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Associations between air pollution and socioeconomic characteristics, ethnicity and age profile of neighbourhoods in England and the Netherlands

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A B S T R A C T

Air pollution levels are generally believed to be higher in deprived areas but associations are complex especially between sensitive population subgroups.

We explore air pollution inequalities at national, regional and city level in England and the Netherlands comparing particulate matter (PM_{10}) and nitrogen dioxide (NO_2) concentrations and publicly available population characteristics (deprivation, ethnicity, proportion of children and elderly).

We saw higher concentrations in the most deprived 20% of neighbourhoods in England (1.5 $\mu g/m^3$ higher PM_{10} and 4.4 $\mu g/m^3$ NO_2). Concentrations in both countries were higher in neighbourhoods with >20% non-White (England: 3.0 $\mu g/m^3$ higher PM_{10} and 10.1 $\mu g/m^3$ NO_2; the Netherlands: 1.1 $\mu g/m^3$ higher PM_{10} and 4.5 $\mu g/m^3$ NO_2) after adjustment for urbanisation and other variables. Associations for some areas differed from the national results.

Air pollution inequalities were mainly an urban problem suggesting measures to reduce environmental air pollution inequality should include a focus on city transport.

1. Introduction

Ambient particulates and nitrogen dioxide have been linked to multiple health effects ranging from respiratory irritation to cardiovascular diseases and premature death (COMEAP, 2009). The European Environment Agency (EEA) estimated that in 2005 alone five million years of life were lost due to fine particulate pollution across the EU (EEA, 2010).

Environmental inequality – that more vulnerable communities are more likely to be exposed to higher air pollution levels – is well attested by studies from many parts of the world, in particular the USA, Canada and UK (Jerrett et al., 2001; Marshall, 2008; Richardson et al., 2013). Environmental inequality implies disadvantages in many societies because both increased environmental exposure and socioeconomic deprivation may lead to impaired health (O'Neill et al., 2003). Social gradients in health are well-established (Lynch et al., 2006; Marmot, 2005) and socially and economically disadvantaged people may experience increased susceptibility to the negative air pollution-related health effects because of higher baseline disease rates (O'Neill et al., 2003). Forastiere et al. (2007) showed this effect modification on mortality risks for the city of Rome where individuals of high social class were not as affected by the negative health effects of particulate matter pollution as individuals of lower social classes.

The relationships between the geographical distribution of vulnerable communities and air pollution levels are, however, more complex, and less universal than often implied. Associations

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between environmental risk factors and socioeconomic characteristics have been shown to vary between environmental pollutants (Briggs et al., 2008; Kruize et al., 2007; Vrijheid et al., 2012), study areas (Stroh et al., 2005), measures of socioeconomic status (Jerrett et al., 2004) and scales of measurement (Goodman et al., 2011; Hajat et al., 2013) but population characteristics which explain these relationships at a local level are still not fully understood. It is these local associations that are of particular interest to public health researchers and policy makers in order to understand the public health implications, to specifically target policy needs and to apply mitigation measures. Comparisons have to be made between different societies and countries to identify the societal and political impact on environmental inequality. Due to differences in study design and data this is difficult based on published study results.

This paper investigates neighbourhood (small area) associations in England and the Netherlands between concentrations of long-term ambient particulate matter with aerodynamic diameter ≤ 10 μm (PM_{10}) and nitrogen dioxide (NO_2) and population characteristics to identify subpopulations at higher risk of environmental inequality. Our hypothesis is that the deprived and ethnic minorities are subpopulations more likely to experience higher air pollution levels. Little is known about age-related air pollution inequalities and we include children and the elderly in our analysis to explore associations between air pollution and these vulnerable age groups. To explore previously reported differences in direction and patterns of associations mostly observed at the city level (Forastiere et al., 2007; Havard et al., 2009), we conducted our analysis at the national level, the regional level and the city level. England and the Netherlands are two European countries that are of comparable wealth but have historically a different political system; England has a market oriented, libertarian approach, the Netherlands is known as an egalitarian oriented country. This provided the ideal setting to explore the underlying geographical relationships in environmental inequality.

2. Methods

2.1. Study areas

The unit of analysis for this study was the neighbourhood level. In England, Lower Super Output Areas (SOA) ($N = 32{,}482$) represent socially homogeneous neighbourhoods that are comparable throughout the country because of similar population sizes. In the Netherlands, neighbourhoods (buurt) are administrative areas for which population characteristics are routinely reported ($N = 11{,}132$). Dutch buurten are comparable in population size to the English SOAs (mean of 1500 residents in both countries).

We defined regions in England and the Netherlands using the first level of the EU's Nomenclature for Territorial Units for Statistics (NUTS 1) boundaries (England $N = 8$, Netherlands $N = 4$). We included all cities in both countries that have more than 400,000 residents within their official city boundaries based on the English Census 2001 urban areas statistics (Office for National Statistics (ONS) 2001) and 2004 figures from Statistics Netherlands (Centraal Bureau voor de Statistiek (CBS) 2006) (England $N = 6$ (note that London is included in the city analysis although it is officially classified as a NUTS 1 region), Netherlands $N = 3$). The study areas are shown in Fig. 1. All spatial data were linked using the geographic information system ArcGIS version 10 (ESRI, Redlands, CA).

2.2. Air pollution maps

We used high resolution air pollution maps (100 m × 100 m) of annual mean concentrations for PM_{10} and NO_2 in 2001 modelled in a consistent manner for both countries. These are the most recent high resolution air pollution data available for both countries and correspond to the time period of the population characteristics. Details of air pollution model development and validation are

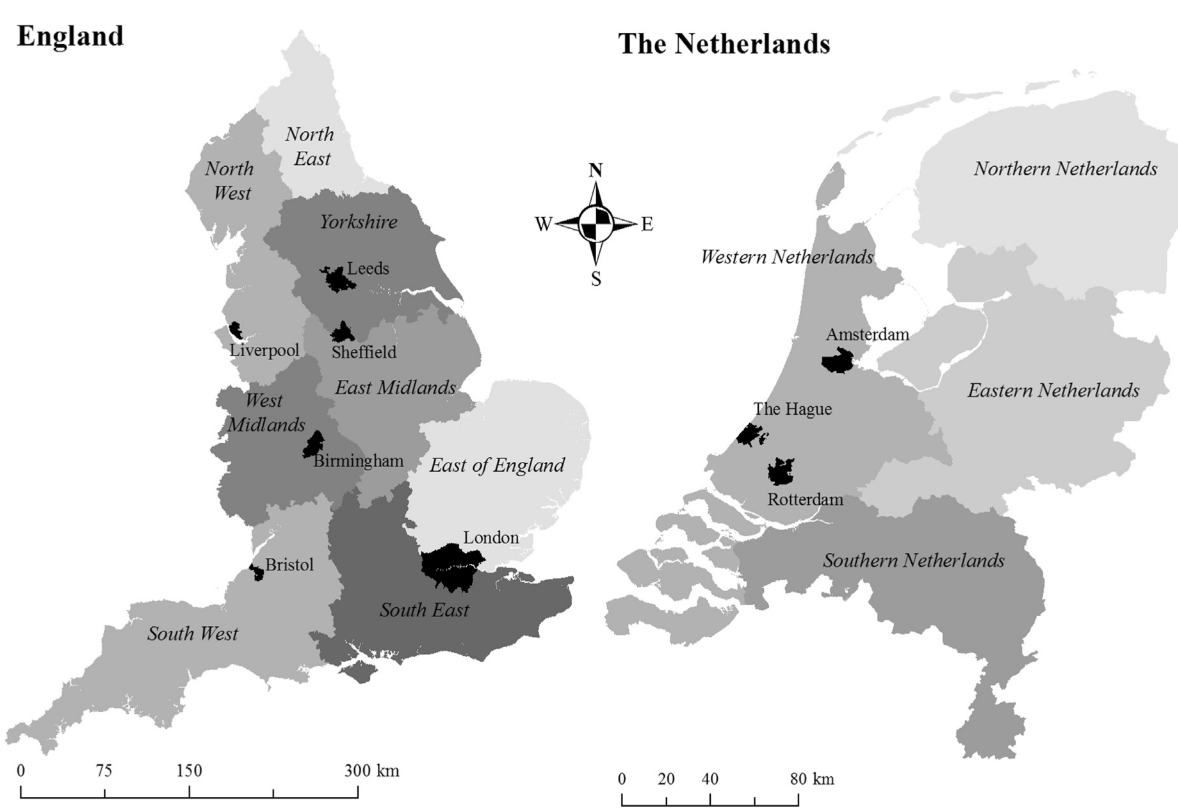

Fig. 1. Study areas in England and the Netherlands: national level, regional level (shown in grey scales) and city level (shown in black).

Table 1
Population characteristics and data sources.

	England			The Netherlands		
	Measure	Description	Source	Measure	Description	Source[a]
Socioeconomic status	Income support recipients	Index of Multiple Deprivation 2004 Income domain: % of adults and children in households receiving income support, job seekers allowance, working families tax credits or disabled person's tax credits, or supported asylum seekers	Office of Deputy Prime Minister, 2004 (Noble et al., 2004)	Benefit recipients	% of income recipients that in September 2003 received a monthly income from benefit payments	CBS, 2006
Ethnicity	Non-White	Ethnic groups other than White British & White other	ONS, Census 2001	Non-Western immigrants	First and second generation immigrants from countries in Africa, Latin America, Asia (excluding Indonesia and Japan) or Turkey	CBS, 2006
Age	Children 65 plus	0–14 years 65 years and over	ONS, Census 2001	Children 65 plus	0–14 years 65 years and over	CBS, 2006

[a] 6-character postal code area level data aggregated to buurt level.

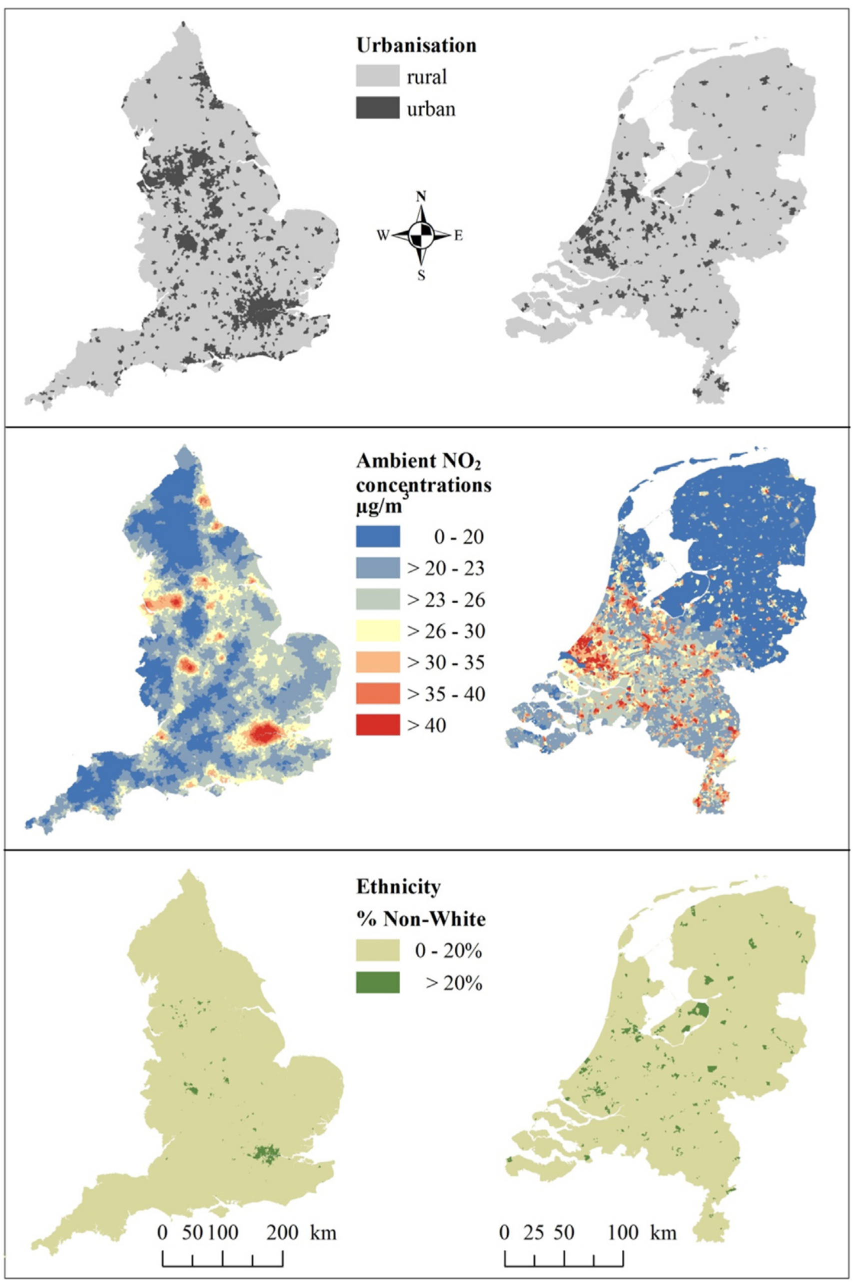

Fig. 2. Maps of England (left) and the Netherlands (right) showing urbanisation (top), annual average NO_2 concentrations (middle) and ethnicity (bottom) at the neighbourhood level.

presented elsewhere (Vienneau et al., 2010). Briefly, maps were modelled using land use regression (LUR) which interpolates regional concentrations measured at routine monitoring sites based on regression equations describing the relationship between a range of predictor variables and the pollutant concentrations. We aggregated the concentrations to the neighbourhood level by calculating population weighted average concentrations using the 2001 Census headcount population at postcodes from ONS for England and the 2004 6-character postal code population from CBS for the Netherlands.

2.3. Population characteristics

We analysed routinely available population characteristics at the neighbourhood level that are comparable between the two countries and indicative for neighbourhood deprivation, ethnicity and age.

In England, we used the income domain from the Index of Multiple Deprivation 2004 as the area-level socioeconomic indicator (Noble et al., 2004). The income domain is expressed as the proportion of people receiving income support (see Table 1) and comparable to the percentage of Dutch households receiving benefits, used as the Dutch socioeconomic indicator. We categorised the percentage of income support recipients into quintiles.

We categorised neighbourhoods in England and the Netherlands according to their ethnic composition as White or non-White (non-Western immigrants in the Netherlands, see Table 1). We used a 20% cut-off point to differentiate between the two categories which reflects approximately twice the national average in the two countries (9% in England and 10% in the Netherlands).

In both countries we defined vulnerable age groups as children (0–14 years) and 65 plus (≥65 years). We categorised the percentage of children and 65 plus into quintiles.

2.4. Urbanisation

In England we used the Rural and Urban Area Classification for SOAs produced by the ONS and the Department for Environment, Food and Rural Affairs (Defra) to characterise the degree of urbanisation for each SOA. This classification differentiates between urban areas with more than 10,000 people and rural areas which are defined as small towns and fringes, villages, hamlets and isolated dwellings. In the Netherlands, we defined urban areas as those neighbourhoods that are categorised by the CBS as moderately, strongly and very strongly urbanised (address density: >1000 N/km^2) as shown in Fig. 2.

2.5. Statistical methods

We used descriptive statistics, Pearson's correlations and box plots to describe air pollution concentrations and the social and demographic variables. Concentrations were approximately normally distributed so not transformed (Supplement material, Fig. S1). We used univariate and multiple linear regression to explore associations between air pollution concentrations (as the dependent variable) and population characteristics. Multivariate regression analysis was conducted at national, regional and city level and models were mutually adjusted for urbanisation (categorised into urban/rural), percentage of income support recipients (quintiles), ethnicity (categorised into White/non-White), percentage children and percentage 65 plus population (quintiles). All statistical analysis was performed with open-source software R version 3.0.1.

3. Results

Descriptive statistics for national and city level are presented in Table 2 and results for regional level in Supplement material, Table S1. All neighbourhoods in England were within the legal limit for PM_{10} (40 $\mu g/m^3$) set by the EU Ambient Air Quality Directive (2008/50/EC); in the Netherlands only two neighbourhoods in the Western region exceeded the limit. In contrast, the NO_2 legal limit (40 $\mu g/m^3$) was exceeded in 11% of neighbourhoods in England and 9% of neighbourhoods in the Netherlands, which accounted for an affected population of 5.4 million and 2.7 million respectively. In both countries we found a statistically significant difference ($p < 0.05$) in mean PM_{10} and NO_2 concentrations between urban and rural neighbourhoods. Neighbourhoods in both England and the Netherlands had similar percentages of income support recipients, non-White, children and 65 plus population (Table 2).

Table 3 shows the correlations between air pollutants and population characteristics at the national level. The two air pollutants PM_{10} and NO_2 showed very high Pearson's correlations ($r > 0.8$) for all analysed areas in England (except the city of Liverpool: $r = 0.54$) whilst in the Netherlands the two pollutants were moderately correlated with the highest correlations observed at the national level ($r = 0.57$) and in The Hague ($r = 0.63$). Most study areas showed only weak correlations ($r < |0.4|$) between air pollution concentrations and social and demographic characteristics of neighbourhoods. The exceptions were some regions and cities in England, with higher correlations between the percentage of non-White and both PM_{10} concentrations (West Midlands $r = 0.60$, Birmingham $r = 0.63$) and NO_2 concentrations (West Midlands $r = 0.64$, Birmingham $r = 0.69$, Bristol $r = 0.61$, Sheffield $r = 0.62$).

Table 4 lists the mean neighbourhood air pollution concentrations by social and demographic characteristics at the national and city level. Results for the regional level are presented in Supplement material, Table S2.

We observed the highest mean PM_{10} and NO_2 concentrations in the most deprived neighbourhoods in both countries. At the national level in England, neighbourhoods in the most compared with least deprived quintile experienced on average 2.6 $\mu g/m^3$ higher levels of PM_{10} and 7.9 $\mu g/m^3$ of NO_2, in the Netherlands 0.3 $\mu g/m^3$ higher for PM_{10} and 6.1 $\mu g/m^3$ for NO_2. These differences were statistically significant ($p < 0.05$) for both countries and for all study regions and cities except Bristol in England and Rotterdam in the Netherlands.

Ethnic composition of neighbourhoods was also associated with air pollution concentrations. We found that at the national level neighbourhoods with >20% non-White had statistically significantly higher mean PM_{10} and NO_2 concentrations than neighbourhoods with ≤20% non-White; in England the difference for PM_{10} was 4.2 $\mu g/m^3$, in the Netherlands 1.4 $\mu g/m^3$ and respectively for NO_2 13.5 $\mu g/m^3$ and 10.4 $\mu g/m^3$ (Table 4). However, while NO_2 mean levels were always higher in neighbourhoods with >20% non-White in all cities and regions, this was not true for PM_{10}, where concentrations were higher in some neighbourhoods with ≤20% non-White (namely the East of England, Yorkshire, Leeds and Amsterdam).

Lower PM_{10} and NO_2 air pollution levels were seen in neighbourhoods with higher percentage of children in the Netherlands but direction of associations varied in England (Table 4). In the Netherlands, mean PM_{10} and NO_2 concentrations were statistically significantly lower in neighbourhoods with the highest compared to the lowest quintile of percentage of children, except in The Hague and the Southern region where this trend was reversed. Lower PM_{10} and NO_2 concentrations were seen in neighbourhoods

Table 2
Descriptive statistics of neighbourhood air pollution, social and demographic characteristics at the national and city level.

	No. of neighbourhoods[a]	PM_{10} (μg/m^3)			NO_2 (μg/m^3)			Population	% Income support recipients	% Non-White	% Children	% 65 plus
		5th pct	Median	95th pct	5th pct	Median	95th pct					
England	32,482	17.0	20.2	26.1	21.0	28.0	45.3	49,138,831	13.8	9.1	18.9	15.9
Birmingham	641	19.2	22.0	23.6	28.6	35.9	44.0	977,087	24.9	29.6	22.0	14.5
Bristol	252	20.0	21.7	23.8	27.7	33.1	39.4	380,615	16.1	8.1	17.9	14.9
Leeds	439	18.5	21.0	22.6	25.9	31.4	38.1	660,964	15.3	8.6	18.8	15.1
Liverpool	291	22.2	23.2	25.5	33.7	36.8	40.4	439,473	30.6	5.7	18.7	15.3
London	4765	22.0	25.1	29.0	33.1	42.5	60.6	7,172,091	17.7	28.8	19.0	12.4
Sheffield	325	17.7	20.0	22.7	24.7	30.0	35.5	492,231	18.7	9.1	18.0	16.4
Netherlands	11,132	23.2	27.2	31.0	12.7	27.5	43.0	16,097,060	13.4	10.3	18.5	13.8
Amsterdam	83	26.5	29.1	31.0	28.6	39.2	45.0	653,450	20.2	30.5	15.7	11.8
Rotterdam	67	28.8	30.4	31.9	29.7	42.4	56.1	540,550	20.8	36.5	17.2	14.2
The Hague	108	28.0	30.0	31.5	33.0	46.9	53.8	459,730	18.5	31.4	17.3	14.0

pct = Percentile.
[a] SOAs in England, buurt in the Netherlands.

Table 3
Correlations between neighbourhood air pollution, social and demographic characteristics at the national level for England (top) and the Netherlands (bottom).

		PM_{10}	NO_2	% ISR[a]	% Non-White	% Children	% 65 plus
England	PM_{10}	-					
	NO_2	0.946*					
	% ISR[a]	0.335*	0.356*				
	% Non-White	0.535*	0.597*	0.396*			
	% Children	−0.003	0.011	0.442*	0.242*		
	% 65 plus	−0.233*	−0.273*	−0.143*	−0.338*	−0.507*	-
Netherlands	PM_{10}	-					
	NO_2	0.574*					
	% ISR[a]	0.049*	0.200*				
	% Non-White	0.209*	0.446*	0.395*			
	% Children	−0.088*	−0.149*	−0.014*	0.027*		
	% 65 plus	0.044*	0.149*	0.316*	−0.020	−0.182*	-

*Indicates statistical significance ($p < 0.05$).
[a] ISR = Income support recipients.

with the highest quintile of percentage of 65 plus at the national level in England. In the Netherlands, we could see an almost reverse trend with lower mean concentrations in neighbourhoods with lower percentage of 65 plus, except in Amsterdam and The Hague where neighbourhoods with the highest quintile of percentage 65 plus had higher NO_2 concentrations.

As evident from Fig. 3, findings were driven by urban neighbourhoods (shown in red), whilst the trend in rural neighbourhoods (in green) between air pollution concentrations and social and demographic characteristics was generally flat.

As none of the social and demographic characteristics were highly correlated with each other ($r < |0.5|$) (see Table 3) all were included in the multivariate analysis (mutually adjustment for urbanisation, % income support recipients, ethnicity, % children and % 65 plus). Differences in trends between national and city level for England and the Netherlands are shown in Fig. 4 for PM_{10} and NO_2 (for regional results see Supplement material, Fig. S2; Coefficients and 95% confidence intervals see Supplement material, Table S3 for PM_{10} and Table S4 for NO_2).

Table 4
Mean air pollution concentrations (μg/m^3) by neighbourhood characteristics at the national and city level.

		% ISR[a]		Ethnicity		% Children		% 65 plus	
		Most deprived quintile	Most affluent quintile	≤20% Non-White	>20% Non-White	Lowest quintile	Highest quintile	Lowest quintile	Highest quintile
PM_{10}	England	22.3*	19.7*	20.1*	24.3*	21.1*	21.0*	21.9*	19.9*
	Birmingham	22.9*	21.2*	21.1*	23.0*	21.8*	22.7*	22.6*	21.2*
	Bristol	21.9	21.6	21.7*	23.5*	22.2*	21.5*	22.4*	21.6*
	Leeds	21.7*	19.9*	21.6*	20.6*	21.0	21.0	21.3*	20.5*
	Liverpool	23.6*	23.0*	23.5	23.7	23.5	23.4	23.7*	23.3*
	London	26.4*	24.3*	24.3*	25.9*	26.2*	25.6*	26.4*	23.8*
	Sheffield	21.0*	18.4*	19.7*	22.4*	19.8*	21.0*	20.8*	19.3*
	Netherlands	27.4*	27.1*	27.1*	28.5*	27.5*	26.9*	27.1*	27.4*
	Amsterdam	28.2	29.1	29.2	28.7	29.9*	27.9*	29.5*	28.1*
	Rotterdam	30.3	30.4	30.0	30.1	30.8	30.1	30.6*	29.5*
	The Hague	30.4*	29.5*	29.4*	30.4*	29.7	30.0	30.3*	29.3*
NO_2	England	35.1*	27.2*	28.2*	**41.7***	31.0*	31.5*	33.9*	27.2*
	Birmingham	**40.2***	33.8*	33.5*	39.6*	35.6*	38.4*	39.0*	33.6*
	Bristol	34.0	33.2	33.1*	39.4*	35.3*	32.1*	36.3*	32.3*
	Leeds	34.5*	29.2*	31.1*	35.8*	32.2	32.6	33.2*	30.8*
	Liverpool	38.1*	35.6*	36.9*	38.6*	37.2*	36.8*	37.1*	36.8*
	London	**48.3***	**40.9***	**40.7***	**46.3***	**48.6***	**44.6***	**47.9***	39.1*
	Sheffield	32.2*	27.5*	29.4*	34.5*	30.9*	31.3*	31.9*	28.6*
	Netherlands	31.5*	25.4*	27.0*	37.4*	30.0*	24.6*	27.5*	31.1*
	Amsterdam	**40.1***	36.3*	38.4	38.9	39.0	37.6	38.0	37.7
	Rotterdam	**40.8**	38.3	**41.2**	**42.3**	**40.7**	**40.7**	**41.0**	**42.0**
	The Hague	**47.9***	**43.0***	**43.9***	**48.9***	**45.6**	**47.0**	**47.3***	**43.2***

*Significant difference (p-value < 0.05) between the two categories shown for each variable.
Bold indicates concentrations above the current European Directive limit of 40 μg/m^3.
[a] ISR = Income support recipients.

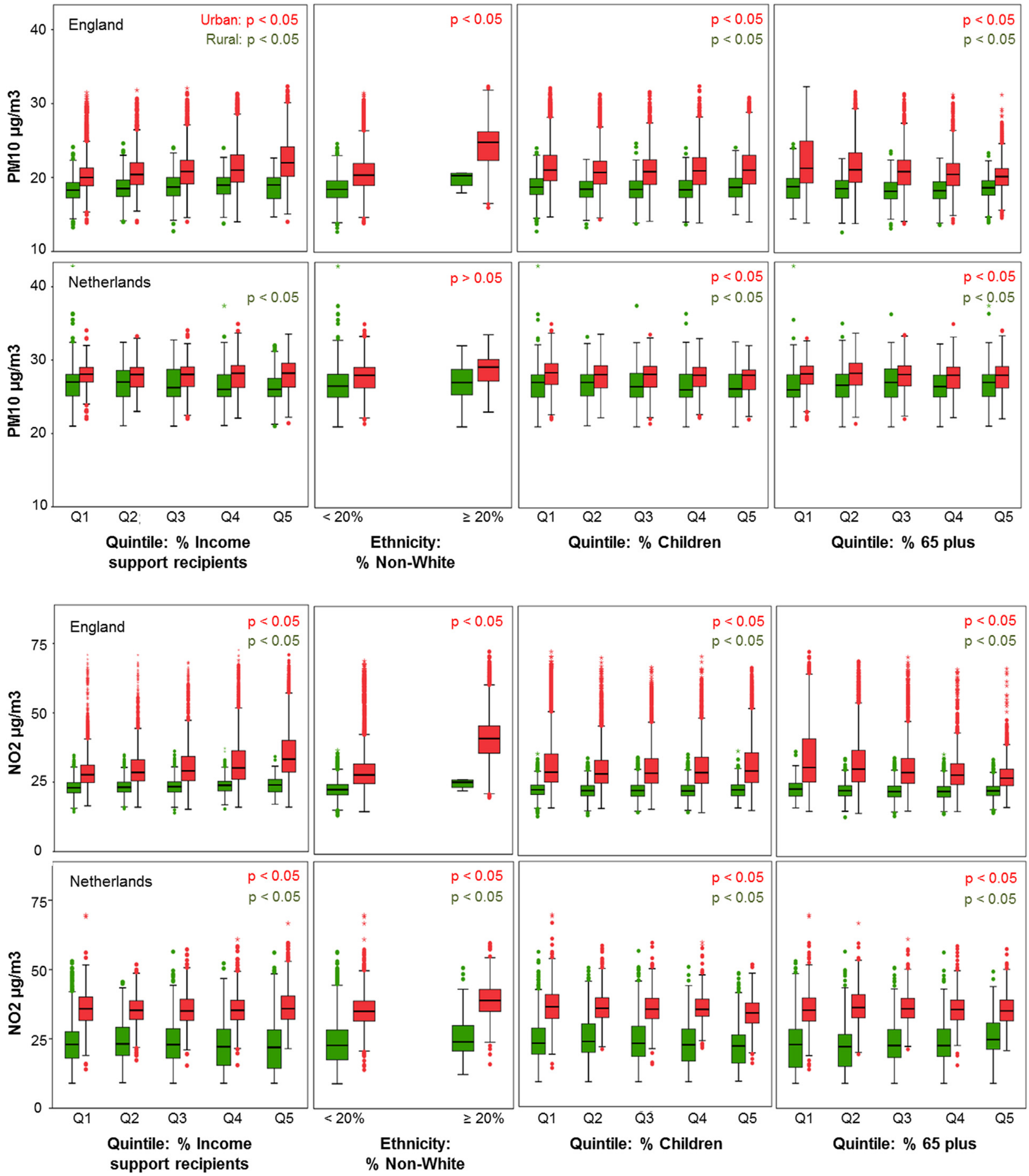

Fig. 3. Box plot showing PM_{10} and NO_2 concentrations by subpopulations for urban (red) and rural (green) neighbourhoods in England and the Netherlands. *P*-values indicate statistical significant differences across subpopulation categories, separately for urban and rural areas. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

In England, air pollution levels showed associations with each of urbanisation, deprivation, and ethnic composition of neighbourhoods in univariate analyses (results not shown), these were attenuated although still statistically significant after adjustment for the other characteristics (Supplement material, Table S3 and S4). At national level, the multivariate analyses showed the strongest positive associations between air pollution levels and neighbourhoods with >20% non-White and urban neighbourhoods (Fig. 4). The most deprived 20% neighbourhoods in England had statistically significant higher PM_{10} and NO_2 concentrations after adjustment compared to the least deprived 20%. This association was larger in London where NO_2 concentrations in the most deprived neighbourhoods were 7.8 µg/m^3 (95% CI: 7.1–8.6) higher after adjustment than in the most affluent neighbourhoods.

In the Netherlands, as in England, we saw higher levels of air pollution in urban and ethnically mixed neighbourhoods, but unlike in England, associations with deprivation were largely removed

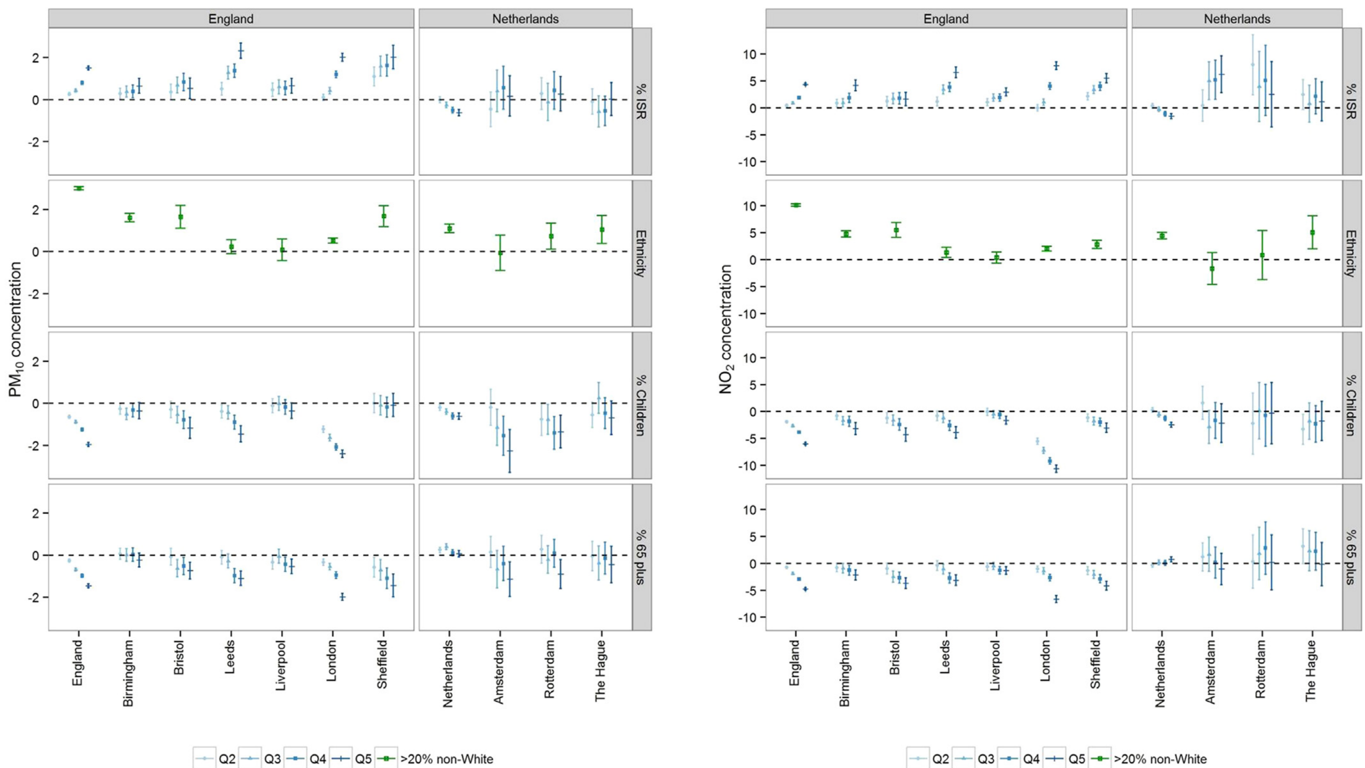

Fig. 4. Multivariate regression analysis assessing the relationship of PM_{10} (left) and NO_2 (right) concentrations and subpopulations at the national and city level in England and the Netherlands. Note the differences in scale between PM_{10} and NO_2. Models are mutually adjusted for urbanisation, % income support recipients (quintiles), ethnicity, % children (quintiles) and % 65 plus (quintiles). Shown are differences in air pollution concentrations in relation to the reference category: quintile 1 (for % income support recipients, % children and % 65 plus) and $\leq$20% non-White. Quintile 1 represents the most affluent neighbourhoods and neighbourhoods with the lowest % of children and 65 plus.

after adjustments for urban, ethnic composition and age. We observed particularly large associations between air pollution levels and the urbanisation component which prevailed after adjustment for deprivation, ethnicity and age, with NO_2 concentrations 12.0 $\mu g/m^3$ (95% CI: 11.7–12.3) higher in urban compared to rural neighbourhoods. Similar to England we also detected higher concentrations for neighbourhoods with >20% non-White at the national level; the highest were found in The Hague where NO_2 concentrations were 5.1 $\mu g/m^3$ (95% CI: 2.0–8.1) higher in neighbourhoods with >20% non-White, after adjustment for deprivation and other factors. At the national level the most deprived neighbourhoods showed higher PM_{10} and NO_2 concentrations than the most affluent neighbourhoods. Unlike in England, this association disappeared after adjustment. In fact, in the Netherlands overall we observed a slight negative trend in both PM_{10} and NO_2 concentrations with deprivation after adjustment; only associations in the Northern and Eastern region prevailed after adjustment.

In England we saw statistically significant negative associations between air pollution levels and the percentage of children and 65 plus after adjustment for urbanisation, deprivation and ethnicity. The magnitude of these associations differed between regions and cities. London showed the largest differences, with neighbourhoods with the highest percentage of children having 10.6 $\mu g/m^3$ (95% CI: 9.9–11.3) lower NO_2 concentrations compared to those with the lowest percentage of children. London neighbourhoods with the highest percentage of 65 plus had 6.6 $\mu g/m^3$ (95% CI: 6.0–7.2) lower NO_2 concentrations compared to neighbourhoods with the lowest percentage of 65 plus. All other regions and cities showed similar direction of effects, but smaller differences, with the exception of the West Midlands region.

Similar to England, we observed lower air pollution concentrations in neighbourhoods with the highest percentage of children in the Netherlands, but results for cities and regions were mostly statistically not significant. Associations with the 65 plus in the Netherlands were much more unclear and often not significant.

4. Discussion

In this study we aimed to disentangle factors associated with air pollution inequalities found in previous studies (Briggs et al., 2008; Kruize et al., 2007; Mitchell and Dorling, 2003) by looking at particular subpopulations, pollutants, study areas and countries. Our study is one of the first to compare neighbourhood associations between air pollution concentration and population characteristics in a consistent manner between two European countries and for different study areas, to highlight the differences in inequalities between different levels of analysis and countries.

Associations between air pollution and both deprivation and ethnic minorities were found to be in line with our original hypothesis that these more vulnerable subpopulations experience higher air pollution levels; in contrast to the associations observed with children and the elderly. Moreover, our results suggest that although neighbourhoods with different population characteristics are exposed to different levels of air pollution, both direction and magnitude of differences vary by study area, country and pollutant. We observed the strongest positive associations for NO_2 with urbanisation, socioeconomic deprivation and ethnically diverse neighbourhoods at the national level in England and the Netherlands and in London but somewhat weaker associations at the regional level and other cities. The main driver of these associations in the two countries was the urban/rural contrast, in particular in the Netherlands, where we observed homogeneous concentrations profiles in rural neighbourhoods of different deprivation, ethnic and age composition.

A prevailing expectation is that subpopulations of lower socioeconomic position are exposed to higher levels of air pollution, due to the proximity of homes to various pollutant sources such as high-traffic roads or industrial facilities. In particular in North America studies have shown higher exposures with lower socioeconomic position (Morello-Frosch et al., 2002; Neumann et al., 1998; Perlin et al., 1999). In Europe results are more mixed (Brainard et al., 2002; Mitchell and Dorling, 2003; Richardson et al., 2013; Wheeler and Ben-Shlomo, 2005). Negative associations have been observed in some cities and higher air pollution concentrations have been reported in midlevel deprivation areas in Strasbourg (Havard et al., 2009) and affluent areas in Rome (Forastiere et al., 2007). We observed similar nonlinear neighbourhood associations between air pollution concentrations and deprivation for Dutch cities and Bristol in England. Reasons for these non-linear or negative associations have been discussed in the literature. One possible explanation is the gentrification of inner cities. People of higher social class might tolerate higher levels of air pollution in inner city areas for the multitude of benefits association with inner city living (Buzzelli and Jerrett, 2007). This hypothesis is supported by the steeper increase in house prices seen in cities compared to rural areas (ONS, 2014).

Research into the associations between air pollution levels and ethnicity has a long tradition in the US but less so in Europe. Previous studies conducted in the UK questioned the observed racial inequalities because of potential confounding with deprivation (Brainard et al., 2002). McLeod et al. (2000), however, detected higher air pollution concentrations in areas with greater proportions of ethnic minorities in England after controlling for socioeconomic status. This is in line with our findings where the large associations between high air pollution levels and ethnic diverse neighbourhoods prevail after adjustment for deprivation and other demographic factors. The underlying reasons need further investigation. England and the Netherlands have a long history of immigration and immigrants settled in particular areas may tolerate poorer air quality for the benefits of living in a neighbourhood with friends and families rather than move when they become better established and deprivation levels reduce.

Only few studies so far have looked at environmental inequality related to age and the findings are not directly comparable to our study because of different study designs and age definitions. Mitchell and Dorling (2003), for example, found that NO_2 levels in Great Britain tend to be higher in areas where young children and their parents are likely to live. This is in contrast to our findings from both England and the Netherlands where neighbourhoods with a high percentage of children had consistently lower average PM_{10} and NO_2 concentrations. Trends of lower average concentrations in neighbourhoods with high percentage of the elderly are consistent with our findings.

The profound differences between the two countries – a big social contrast, in particular for NO_2 pollution in England but neighbourhoods with high levels of air pollution concentrations cross social and demographic boundaries in the Netherlands – are probably due to the different spatial distribution of the subpopulations and social profiles in the two countries. The percentage of children and elderly in Dutch cities, for example, is much lower as in English cities (Table 1). Also the historical social contract that exists in society is in the Netherlands driven by an egalitarian approach which strives to eliminate any form of inequality in society whilst in England the traditional class system is still present in today's housing stock.

We also found differences in associations with subpopulations by pollutant type. Particle concentrations are mostly driven by background sources and long-range transport (Keuken et al., 2013) which is reflected in a homogeneous distribution for PM_{10} (inter-quartile range in England: 3.2 $\mu g/m^3$; in Netherlands: 3.7 $\mu g/m^3$). NO_2 concentrations mostly arise from traffic-contributions and therefore vary greatly over short-distances with clusters of high concentrations close to roads (inter-quartile range in England: 9.0 $\mu g/m^3$; in Netherlands: 13.4 $\mu g/m^3$).

4.1. Strength and limitations

This study is the first to compare neighbourhood associations between air pollution levels and population characteristics across two European counties, differentiating between associations found at the national level as well as regions and cities within these countries. A particular strength of the study is that we were able to harmonise comparisons across countries, by using air pollution concentrations modelled using the same methodology and at much higher spatial resolution than in previous studies (Richardson et al., 2013) and by selecting population characteristics that are recorded almost identically in England and the Netherlands. We made every effort to select indicators of socioeconomic deprivation and neighbourhood characteristics that were as comparable as possible between the two countries; nevertheless there remains some difference in classification. In particular, differences in measuring socioeconomic deprivation, non-White ethnicities and urban neighbourhoods might explain some of the reversed patterns observed in the two countries. In addition, the LUR models used to predict air pollution concentrations include information on total built-up land and high residential land. Although these are different from the classifications used to define urban neighbourhoods in this study they might contribute to some degree to the associations seen with both PM_{10} and NO_2.

One limitation of our study is that it only examined two pollutants. We analysed association with PM_{10} and NO_2 because comparable LUR models across the two countries are available for these pollutants. Associations might differ for other pollutants, in particular ozone which usually has higher concentrations in rural areas. We looked at air pollution concentrations in neighbourhoods covering small areas (SOAs in England and buurten in the Netherlands). In urban areas, where air pollution variability is very high (Wilson et al., 2005), the average size of a neighbourhood was only 0.9 km^2 in England and 0.7 km^2 in the Netherlands. This should allow reasonable detection of air pollution variability. We make, however, the assumption that concentrations are evenly distributed across those small areas and some of the extremes, such as very high concentrations along major roads that drop off steeply over short distances, will be lost. The effect of deprived individuals living along main roads might be masked by our analysis at neighbourhood level and the true individual effect could be much higher.

Further, ambient air pollution concentrations can only be a proxy for personal exposure. For different subpopulations, in particular with restricted mobility such as the deprived, children and the elderly, air pollution concentrations at the place of residence, however, are likely to be important in characterising personal exposure.

4.2. Research and policy implications

This study has implications for future environmental health studies as well as environmental policies. Our results underline that environmental inequality is not a homogenous construct as often implied, but that its manifestation can differ between subpopulations, local areas and countries that might be considered fairly similar. To target environmental inequalities and the consequent health inequalities Marshall (2008), for example, describes in his conception of an environmental justice framework, that both air pollution exposure and the consequent health impact should be equal for all individuals and subpopulations. Given that susceptibility to the negative health impacts of air pollution varies by socioeconomic deprivation, age and pre-existing health impairment he postulates a different form of environmental inequality which sees the most susceptible subpopulations exposed to lower concentration levels in order to realise a fair burden across society. To achieve these goals subpopulations at risk of higher air pollution levels need to be identified. Our work takes a step towards this goal.

Understanding the local level differences is particularly important for health studies, impact assessments and policy strategies to provide specific-policy relevant information to local governments, to focus strategies to reduce environmental inequalities and to ensure that no subpopulations are unduly burdened.

Furthermore, identifying environmental inequalities for specific subpopulations has important implication for establishing susceptibility to relevant health outcomes. Our analyses not only considered inequalities in air pollution exposure for deprived and ethnic minority groups but also by age. In particular, older or more deprived people might already experience compromised health. Forastiere et al. (2007) argue that the main explanation of the strong effect modification observed in many studies (Jerrett et al., 2004; Villeneuve et al., 2003) by socioeconomic status is due to different susceptibility caused by life-long accumulation of risk factors including stress, malnutrition, smoking and excess drinking as well as inadequate access to good quality health care. Whilst affluent people have a greater ability to avoid living in unpleasant surroundings and tend to have better general health, children are powerless to influence residential location decisions and also have a higher susceptibility due to not fully developed lung function and immune system (Schwartz, 2004). In our study we found that areas with higher proportions of children and 65 plus largely experienced lower air pollution levels, which may confer public health benefits.

5. Conclusions

Our analysis suggests that associations of air pollution concentrations with socioeconomic characteristics, ethnicity and age are complex and can vary by country, by urban or rural setting and by subpopulation. Whether a neighbourhood is urban or not is one of the strongest determinants of environmental inequality in exposure to air pollution. Substantial inequalities in air pollution exposure also exist for areas with high proportions of ethnic minorities, even when area level deprivation is taken into account. Both PM_{10} and NO_2 are markers for traffic-related pollution, thus our results suggest that measures to reduce environmental inequality should include a focus on traffic-related measures in urban areas.

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Competing financial interests declaration

The authors declare they have no competing financial interests.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.envpol.2014.12.014.

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