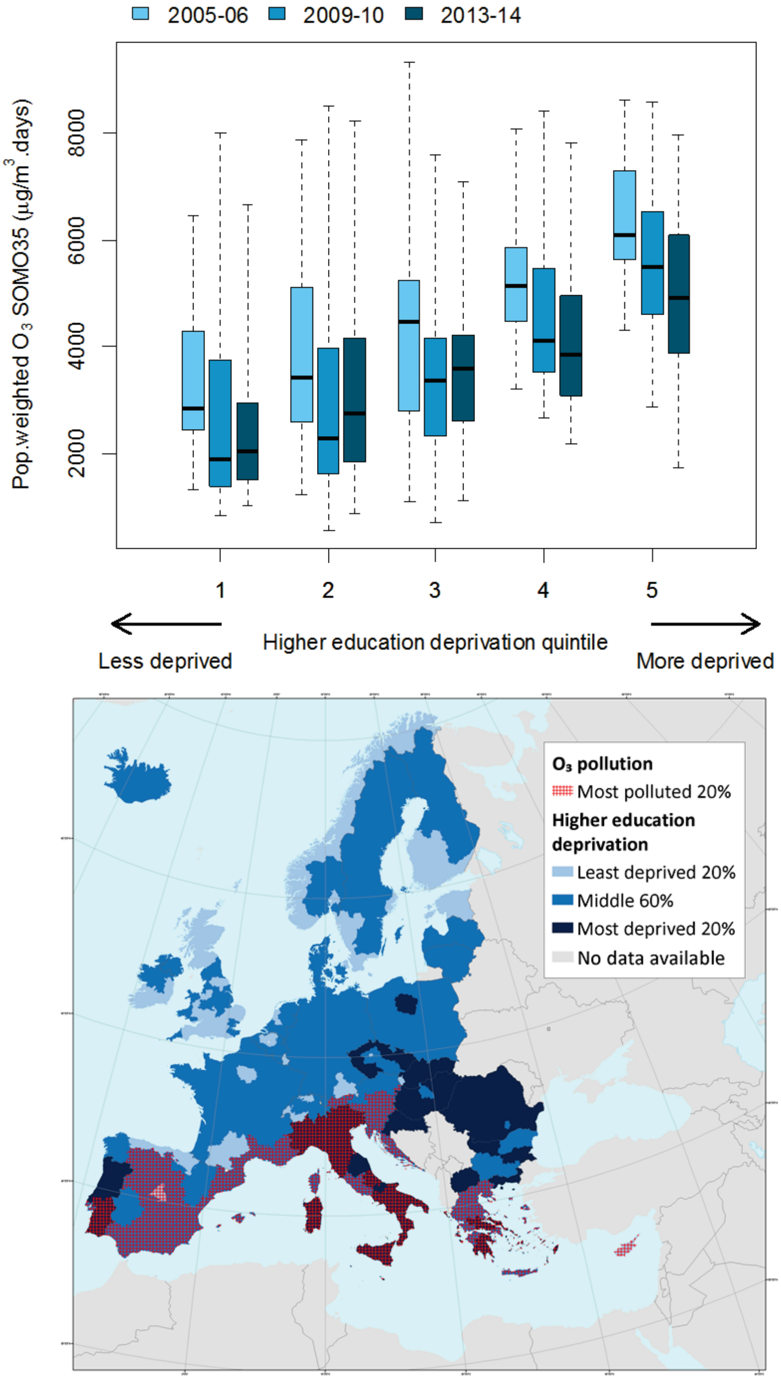
Across the time period studied, NUTS 2 regions with a higher proportion of people with higher education deprivation (i.e. less qualified) tended to have higher exposure to ozone, with people in the most deprived 20% of regions according to this measure being exposed to around twice the ozone SOMO35 as people in the least deprived 20% of regions (**Table 6.2**). For instance, those values were 4884 versus 2499 $\mu g/m^3 \cdot$days respectively in 2013-14 (**Figure 6.3**, top). This is a considerably larger ratio than observed for associations between deprivation and NO_2 or particulate matter exposure, but this is in the context of greater geographic variation in ozone exposure overall.

Figure 6.2 **Association between ozone exposure and GDP per capita deprivation across NUTS 3 regions, over time (top), and in 2013-14 (map, bottom)**



The regions which are both in the top 20% by ozone exposure, and in the most deprived 20% by higher education qualifications are all found in Southern Europe, in parts of Italy, Portugal and Greece (**Figure 6.3**, bottom).

Figure 6.3 Association between ozone exposure and higher education deprivation across NUTS 2 regions, over time (left), and in 2013-14 (map, right)



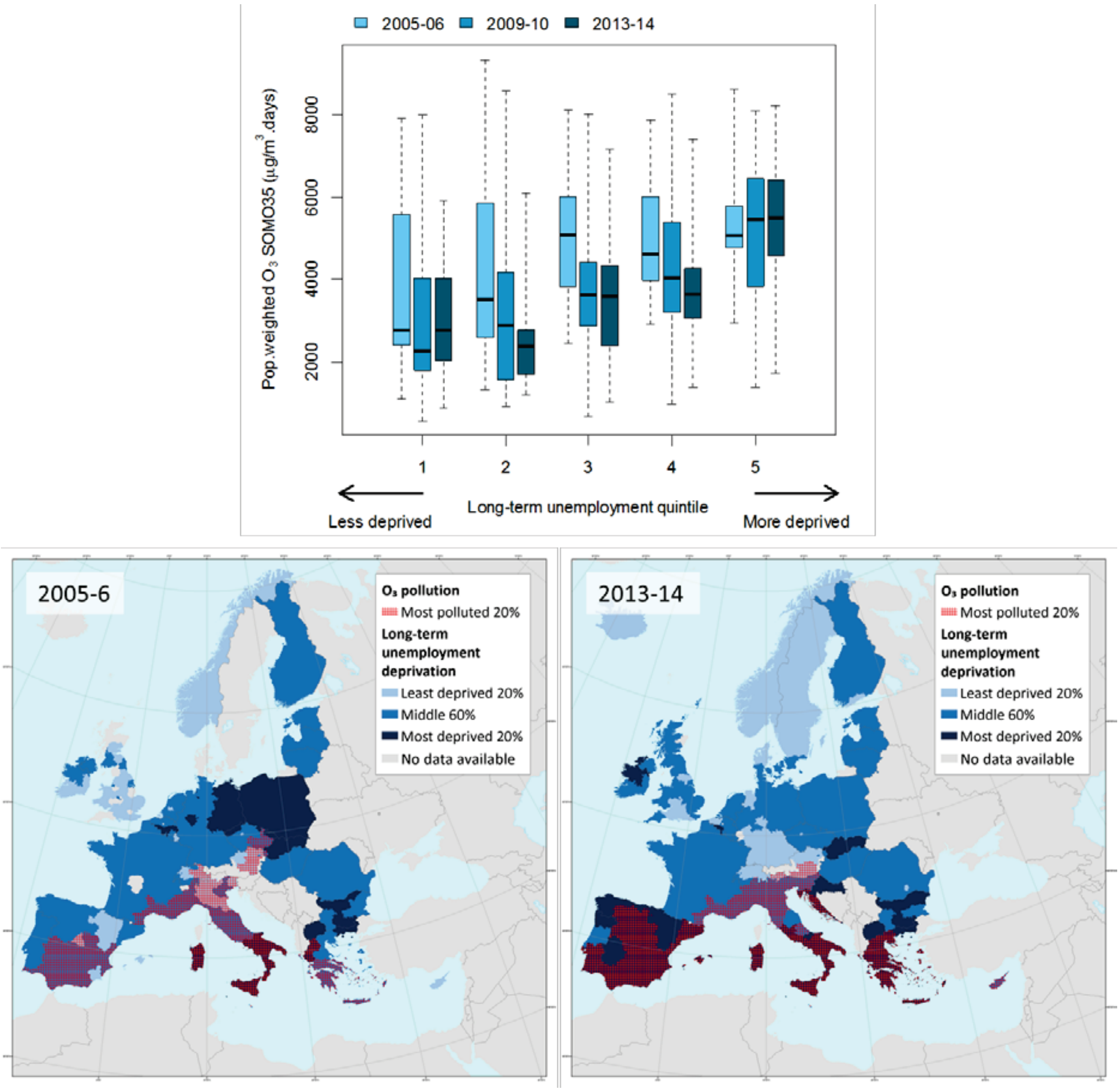
6.2.3 Ozone exposure and long-term unemployment at NUTS 2 level

In 2013-14, people in the most deprived 20% of NUTS 2 regions by long-term unemployment rate were exposed to about 1.7 times the ozone SOMO35 as those in the least deprived 20% (**Table 6.2**), at 5392 and 3097 µg/m^3·days respectively (**Figure 6.4**, top). As was the case for higher education deprivation, the regions both in the top 20% of ozone exposure, and in the most deprived 20% by long-term unemployment in 2013-14 were found in parts of Southern Europe (**Figure 6.4**, bottom).

However, in 2013-14 the lowest ozone SOMO35 levels were found in the 2nd quintile of the long-term unemployment distribution in 2013-14, at 2399 µg/m^3·days.

Between 2005-6 and 2013-14, the inequality in ozone exposure across levels of long-term unemployment deprivation has increased slightly, due to overall increases in ozone exposure in the most deprived quintile, versus decreases in other quintiles. Geographically, the reason for this is shown by the two overlap maps showing long-term unemployment and ozone exposure in 2005-6 and 2013-14 (**Figure 6.4**, bottom). The location of the 20% of NUTS 2 regions with the highest ozone exposure has changed little, but the location of those with the highest long-term unemployment has shifted slightly, to be focused more in the South of Europe.

Figure 6.4 Association between ozone exposure and long-term unemployment across NUTS 2 regions over time (top), and comparison of spatial association in 2005-6 and 2013-14 (maps, bottom)

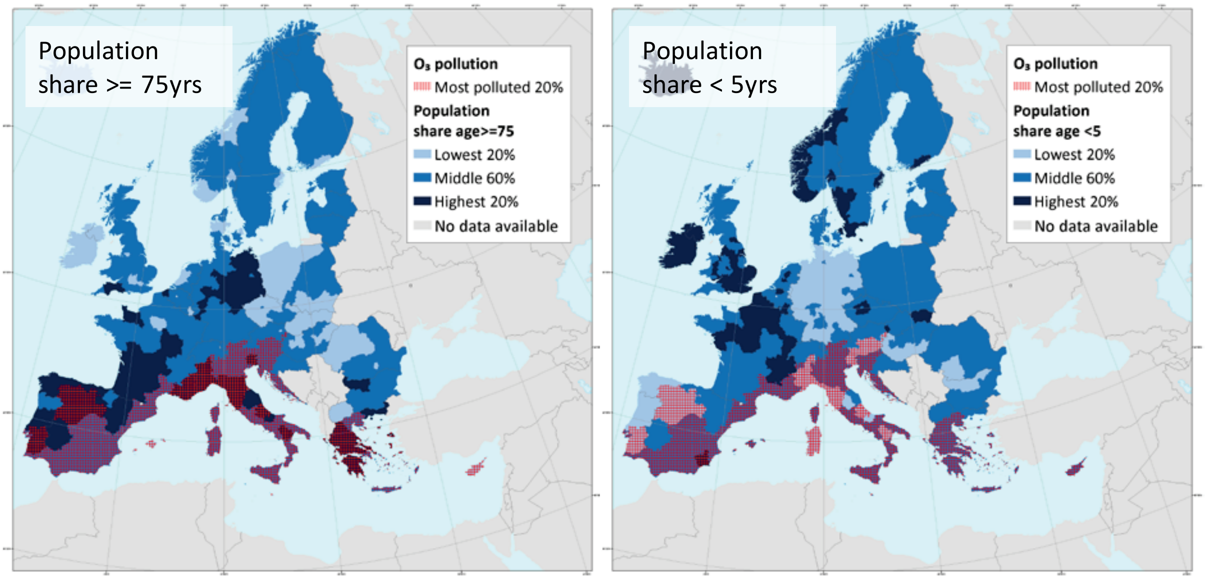


6.2.4 Ozone exposure and age-related vulnerability at NUTS 2 level

The relationship between ozone exposure and the proportion of vulnerable age-groups in the population shows a contrasting pattern for the very young and the elderly across NUTS 2 regions in 2013-14. Regions in Southern Europe with high ozone exposure tend to also have a relatively high proportion of people aged 75 years or over in the population (**Figure 6.5**, left), but a relatively low proportion of people aged less than 5 years (**Figure 6.5**, right).

The association of ozone exposure and proportion of people aged 75 years increased in strength between 2005-6 and 2013-14, though without further analysis it is difficult to say the extent to which this is due to a shift in the spatial distribution of ozone exposure, or of the demographic make-up of the population.

Figure 6.5 Association between ozone exposure and the proportion of vulnerable age-groups in the population across NUTS 2 regions in 2013-14

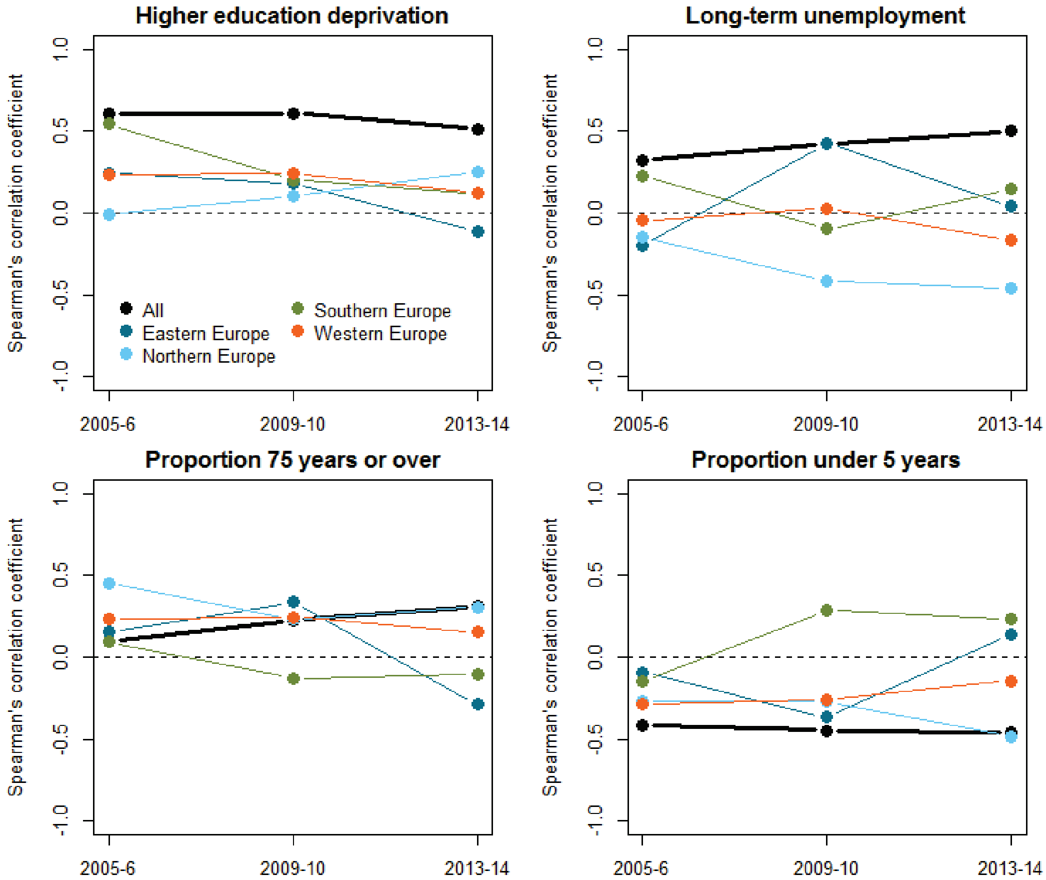


6.3 Differences among sub-regions of Europe

The large-scale gradient in ozone exposure seems to be the main driver of associations between ozone exposure and deprivation at the whole-Europe scale (Figu**re 6.6**). As seen for particulate matter, when the same variables are examined for individual groups of countries, associations are weaker, and may even show the opposite direction.

This is the case, for example, for the association between ozone exposure and long-term unemployment. In Northern Europe, areas with lower long-term unemployment tend to be exposed to higher levels of ozone - the opposite pattern to the whole-Europe association. This may be linked to urban-rural gradients in ozone exposure, which can be caused by interactions between other air pollutants.

Figure 6.6 **Spearman's rank correlation between ozone exposure and selected deprivation indicators at NUTS 2 level, split by region**



7 Noise

7.1 Limitations of the noise data

Before presenting the results of the analysis of road noise exposure and the association of this with social indicators, it is worth noting that this analysis is likely to have greater uncertainty than the analyses involving air pollutants above, due to data limitations. The uncertainty has several sources:

- Firstly, there are a number of NUTS regions and Urban Audit cities which had to be excluded from the analysis due to lack of data (see Annex 1), meaning the geographic coverage and representativeness of the analysis is poorer than for air pollutants.
- Secondly, there is also uncertainty introduced by the methodology for obtaining noise exposure estimates outside of major urban agglomerations, which uses modelled rather than observed exposure values.
- Thirdly, the methodology used to estimate and report noise exposure can differ slightly between countries, which adds a confounding factor to comparisons of exposure across Europe.

Given this uncertainty, the results presented below should be interpreted with caution.

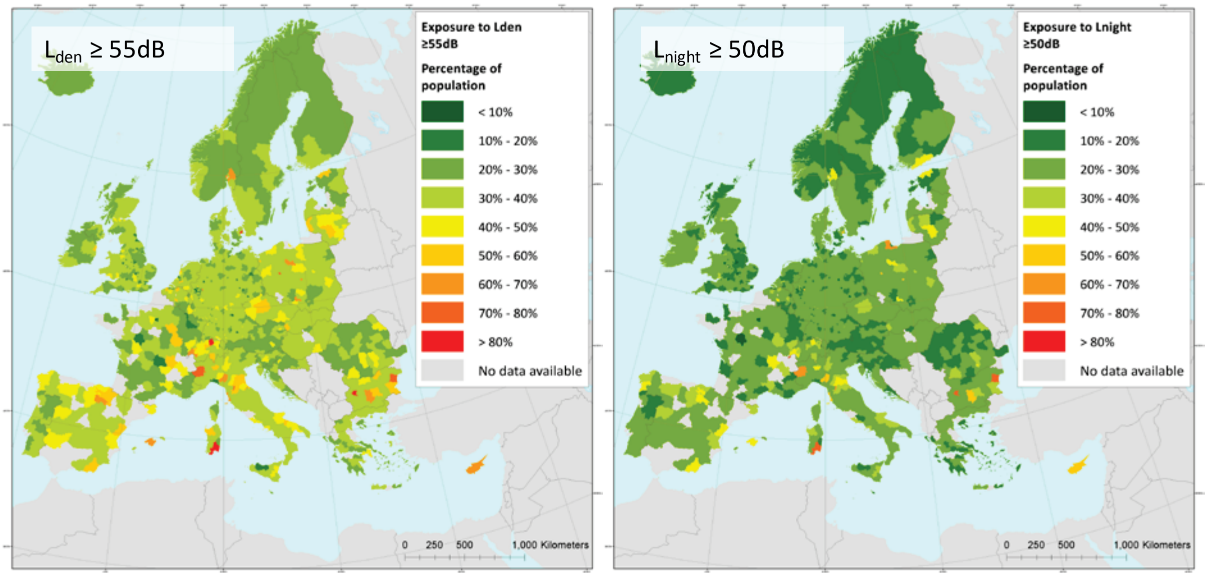
Section 8 provides a more detailed explanation of these issues, as well as more general considerations for the interpretation of results.

It is also important to note that, while in the case of air pollutants we are comparing social deprivation indexes with air pollutants concentrations weighted by population, when analysing noise exposure data we are comparing social deprivation indexes with the percentage of people exposed to a certain noise level. This difference in the input data considered for the analysis may have an influence on the measures of association used in this study, although it is difficult to predict the extent of the difference.

7.2 Geographic variation in road noise exposure

In 2011, the percentage of people exposed to 24-hour average road noise levels of 55 dB or more (L_{den} ≥55dB) varied between 0.3% and 90% across all NUTS 3 regions. Exposure to night-time road noise levels of 50 dB or more (L_{night} ≥50dB) was generally lower, although it ranged between 0.2% and 97% of the population.

Map 7.1 **Percentage of the population exposed to 24-hour average noise levels of 55 dB or more (L_{den} ≥55dB) and night-time noise levels of 50 dB or more (L_{night} ≥50dB) by NUTS 3 region in 2011**



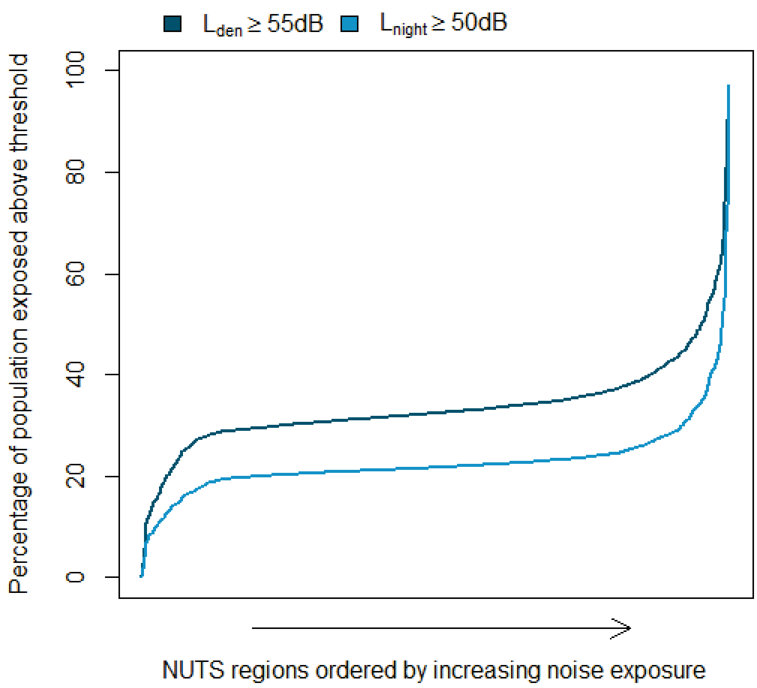
On average 46% of people were exposed to L_{den} ≥55dB in the quintile of NUTS 3 regions with the highest exposure, about 1.9 times the percentage in the quintile of regions with lowest exposure, at 24%. At night, exposure to noise levels of 50 dB or more (L_{night} ≥50dB) was slightly less prevalent, with 32% and 16% of people exposed on average in the most and least heavily affected 20% of NUTS 3 regions (**Table 7.1**). Although there is a large difference between exposure in the extremes, most of the NUTS3 regions are very similar in terms of number of people exposed to L_{den} ≥55dB: in 60% of the NUTS regions noise exposure ranges between 31 and 35 % (**Table 7.1**), illustrated by the large flat regions of the curves in **Figure 7.1**.

The spatial distribution of exposure to road noise in 2011 did not show any large-scale patterns across Europe (**Map 7.1**). Perhaps counter-intuitively, there did not appear to be a systematic difference between urban and rural areas; some urban areas such as Sofia, Prague and Oslo have higher road noise exposure than their surroundings, whereas for cities in the UK and Germany the opposite seems to be more common (**Map 7.1**). This may be partly due to differences in the input data and calculation methods used in different countries, especially concerning the types of road being included (for example in the UK, only major roads were considered in the 2012 mapping, whereas minor roads are included in other countries). In more rural areas, noise exposure could be high if dwellings are concentrated around major roads with heavy traffic, which tends to happen in surrounding areas of the main cities.

Table 7.1 **Percentage of the population exposed to 24-hour average noise of 55 dB or more (L_{den} ≥55dB) and night-time noise of 50 dB or more (L_{night} ≥50dB) the most and least exposed 20% of regions, in 2011**

Noise	Percentage of population exposed above threshold						
	Least exposed 20% (Q1)	Q2	Q3	Q4	Most exposed 20% (Q1)	Ratio of Q5/Q1	Absolute difference (Q5-Q1)
Lden ≥55 dB	24.2	30.5	32.3	34.8	45.6	1.88	21.4
Lnight ≥50 dB	16.0	20.5	21.6	23.1	32.2	2.01	16.2

Figure 7.1 **Rank-value chart showing the distribution of the proportion of the population exposed to 24-hour average noise levels of 55 dB or more (L_{den} ≥55dB) and night-time noise levels of 50 dB or more (L_{night} ≥50dB) in NUTS 3 regions in 2011**



7.3 Relationship of noise exposure with deprivation-related variables

Associations between reported noise exposure and indicators of deprivation or vulnerability are generally weak in comparison to the air pollutants. This is illustrated in **Table 7.2**, with most of the Spearman's correlation coefficients close to 0, and DQ5/DQ1 pollution ratios close to 1. This finding contrasts with those from other studies comparing smaller areas within individual cities, which found that noise exposure is higher in more deprived districts of cities (EC, 2016).

The relatively coarse spatial resolution of this study is the most likely reason for the contrast between the results for the air pollutants and noise exposure in this study, as well as the discrepancy with more fine-grained local studies of noise exposure. Whereas air pollution varies at the local, regional and national levels, noise exposure is a more local phenomenon (EC, 2016). Even the smallest spatial units considered (NUTS 3 regions and Urban Audit cities) tend to contain a heterogeneous mix of neighbourhoods. Large towns and cities are often represented by only one or a small number of NUTS regions (for example, Berlin is represented by a single NUTS 2 and NUTS 3 region). This means that fine-scale variation in noise exposure (and in social indicators) between different neighbourhoods is not detected.

The mechanisms underlying the associations between socio-economic status and exposure to noise between neighbourhoods in cities found in other studies are not well proven, and may vary from place to place. The proposed mechanisms include the differentiation of property prices based on proximity to noise sources along gradients of urbanisation, and perhaps a tendency for cheaper areas to attract more polluting sources (EC, 2016). Whichever mechanisms are at play at the city scale, it is unlikely that these same mechanisms would operate to differentiate large spatial units across the whole of Europe, which may explain why this study has failed to find systematic associations at this scale.

The strongest association found was between noise exposure and unemployment, when considered across Urban Audit cities, which is discussed in more detail below.

Table 7.2 Association between the percentage of people exposed to noise pollution above 24-hour and night-time limits and social indicators at the NUTS3, NUTS 2 and City scales in 2011

Spatial scale	Social indicator	Percentage exposed L_{den} ≥55dB			Percentage exposed L_{night} ≥50dB		
		Spearman correlation	Ratio DQ5/DQ1	Difference DQ5-DQ1	Spearman correlation	Ratio DQ5/DQ1	Difference DQ5-DQ1
NUTS 3	GDP per capita deprivation	-0.09	0.98	-0.6	-0.04	1.01	0.3
NUTS 2	Higher education deprivation	0.03	0.96	-1.6	0.06	0.96	-1.0
	Household income deprivation	0.21	1.16	5.1	0.22	1.17	3.7
	Long-term unemployment	0.04	1.00	0.1	0.08	1.04	1.0
	Proportion 75 years or over	-0.10	0.96	-1.6	-0.09	0.95	-1.2
	Proportion under 5 years	-0.04	0.96	-1.3	-0.04	0.96	-1.0
Urban Audit Cities	Higher education deprivation	0.07	1.17	7.2	0.04	1.11	3.3
	Unemployment	0.26	1.74	26.0	0.30	2.13	25.5
	Proportion 75 years or over	0.02	1.11	4.6	0.05	1.23	7.2
	Proportion under 5 years	0.01	0.92	-2.9	0.02	0.88	-3.1
	Respiratory disease death rate	0.06	1.15	7.2	0.02	1.02	0.9
	Green space deprivation	0.11	1.13	5.1	0.13	1.32	8.4

7.3.1 Noise exposure and unemployment in Urban Audit cities

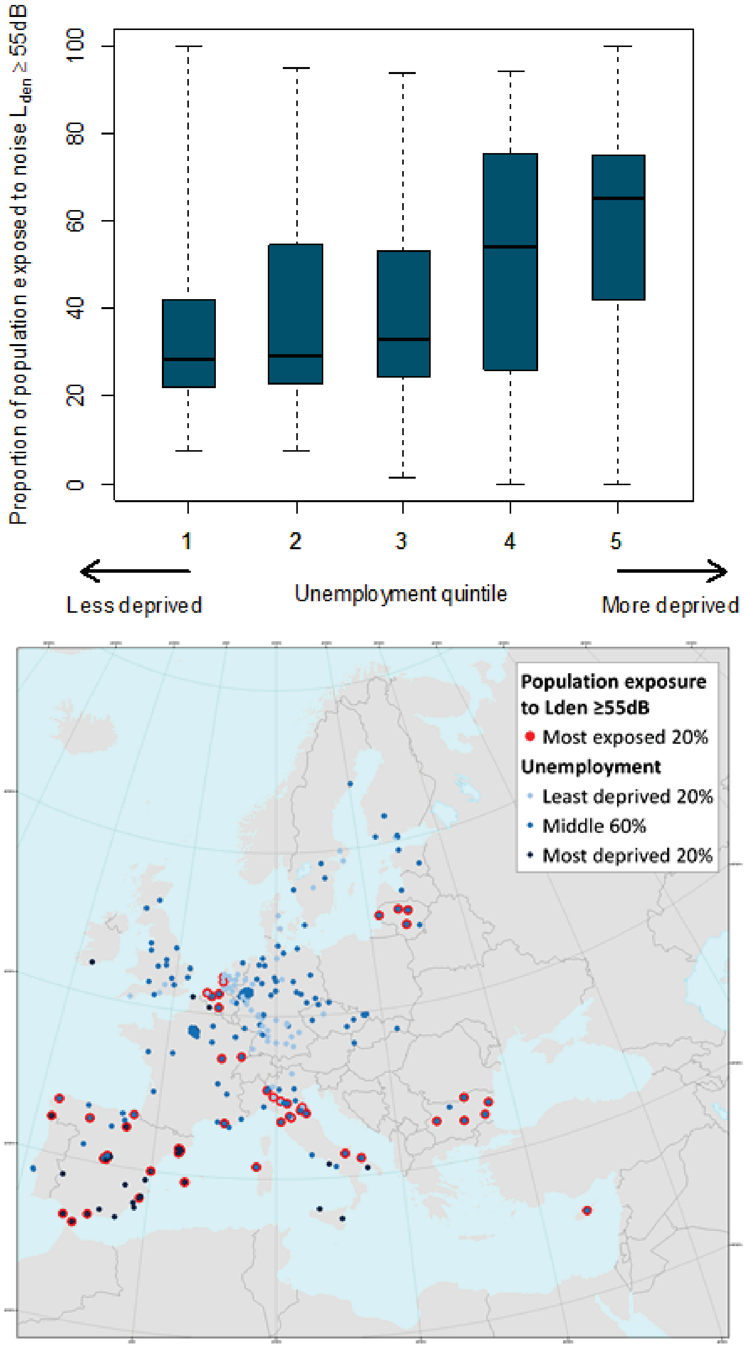
Comparing across Urban Audit cities, in 2011 the proportion of people exposed to L_{den} ≥55dB average noise in the quintile of cities with the highest unemployment was around 1.7 times as high as in the quintile with the lowest unemployment, at 61% and 35% respectively (**Table 7.2**; **Figure 7.2**, top).

The relative difference in exposure between most and least exposed cities was even greater for night-time noise (2.1 times), at 48% and 23% of the population respectively. However, it should be noted that across cities within each unemployment quintile there is a great variability in the percentage of people exposed, meaning that there are cities with relatively high exposure across all ranges of deprivation.

Geographically, the cities found in both the top 20% by unemployment and by noise exposure are mainly in the Mediterranean area, in particular Spain (**Figure 7.2**, bottom). These results can be understood in the context of economic crisis that hit Europe in 2007, from which the impacts were still felt in 2011. However, it must be noted that a major limitation of the noise exposure data at the city scale is the incomplete and possibly unrepresentative data coverage. Using the methodology described in **Annex 1**, noise exposure data could only be obtained for around 35% of cities in the Urban Audit, comprising only 24 of the 31 countries included in air pollution data. Most notably, unemployment data are missing for cities in Greece and Romania, both of which have relatively high unemployment levels at the NUTS 2 level.

As such the associations reported above may not be representative of the situation for all cities. Additionally, there are some caveats and assumptions involved in the method of assigning noise exposure figures to Urban Audit cities, which add uncertainty to the estimates (see section 8.2.2).

Figure 7.2 Association between the proportion of the population exposed to L_{den} ≥55dB and unemployment across Urban Audit cities in 2011



7.4 Differences among sub-regions of Europe

Due to the low number and potentially unrepresentative nature of cities for which noise exposure data was available, no associations within country groupings were explored in detail. Nonetheless, the summary measures of association can be found in tabulated form in Annex 2.

8 Limitations of the data and methodology

There are a number of caveats and limitations of this analysis which must be borne in mind when interpreting the results. This is particularly important when comparing these results with those of numerous other studies investigating similar questions, but with a different scope and making use of different data sources.

8.1 Spatial scale of analysis

The geographic extent and spatial granularity of the analysis is probably the most important factor affecting both its ability to detect associations between pollution exposure and social indicators, and the interpretation of patterns detected. This factor is highlighted as a key methodological issue in observational studies of pollution and socio-economic status (EC, 2016).

This study analyses the spatial association between pollution exposure and social indicators in relatively large units (NUTS 3 regions generally contain between 150 000 and 800 000 people, NUTS 2 regions between 800 000 and 1.5 million people), across the whole of Europe. Within individual NUTS regions there is likely to be a great deal of heterogeneity in both pollution exposure and social indicators. Consequently, this study can detect large-scale variation in pollution exposure and social indicators which are driven by similarly large-scale gradients in geography, meteorology, social, cultural and economic factors. At the same time, this analysis cannot detect the differences in pollution exposure and social indicators which occur between small neighbourhoods in different parts of cities. The causal mechanisms driving large-scale and small-scale associations may differ considerably, so it is vital to bear in mind the spatial scale of analysis.

In contrast, a large number of other studies have investigated the spatial association between pollution exposure and indicators of deprivation or socio-economic status in much smaller and more homogeneous neighbourhood units (100s to 1000s of people) across individual cities or countries.

The discrepancy in the spatial extent and granularity between this study and others will inevitably lead to different results in some cases, and this may depend upon the sources and properties of the pollutant in question. For example, the finding that population-weighted NO_2 concentration was higher in NUTS 3 regions with higher GDP per capita seems contrary to the results of other studies. NO_2 concentrations can vary considerably over very short distances away from sources, but these small-scale variations have been averaged away when aggregating concentrations to larger units. Similarly, this study found little correlation between noise exposure and social indicators, despite many other studies finding a strong link.

As with NO_2 concentrations, noise exposure also varies considerably over short distances away from sources, so fine-scale variation within towns and cities may be more important than larger-scale variation in determining associations with social indicators. Equally, whilst the associations found in this study between particulate matter and ozone exposure and socio-economic status are qualitatively similar to those found in other studies at smaller scales (higher exposure in more deprived areas), the processes underpinning the association may be quite different.

8.2 Limitations of the air pollution and noise exposure data

8.2.1 Air pollution data

There are several caveats specifically relating the air pollution data used in the study.

- Firstly, air pollutant concentrations may vary from year to year due to annual variations in prevailing weather conditions. This has the potential to confound comparisons of pollutant concentrations over time, as the year-to-year volatility could mask the effects of underlying trends in emissions. In this analysis, where possible 2 or 3 years of air pollution data were averaged to minimise the effect of weather-related volatility. However, some effect of this volatility is likely to remain, as much longer averaging periods would be required to eliminate this completely.
- Secondly, the 1 x 1km air pollutant concentration grids used in the analysis are created based on interpolation of background measurements (ETC/ACM, 2016b). In some parts of Europe the density of monitoring stations is low (i.e. less than one station per NUTS 3 region), so in these areas the interpolation will smooth out actual differences in pollution levels between neighbouring units with similar characteristics.
- Thirdly, the measure used in this analysis to quantify exposure to air pollution is the population-weighted average concentration (SOMO35 for ozone) within a given NUTS regions or Urban Audit city. This captures the typical outdoor background concentration which is present for a typical resident in that NUTS region or city. However, actual personal exposure depends on a variety of other factors such as amount of time spent outdoors. If any of these other factors vary systematically between regions (e.g. outdoor working is more common in one region than another), then the population-weighted average concentration will not fairly represent differences in actual exposure.

8.2.2 Noise exposure data

In this analysis the percentage of the population exposed to average road noise levels of 55dB or more over 24 hours and of 50dB or more at night was estimated for NUTS regions and Urban audit cities. The estimates were based partly on road noise exposure figures reported for urban agglomerations of over 100 000 people through the Environmental Noise Directive (2002/49/EC), and partly on a 1 x 1 km modelled dataset of road noise exposure outside of agglomerations for the whole of Europe. The main factors affecting the quality of the noise data used in this analysis are described below.

- Firstly, there are a number of NUTS regions and Urban Audit cities which had to be excluded from the analysis due to lack of data (see Annex 1), meaning the geographic coverage and representativeness of the analysis is poorer than for air pollutants. This is a particular issue for Urban Audit cities, where estimates could only be made for around 35 % of cities.
- Secondly, there is also uncertainty introduced by the use of gap filled data to estimate the number of people exposed to road noise outside agglomerations.
- Thirdly, the method used in this study to assign agglomeration-level road noise exposure to NUTS regions or Urban Audit cities is simple area weighting (see Annex 1). This assumes that noise exposure is uniformly distributed within agglomerations, which is unlikely to hold in most

cases. Where a NUTS region or Urban Audit city occupy only a small fraction of the area of an agglomeration (for example in Greater London), the error introduced could be considerable. This assumption also led to some NUTS regions and Urban Audit cities having estimates of over 100 % of the population exposed to above-threshold noise levels, leading to the exclusion of these units from the analysis.

- Finally, the methodology used to estimate and report noise exposure can differ slightly between countries, which adds a confounding factor to comparisons of exposure across Europe.

8.3 Limitations of the social indicators

Social indicator data was obtained predominantly from Eurostat. The main data quality issue encountered was the poor geographic and temporal coverage of some of the indicators available.

To a large extent this issue was solved by excluding indicators with poor coverage from the analysis. However, even for indicators where a high proportion of NUTS regions and/or Urban Audit cities have data, if data for key countries (i.e. countries which may have a large impact on the observed association) is missing this could strongly affect the association found. For example, there was little association between $PM_{2.5}$ exposure and unemployment across Urban Audit cities despite a relatively strong association with long-term unemployment across NUTS 2 regions. This is likely due to missing Urban Audit data for Greece and Romania which have relatively high levels of unemployment.

Table A1.3 in Annex 1 provides an overview of the geographical coverage of social indicators.

A second caveat relates to the definition of the social indicators used. Where an indicator is a mean value for a particular NUTS regions or city, this may conceal considerable heterogeneity within the unit. This is particularly relevant for the GDP per capita and average household income indicators, where wealth may be concentrated in a small proportion of households in some cases. In such a case, the average figure for the unit would not be truly representative of the level of wealth of a typical person living in that region.

8.4 Analysis within sub-groupings of countries

Part of this study aimed to repeat the European scale analysis for smaller groups of regions or countries, to explore variations among the groups in the association between pollution exposure and social indicators.

Based on the literature, urbanisation was identified as a common factor to the sources of air and noise pollution, as well as social deprivation. Therefore, the use of an urban-rural typology of NUTS regions was investigated[3]. However, this is only applicable to NUTS 3 regions, for which GDP per capita was the only social indicator available from Eurostat. Application of this typology to NUTS 2 regions is not advised as these are often internally heterogeneous. Consequently, an urban-rural grouping of regions was not applied.

In the absence of any other identified theoretical framework for grouping countries or regions, the official United Nations classification of countries into Northern, Eastern, Southern and Western Europe was used (UNSD, 2018). The difference between the results of the whole-Europe scale

[3] http://ec.europa.eu/eurostat/statistics-explained/index.php/Archive:Urban-rural_typology

analyses and those for the individual country groupings help to underline how crucial the geographic scope of analysis is in determining the results for some pollutants. However, because countries with rather different characteristics are bundled together in the same groups under the UNSD classification, interpretation of why the results for one group differ for those for another is difficult and is unlikely to provide great insight.

In future analyses of this kind, it would be beneficial to establish a grouping of regions and countries which does follow a relevant theoretical framework, to aid interpretation of between-group differences.

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Annex 1 – Methodology Description

Methodology

In summary, the study combined population-weighted air pollution data (NO_2, PM_{10}, $PM_{2.5}$ and O_3) and population exposure to noise with social indicators, to assess the extent to which they correlate spatially across Europe at various levels of spatial granularity: NUTS3 regions, NUTS2 regions and cities. Where possible we considered how patterns in the data and relationships have changed over time, between 2005 and 2014. This section describes the datasets used and the methods used to combine and analyse them.

Geographical units

The regional statistics on per-capita GDP and other indicators of social deprivation or vulnerability used in this study were obtained from Eurostat (Eurostat, 2018a) for areas defined by NUTS 3, NUTS 2 and Urban Audit city boundaries.

The NUTS classification - "Nomenclature of Territorial Units for Statistics" - is made up of three hierarchical subdivisions of a country, with NUTS 1 regions being the largest and NUTS 3 regions being the smallest level of subdivision. NUTS regions are defined by existing administrative units within member states where possible, so long as the population falls within particular bounds. NUTS 3 regions generally have between 150 000 and 800 000 inhabitants, and NUTS 2 regions between 0.8 and 3 million.

The Urban Audit city statistics are available at three levels: "core cities" are the administrative units delineating the urban boundary of a city or a district within a large city, "greater cities" comprise the boundaries of large cities, and "functional urban areas" comprise the city plus the surrounding commuting zone. This study focused on core cities (and some greater cities for the noise exposure analysis), to ensure that the composition of the cities was as comparable as possible.

Data sources and preparation

Air pollution data

Air quality data were obtained from ETC/ACM partners for Europe on an interpolated 1 km by 1 km grid (ETC/ACM, 2016b). The pollutants considered in this study were nitrogen dioxide (NO_2), particulate matter (PM_{10} and $PM_{2.5}$) and ozone (O_3), being the main air pollutants currently posing a risk to human health in Europe. We used metrics of air pollution that represent long-term measures of concentration, because these are considered more relevant for assessing health impacts than short-term exposure measures:

- NO_2 – annual average concentration
- PM_{10} – annual average concentration
- $PM_{2.5}$ – annual average concentration
- Ozone - SOMO35 (sum of daily maximum 8-hour running average concentrations over 70 µg/m^3 [= 35 ppb])

In order to compare the socio-economic variables with the 1 km by 1 km gridded air pollution data, the latter was aggregated to a summary figure for each city, NUTS 3 and NUTS 2 region.

Annual population-weighted averages of air pollutant concentration were calculated for each region, by weighting the pollution concentration data for each 1 km by 1 km grid cell with Geostat population data for Europe in 2011 on the same 1 km by 1 km grid (Eurostat, 2018b), then calculating an average. This annual population-weighted average characterises the level of exposure to air pollution for an average person in that region in a given year, which is an appropriate measure for this analysis.

The following formula was used to perform population-weighting:

Equation 1

$$P_r = \frac{\sum_{i=1}^{n_c}(P_i \times pop_i)}{\sum_{i=1}^{n_c}(pop_i)}$$

Where P_r is the population-weighted concentration for NUTS region r, P_i is the concentration in the ith grid cell within region r, pop_i is the population within the ith grid cell, and n_c is the total number of grid cells within that region.

Grid cells with a population of 0 give zero weight to the air pollutant concentration within that region, so these cells do not count towards the population-weighted average of the region containing them.

Where a 1 km by 1 km grid cell straddled the border of two or more regions, the cell was assigned to the region containing the centre of the cell.

In order to minimise the impact on the analysis of weather related variations, the annual population-weighted pollution concentrations calculated by the steps above were subsequently averaged across years, with the years chosen determined by data availability. The year groupings are defined in **Table 1** below. At the city scale only one time-period was considered because of the limited availability of social indicators. In the main report, for brevity population-weighted concentration is frequently also referred to as “exposure” (or “pollution”).

Noise data

In this study a combination of two datasets was used to estimate the proportion of people exposed to 24-hour average noise levels of 55dB or more (L_{den} ≥ 55dB) and night-time average levels of 50dB or more (L_{night} ≥ 50dB) for NUTS regions and cities.

Noise exposure in agglomerations

Firstly, the NOISE database (EEA, 2018) contains estimates of the number of people exposed to noise from roads, rail, aircraft and industry within “agglomerations” – urban areas containing 100 000 people or more – in Europe, reported under the Environmental Noise Directive (END; 2002/49/EC). Only exposure to road noise was considered in this study, as this is the dominant source of noise exposure in most cities, and exposure figures from all sources were available for very few cities. The agglomeration-level noise exposure data was used to estimate the number of people exposed to road noise of L_{den} ≥ 55dB and L_{night} ≥ 50dB for the parts of NUTS regions and cities overlapping agglomerations.

In line with the END, data for people exposed to environmental noise was reported in 2007 and 2012, referring to the situation in the preceding calendar year (2006 and 2011, respectively). The data reported in 2012 (for 2011) is reported for agglomerations with more than 100 000 inhabitants and has better coverage than the 2007 dataset (which only includes agglomerations with more than 250 000 inhabitants), so in this study only the data reported in 2012 (for 2011) was taken into consideration. In this analysis, for the purposes of describing the association with social indicators, the calendar year of the road noise exposure data is taken to be 2011.

Agglomerations with missing data were excluded from the analysis. The corresponding NUTS regions overlapping at least one agglomeration with missing data were also excluded from the analysis. Simple area-weighting was used to disaggregate road noise exposure figures from agglomerations to NUTS regions and cities, according to the area of intersection between a NUTS region or city and one or more agglomerations (equation 2). For a focal NUTS region or city Reg, the number of people exposed above a given noise threshold in agglomerations, NEA_{Reg}, is given by:

Equation 2.

$$NEA_{Reg} = \sum_{i=1}^{n} NE_{Agg_i} \left(\frac{Area_{Reg \cap Agg_i}}{Area_{Agg_i}} \right)$$

Where Reg is the NUTS region or city in question, n is the number of agglomerations intersected by that NUTS region or city Reg, NE_{Agg_i} is the total number of people exposed to noise above the chosen threshold in the i^{th} agglomeration, $Area_{Agg_i}$ is the total area of the i^{th} agglomeration, and $Area_{Reg \cap Agg_i}$ is the area of overlap between the Reg and the i^{th} agglomeration.

For example, if 50% of the surface area of an agglomeration X is intersected by NUTS region A, then 50% of the people exposed to $L_{den} \geq 55$dB and $L_{night} \geq 50$dB in agglomeration X are assigned to NUTS region A. This technique assumes homogeneity of noise exposure within agglomerations. If NUTS region A also intersects 60% of the area of a second agglomeration Y, then 60% of the people exposed to $L_{den} \geq 55$dB and $L_{night} \geq 50$dB in agglomeration Y are added to the total.

Noise exposure outside of agglomerations

For parts of NUTS regions which do not intersect an agglomeration, a second dataset was used to estimate the number of people exposed to road noise of $L_{den} \geq 55$dB and $L_{night} \geq 50$dB outside of agglomerations. This comprises modelled estimates of the population exposed to road traffic noise L_{den} and L_{night} with a full European coverage, at 1 x 1 km grid resolution (ETC/ACM, 2016c).

For a focal NUTS region or city Reg, the total number of people exposed above a given noise threshold outside of agglomerations, NEO_{Reg}, was obtained by summing the number of people exposed across all 1 x 1 km grid cells as follows:

Equation 3.

$$NEO_{Reg} = \sum_{c=1}^{C} NE_c$$

Where Reg is the NUTS region in question, C is the number of 1 x 1 km grid cells contained within Reg and outside an agglomeration, and NE_c is the number of people exposed to noise above the chosen threshold in the c^{th} grid cell.

Note that this second dataset was not for Urban Audit cities, due to the uncertainty of the modelled road noise exposure data outside agglomerations when used at small scales. Instead, cities having less than 70% of their area overlapping an agglomeration were excluded from the analysis.

Total noise exposure in NUTS 2 and 3 regions

Finally, for NUTS 2 and 3 regions, the number of people exposed to Lden ≥55dB and Lnight ≥50dB inside and outside of agglomerations was added together to produce a combined total, then scaled by the total 2011 population of the region (Eurostat, 2018a) to express the figures as a percentage. For a focal NUTS region Reg, the percentage of people exposed to noise above the chosen threshold, $PercE_{Reg}$, is given by:

Equation 4.

$$PercE_{Reg} = 100 \cdot \left(\frac{NEA_{Reg} + NEO_{Reg}}{Pop_{Reg}}\right)$$

Where Reg is the NUTS region in question, NEA_{Reg} is the number of people exposed inside agglomerations, NEO_{Reg} is the number of people exposed outside of agglomerations, and Pop_{Reg} is the population of the NUTS region on the 1st January 2011.

In a few NUTS 3 regions and cities, apparent noise exposure rates greater than 1 occurred due to the limitations of the methodology described above. These regions were excluded from the analysis. NUTS regions intersecting agglomerations with missing data were also excluded from the analysis, the total exposure figure for these regions will likely be an underestimate.

Note that for Urban Audit cities the same equation applies, but the number of people exposed outside of agglomerations (NEO_{Reg}) is always 0, as this was not estimated.

Choice of time period for analyses of air and noise pollution

Annual data on air and noise pollution data are available between 2005 and 2014, with the availability differing between pollutants. As mentioned above, population-weighted air pollution data was averaged across two or three consecutive years, to reduce the impact of year-to-year variability in air pollutant concentrations resulting from differing weather. At the NUTS 2 and 3 scales three separate time points were defined for each pollutant, and a single year grouping was defined at the city scale to align with the greatest availability of social indicators in 2011. The availability of pollution data and grouping of years used in analyses is shown in **Table A1.1** below.

Table A1.1 **Years available (orange) and years averaged (dark outlines) for the analysis of air pollution and noise**

For NUTS 2 and NUTS3

Pollutant	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
PM_{10}										
$PM_{2.5}$										
NO_2										
Ozone										
Noise L_{den}										
Noise L_{night}										

For City level analysis

Pollutant	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
PM_{10}										
$PM_{2.5}$										
NO_2										
Ozone										
Noise L_{den}										
Noise L_{night}										

Datasets to represent social deprivation and vulnerability

There are a variety of variables available from Eurostat related to social deprivation, poverty or vulnerability to the impacts of air/noise pollution for cities and NUTS 2/3 regions (Eurostat, 2018a).

Initially, analyses were undertaken with a range of relevant indicators (results for all of which are contained in Annex 2), then a smaller subset of indicators were selected for more detailed reporting, based on their uniqueness, relevance and the completeness of geographic coverage. Details of the geographic coverage of each combination of environmental and social indicator are provided in table A1.3.

In order to ensure consistent interpretation of results from the subsequent analyses, some indicators were inverted, so that for all indicators higher values signify more deprived/vulnerable regions, and lower values less deprived.

The indicators initially considered are listed in **Table A1.2** below, grouped by the level of spatial resolution at which they are available and broad theme. Those chosen for detailed reporting are highlighted in green. Where relevant the operation applied to invert the indicator and reasons for exclusion is given.

Table A1.2 Details of indicators of social deprivation and vulnerability

Spatial scale	Theme	Indicator definition	Indicator short name	Inversion applied	Reason for exclusion	Eurostat table code or source URL	Additional filter applied or indicator codes extracted
NUTS 3	Economy	Per capita GDP, Purchasing Power Standard (PPS)	GDP per capita deprivation	Max (x) - x		nama_10r_3gdp	Unit = PPS_HAB
NUTS 2	Economy	Per capita household income after social transfers, Purchasing Power Standard (PPCS)	Household income deprivation	Max (x) - x		nama_10r_2hhinc	Unit = PPCS_HAB; na_item = B6N
	Demography	Percentage of population aged < 5 years	Proportion under 5 years			demo_r_pjangroup	Sex = T; Age = Y_LT5 (and TOTAL to transform to %)
		Percentage of population aged >= 75 years	Proportion 75 years and over			demo_r_pjangroup	Sex = T; Age = Y_GE75 (and TOTAL to transform to %)
	Labour market	Long-term unemployment (12 months or more) rate, % of economically active population	Long-term unemployment			lfst_r_lfu2ltu	Unit = PC_ACT
		Unemployment rate, % of 15- to 74-year-olds			Less salient than alternative	lfst_r_lfu3rt	Unit = PC; Sex = T; Age = Y15-74
	Education	Percentage of 25- to 64-year-olds with ISCED level 0-2			Less salient than alternative	edat_lfse_04	Sex = T; Age = Y25-64; Isced11 = ED0-2
		Percentage of 25- to 64-year-olds with ISCED level 5-8	Higher education deprivation	100 - x		edat_lfse_04	Sex = T; Age = Y25-64; Isced11 = ED5-8
Urban Audit Cities	Economy	Median disposable household income (Euros)			Poor coverage	urb_cecfi	EC3039V
		Average (mean) disposable household income (Euros)			Poor coverage	urb_cecfi	EC3040V
	Demography	Percentage of population aged < 5 years	Proportion under 5 years			urb_cpopstr	DE1040I
		Percentage of population aged >=75 years	Proportion 75 years and over			urb_cpopstr	DE1055I

Spatial scale	Theme	Indicator definition	Indicator short name	Inversion applied	Reason for exclusion	Eurostat table code or source URL	Additional filter applied or indicator codes extracted
	Labour market	Unemployment rate (% of economically active population)	Unemployment			urb_clma	EC1020I
	Education	Percentage of people aged 25-64 with ISCED level 0, 1 or 2 as the highest level of education			Less salient than alternative	urb_ceduc (and urb_cpop1 to transform to %)	TE2025V (and DE1025V + DE1058V + DE1061V + DE1064V to transform to %)
		Percentage of people aged 25-64 with ISCED level 5-8 as the highest level of education	Higher education deprivation	100 - x		urb_ceduc (and urb_cpop1 to transform to %)	TE2031I (and DE1025V + DE1058V + DE1061V + DE1064V to transform to %)
	Poverty and social exclusion	Share of persons at risk of poverty after social transfers -%			Poor coverage	urb_clivcon	EC3065V
		Share of persons at risk of poverty or social exclusion -%			Poor coverage	urb_clivcon	EC3067V
	Housing	Percentage of households in social housing			Poor coverage	urb_clivcon	SA1012V (and DE3001V to transform to %)
	Health	Death rate per year of people under 65 due to diseases of the circulatory or respiratory systems	Respiratory disease death rate			urb_cfermor (and urb_cpop1 to transform to %)	SA2013V (and DE1025V + DE1058V + DE1061V + DE1064V + DE1049V + DE1046V + DE1077V + DE1074V to transform to %)
	Landscape	Share of green urban areas and forests (2012) (% of land area)		100 - x	Less salient than alternative	http://ec.europa.eu/regional_policy/sources/docgener/work/data_wp_01_2018_green_urban_areas.xls	Tab = “cities_greater_cities”, column = GUA_f_share
		Population without green urban areas in their neighbourhood (% of total population)	Green space deprivation			http://ec.europa.eu/regional_policy/sources/docgener/work/data_wp_01_2018_green_urban_areas.xls	Tab = “cities_greater_cities”, column = popl_share_no_gua

Note: The rightmost column contains additional information on which subsets of the data tables specified in the column to the left were used in this study to define indicators, For NUTS 2 and 3 level tables, the subset is defined as the filter applied to relevant columns, and for Urban Audit cities, the relevant indicator codes selected.

Table A1.3 Coverage of social indicator variables in analysis for NUTS regions (top) and Urban Audit cities (bottom)

NUTS regions

Spatial scale	Social indicator	NO_2			$PM_{2.5}$			PM_{10}			O_3			Lden ≥55dB	Lnight ≥50dB	Total units in coverage	Total countries in coverage
		2007	2011	2013-2014	2007-2008	2010-2011	2013-2014	2005-2006	2009-2010	2013-2014	2005-2006	2009-2010	2013-2014	2011	2011		
NUTS 3	GDP per capita deprivation	95% (29)	96% (30)	96% (30)	95% (29)	96% (30)	96% (30)	95% (29)	95% (29)	96% (30)	95% (29)	95% (29)	96% (30)	92% (29)	92% (29)	1406	34
NUTS 2	Higher education deprivation	96% (31)	98% (32)	98% (32)	96% (31)	98% (32)	98% (32)	93% (29)	98% (32)	98% (32)	93% (29)	98% (32)	98% (32)	86% (30)	86% (30)	289	34
	Household income deprivation	91% (26)	92% (27)	92% (27)	91% (26)	92% (27)	92% (27)	91% (26)	91% (26)	92% (27)	91% (26)	91% (26)	92% (27)	81% (26)	81% (26)	289	34
	Long-term unemployment	88% (30)	94% (32)	95% (32)	90% (30)	94% (32)	95% (32)	83% (27)	94% (32)	95% (32)	83% (27)	94% (32)	95% (32)	82% (30)	82% (30)	289	34
	Proportion 75 years or over	98% (33)	98% (33)	98% (33)	98% (33)	98% (33)	98% (33)	96% (32)	98% (33)	98% (33)	96% (32)	98% (33)	98% (33)	87% (31)	87% (31)	289	34
	Proportion under 5 years	98% (33)	98% (33)	98% (33)	98% (33)	98% (33)	98% (33)	96% (32)	98% (33)	98% (33)	96% (32)	98% (33)	98% (33)	87% (31)	87% (31)	289	34

Urban Audit cities

Social indicator	NO_2	$PM_{2.5}$	PM_{10}	O_3	Lden ≥55dB	Lnight ≥50dB	Total units in coverage	Total countries in coverage
	2010-2012	2010-2012	2010-2012	2010-2012	2010-2012	2010-2012		
Higher education deprivation	88% (23)	88% (23)	88% (23)	88% (23)	32% (20)	32% (20)	905	31
Unemployment	81% (22)	81% (22)	81% (22)	81% (22)	29% (20)	29% (19)	905	31
Proportion 75 years and over	94% (27)	94% (27)	94% (27)	94% (27)	35% (24)	35% (23)	905	31
Proportion under 5 years	94% (27)	94% (27)	94% (27)	94% (27)	35% (24)	35% (23)	905	31
Respiratory disease death rate	90% (23)	90% (23)	90% (23)	90% (23)	34% (20)	33% (20)	905	31
Green space deprivation	87% (31)	87% (31)	87% (31)	87% (31)	33% (23)	32% (22)	905	31

Note: Coverage is reported as the percentage of NUTS 3, NUTS 2 or Urban Audit units having valid data for each year grouping used in the analysis, with the number of countries this comprises given in brackets underneath. The rightmost two columns contain the total number of units and countries in the coverage for which air and noise pollution data was available. Cells are colour coded to highlight variables and year-groupings with poor coverage (orange cells).

All the social indicators were downloaded from Eurostat, (Eurostat, 2018a), with the exception of the Urban Audit city “Landscape” variables. Landscape variables were obtained from a European commission working paper on access to green areas in Europe’s cities (EC 2018).

In order to draw the most appropriate comparisons between air pollution and deprivation-related indicators, for each pollutant the deprivation-related indicators were averaged over the same year-groupings as used for that particular pollutant. This ensured that the apparent association of air quality and deprivation variables is not biased by an arbitrary choice of a single reference year.

Urban audit city indicators were averaged over the years 2010 – 2012 in all cases in order to maximise the coverage achieved for social indicators at this scale, because the availability of data varies considerably across years.

The social indicators were not combined together in any way during the analyses described below, but rather were kept separate in order to maintain the interpretability of results.

Methods of analysis and presentation of results

Geographic variation and spatial patterns in exposure to air and noise pollution, and change over time

Initially, it was important to quantify the overall degree of geographic variation in exposure to air and noise pollution and changes over time. This provides important context, helping to put the magnitude of any differences with respect to deprivation into perspective.

At each time point, we calculated the absolute difference and the ratio of mean exposure for the 20% of NUTS3 regions with the highest exposure (Q5), and the 20% of regions with the lowest exposure (Q1), as used in the 2013 CRESH study. These are a useful measure of the magnitude of the difference between the two extremes of exposure, and are the main measures of pollution exposure inequality reported in this study. When interpreting changes over time, a shift in the pollution ratio (Q5/Q1) towards 1 or the absolute difference (Q5-Q1) towards 0 implies a reduction in relative and absolute pollution exposure inequality respectively.

Two other commonly used measures of inequality or spread of values - the coefficient of variation and Gini inequality coefficient - were also calculated for pollution exposure, and these can be found in the full results tables provided in Annex 2. These measures are provided for readers who are familiar with their interpretation, but they do not add substantially to the insights over and above the measures focused on in this report.

In order to visualise the distribution of pollution exposure and how it has changed over time, choropleth maps were created showing the population-weighted concentration of each pollutant in 2013-14, and the change between the first time-point and 2013-14, at NUTS 3 level. Additionally, rank-value charts were created showing population-weighted exposure ordered from lowest to highest in each year grouping, allowing the entire distribution of values to be compared at each time-point. Statistics on pollutant concentrations are only presented for NUTS 3 regions, because this spatial scale represents the best balance between geographic coverage and detail.

Change over time was not considered for noise pollution, as the two reference years of noise data available for Europe (2007 and 2011) cannot be easily compared, so only 2011 data is used in this study.

Measuring the spatial association between social deprivation and air/noise pollution exposure, and change in this association over time

At each spatial scale (NUTS2, NUTS3 and cities) and time-point, the association between exposure to each air pollutant/noise and each indicator of deprivation and vulnerability has been quantified using the same set of metrics and visualisations.

For each pair of deprivation and air/noise pollution variables at each time point, the main measures of association reported were the following:

- The Spearman's rank correlation coefficient. This is a measure of the tendency for high- or low-ranked values of one variable to be associated with high- or low-ranked values of another, so communicates how closely associated the variables are with each other. This measure is less influenced by outlier values than the usual (Pearson's) correlation coefficient, so is preferred in this study due to the very skewed distribution of variables such as GDP per capita and unemployment. Correlation can range between -1 and 1.
    - Positive numbers indicate that areas with higher deprivation/vulnerability tend to have higher pollution exposure, with 1 being the strongest association possible.
    - Negative numbers indicate that areas with higher deprivation/vulnerability tend to have lower pollution exposure, with -1 being the strongest association possible.
    - Values close to zero indicate that there is little association between deprivation/ vulnerability and pollution exposure.
- The difference and ratio of the mean pollution exposure of the most deprived or vulnerable 20% of regions, compared to the least deprived or vulnerable 20% of regions ("pollution ratio"). These measures communicate the magnitude of the difference in pollution exposure between regions at the two ends of the deprivation or vulnerability indicator in question. Generally, when considering inequalities, the ratio of least to most deprived is the important variable, that is, the extent to which they vary relative to each other. For example, the level of household income in the lowest quintile is compared to that in the highest quintile, with the ratio of one to the other providing a measure of inequality. In contrast, the health effects of air pollution are often associated with the absolute exposure and for pollutants where the dose response relationship is linear (as is suggested for $PM_{2.5}$), the health benefit is derived from the absolute reduction in exposure concentration regardless of the initial concentration level.

  To give an illustration, if the most exposed communities had an average concentration of 100 units and the least 10 units, the ratio of most to least exposed is 10:1. This is normally the measure of inequality, although the difference between absolute levels is 90 units. If, over time, the most exposed value reduces to 50 and the least to 5, the ratio remains 10:1 but the absolute difference is now 45 units. Depending on which measure is used, either the inequality remains the same or it has halved. If the health benefit relates to the change in absolute exposure concentration, it could be argued that those in the most exposed area benefited most from the reduction in air pollution.
    - An absolute difference of 0 or ratio of 1 means that there is no difference in pollution exposure between regions with different levels of deprivation/vulnerability.
    - Positive absolute differences and ratios > 1 indicate the most deprived 20% of regions have higher pollution levels than the least deprived 20%.
    - Negative absolute differences and ratios < 1 mean the opposite.

A summary table providing these two measures for each pollutant-deprivation pair, at each time-point, is provided in the main report. When interpreting changes over time, a shift in the Spearman's rank correlation coefficient towards 0 or a shift in the pollution ratio towards 1 would indicate a reduction in systematic pollution exposure inequality between regions of differing deprivation and vulnerability.

The Pearson's correlation coefficient was also calculated, but not reported in the main results. It can be found within the tabulated results provided in Annex 2.

For selected cases where results indicate strong associations between exposure to pollution and deprivation or vulnerability, or large changes in associations over time, the results are presented visually using:

- Box-and-whisker plots of pollution levels for regions in each quintile of the deprivation or vulnerability indicator;
- Maps to show the location of regions ranked in the worst 20% by deprivation/vulnerability and by pollution exposure

Identifying localised patterns of association between deprivation and air/noise pollution by grouping countries

As well as asking how the relationship between deprivation and air pollution has changed over time, there is also interest in how the relationship may vary when focusing analysis on different subsets or clusters of countries or regions. Ideally, countries would be grouped according to a relevant theoretical basis, likely to highlight differences between regions. Many of the underlying drivers of differences in social indicators and pollution exposure (such as road density) follow an urban-rural gradient, so this would appear to be a suitable categorisation. However, a meaningful urban-rural typology is only available for NUTS 3 level of granularity or below (and even at this level many regions would be internally heterogeneous), which would not allow the analysis to include the wide range of social indicators available at NUTS 2 level.

Therefore, in the absence of a theoretical categorisation, the four-group geographic classification of European countries from the United Nations Statistics Division (UNSD) was chosen; it has been used in other similar studies (UNSD, 2018). The four groups are defined as follows (Map A1.1):

Map A1.1 Categorisation of European countries included in this study according to the UNSD definition

1. **Eastern Europe**

   Bulgaria, Czech Republic, Hungary, Poland, Romania, Slovakia

2. **Northern Europe**

   Denmark, Estonia, Finland, Iceland, Ireland, Latvia, Lithuania, Norway, Sweden, United Kingdom

3. **Southern Europe**

   Croatia, Cyprus, the Former Yugoslav Republic of Macedonia, Greece, Italy, Malta, Portugal, Serbia, Slovenia and Spain

4. **Western Europe**

   Austria, Belgium, France, Germany, Luxembourg, Liechtenstein, Netherlands, Switzerland

Note that countries for which air quality and noise exposure data was not available are not included in the categorisation or map A1.1 (comprising Turkey, Bosnia and Herzegovina, Albania, Montenegro and Kosovo[4]).

All of the summary statistics described above were additionally calculated for each of these four country groupings.

Where there were large differences in results between country groups, or where the results for Europe as a whole differed substantially from results within the country groups, the summary statistics are displayed visually using line graphs.

All other results for country groups can be found in the tabulated results provided in Annex 2.

Calculation of summary statistics was performed in R version 3.4.1 (R Core Team, 2017), and maps created using ArcGIS version 10.4.1 (ESRI, 2015).

[4] under UNSC Resolution 1244/99

Annex 2 – Detailed Statistical Summaries

Detailed statistical summaries are provided in the accompanying spreadsheet **Annex_2_statistical_summaries.xlsx**.

The spreadsheet provides:

- All of the measures of the geographical variation in air pollution and noise exposure reported in this document, as well as additional measures (coefficient of variation and Gini inequality index) commonly used in other studies.
- All of the measures of the association between air pollution / noise exposure and social indicators reported in this document, as well as additional measures (Pearson's correlation and Gini inequality index).
- Details of the number of geographical units and having valid data for each summary statistic, and the number of countries this comprises.

Annex 3 – Summary answers to research questions

1. How does exposure to air and noise pollution vary across NUTS 3 regions of Europe, and how has the degree of variation in air pollution exposure changed over time?

Exposure to air pollution and noise at the NUTS 3 scale is not uniform across Europe and there is a clear difference between the areas with the greatest and least exposure, with ratios of the greatest to the least of between 1.9 (for Lden ≥55dB in 2011) and 3.7 (for ozone exposure, in 2013-2014).

In general, exposure has decreased over the time period (2005-2014, though the initial year depends on the pollutants) and the ratios between the areas of greatest and least exposure remain broadly consistent, meaning that improvements or reductions in air quality have tended to act equally across all areas. Pollutant specific findings are summarised in sections 2.1 and 2.2 above and provided in more detail in the sections below.

2. What is the relationship between per-capita GDP and exposure to air and noise pollution across NUTS 3 regions of Europe, and how has the relationship with air pollution changed over time?

There are positive correlations for all pollutants other than NO_2 and noise, where there is a negative correlation with a Spearman's correlation value of -0.49 for NO_2 and -0.09 and -0.04 for L_{den} ≥55dB and L_{night} ≥55dB, respectively. The strongest positive correlation is for PM_{10} with a value of 0.33 and the weakest is for O_3 with a value of 0.16. The correlations for O_3 and $PM_{2.5}$ exposure have weakened slightly over time (0.24 to 0.16 and 0.24 to 0.22 respectively) whereas the relationships for PM_{10} and NO_2 exposure have strengthened (0.28 to 0.33 and -0.45 to -0.49 respectively).

3. What is the relationship between the proportion of the population that is vulnerable to air pollution (<5 years and >75 years) and exposure to air and noise pollution across NUTS 2 regions[5] of Europe, and how has the relationship with air pollution changed over time?

The pattern is more complex, with correlations either less strong or, in the case of PM, the inverse of those for the other indicators analysed in this report.

For NO_2, the correlation has become more strongly negative over time for older populations and weaker for younger populations (-0.01 to -0.14 and 0.15 to 0.06 respectively). This means that the two indicators are moving in different directions, which makes interpretation difficult. However, the association is not strong.

For $PM_{2.5}$ and PM_{10} exposure, the relationships with the share of elderly and infants in the population are negative across all time points. This means that both older and younger populations are less likely to be exposed to higher concentrations of PM. However, all of these negative associations have weakened over time.

For O_3, the correlation for older populations is positive and strengthens over time (0.10-0.31), which means that populations with a higher proportion of older people are more likely to be exposed to higher levels of O_3. This is consistent with the pattern for populations with a higher proportion of young children, where the correlation is negative (-0.46) and stable over time.

For noise, both noise indicators (L_{den}≥55dB and L_{night}≥50dB) show a weakly positive correlation with both age-related indicators, -0.10 and -0.09 for older populations and -0.04 and -0.04 for younger ones.

[5] Consistent data is unavailable for NUTS 3 areas so NUTS 2 was analysed.

4. What is the relationship between measures of social deprivation and exposure to air and noise pollution across NUTS 2 regions of Europe, and for air pollution how has this relationship changed over time?

In general terms, the correlations with air pollution exposure are more strongly positive for the more specific measures of social deprivation at NUTS 2 level than they are for GDP per capita at NUTS 3 level (see **Table 1.1** and **Table 2.1**). Again, this holds for all pollutant variables other than NO_2. For NO_2, the correlations are negative and strongest for household income deprivation. The correlations for the two noise indicators are weakly positive for Higher education deprivation and Long-term unemployment (less than 0.1), with the highest Spearman correlation value shown for Household income deprivation (0.21 and 0.22 respectively). Most of the correlations remain stable over time, with some notable exceptions:

- Higher education deprivation and long-term unemployment against NO_2 exposure, where the correlations become more strongly negative over time (-0.17 to -0.21 and -0.13 to -0.22 respectively);
- Long-term unemployment against $PM_{2.5}$, where the correlation becomes less strongly positive over time (0.41-0.28); and
- Long-term unemployment against PM_{10} and O_3, where the correlations become more strongly positive over time (0.33-0.49 and 0.32-0.50 respectively).

5. What is the relationship between measures of social deprivation and exposure to air and noise pollution across different cities in Europe?

In general, the correlations show a similar pattern to those shown for NUTS 2 areas. These are the main features:

- For NO_2, there is a positive correlation for populations with a higher proportion of young children (0.20) but negative correlations for all other indicators, with the strongest associations being with unemployment (-0.29) and respiratory disease death rate among people under 65 (-0.27). This is consistent with NO_2 being a pollutant most prevalent in economically active urban areas.

- For $PM_{2.5}$, the pattern of correlations is the same as at NUTS2 level, with the exception of unemployment, which has a weakly negative correlation (-0.1). The correlation with Respiratory death rate is the strongest positive value (0.28). PM_{10} shows a weaker association with Respiratory death rate, and the strongest positive correlation is for Unemployment (0.27)

- O_3 shows a negative correlation for respiratory disease death rate among people under 65 (-0.19) and a much less strong positive correlation for higher education deprivation than at NUTS 2 level (0.12 compared to 0.51). Otherwise, the relationships are similar in strength to those for NUTS 2 areas.

- For the two noise indicators, both showed weak positive correlations (less than 0.1) other than unemployment (0.26/0.3) and green space deprivation (0.11/0.13).

6. Concerning measures of social deprivation for which data are available at multiple levels of spatial aggregation, how do the observed relationships with air pollution differ according to the level of spatial aggregation used in analysis?

There was insufficient data to undertake this analysis for more than a few indicators. Where significant differences where identified for the same indicator at different spatial scales, this has been noted in the analysis above.

7. How do the relationships analysed above vary between different parts of Europe, or different clusters of cities and regions?

Analysis was undertaken using Northern, Western, Southern and Eastern Europe as a proxy for regional differences. For NO_2, the all Europe pattern was mid-way between the patterns for the regions, suggesting that the exposure-deprivation relationship is the same within regions as it is between regions. This is not the case for $PM_{2.5}$ or O_3, where the relationship is stronger between regions than is it within regions. This may be because for the latter two pollutants, higher exposure is more closely associated with one or more regions (Eastern Europe for $PM_{2.5}$ and Southern Europe for ozone), whereas NO_2 is a more urban centred pollutant and so high concentrations occur in all regions.

Caution is needed in interpreting this analysis given the arbitrary nature of the regional split. It is certainly the case that some pollutants, e.g. $PM_{2.5}$ and O_3 have a more regional distribution whereas others are more strongly split along urban/rural lines, and the same is true for some indicators of deprivation and vulnerability. Further analysis of this issue is required.

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