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Particulate air pollution and health inequalities: a Europe-wide ecological analysis

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Abstract

Background: Environmental disparities may underlie the unequal distribution of health across socioeconomic groups. However, this assertion has not been tested across a range of countries: an important knowledge gap for a transboundary health issue such as air pollution. We consider whether populations of low-income European regions were a) exposed to disproportionately high levels of particulate air pollution (PM_{10}) and/or b) disproportionately susceptible to pollution-related mortality effects.

Methods: Europe-wide gridded PM_{10} and population distribution data were used to calculate population-weighted average PM_{10} concentrations for 268 sub-national regions (NUTS level 2 regions) for the period 2004–2008. The data were mapped, and patterning by mean household income was assessed statistically. Ordinary least squares regression was used to model the association between PM_{10} and cause-specific mortality, after adjusting for regional-level household income and smoking rates.

Results: Air quality improved for most regions between 2004 and 2008, although large differences between Eastern and Western regions persisted. Across Europe, PM_{10} was correlated with low household income but this association primarily reflected East–West inequalities and was not found when Eastern or Western Europe regions were considered separately. Notably, some of the most polluted regions in Western Europe were also among the richest. PM_{10} was more strongly associated with plausibly-related mortality outcomes in Eastern than Western Europe, presumably because of higher ambient concentrations. Populations of lower-income regions appeared more susceptible to the effects of PM_{10}, but only for circulatory disease mortality in Eastern Europe and male respiratory mortality in Western Europe.

Conclusions: Income-related inequalities in exposure to ambient PM_{10} may contribute to Europe-wide mortality inequalities, and to those in Eastern but not Western European regions. We found some evidence that lower-income regions were more susceptible to the health effects of PM_{10}.

Keywords: Air pollution, Health inequalities, Mortality, Europe, Particulate matter, NUTS regions, Exposure, Susceptibility

Introduction

Groups or places with lower socioeconomic status (SES) typically have substantially poorer health than more advantaged people or areas [1]. Unequal exposure to health-damaging characteristics of the physical environment has been posited as one factor contributing both to this worse health, and to the widening in health inequalities that has been observed in a number of countries [2]. This assertion is consistent with the findings of the WHO Commission on Social Determinants

of Health which suggested that the unequal distribution of health was influenced by the circumstances in which people grow, live, work, and age, including their physical environments [3]. Since the 1970s, a substantial body of evidence has demonstrated that socially disadvantaged groups are often exposed to physical environments that are potentially health damaging [4]. Environmental inequalities research often applies the framework of 'environmental justice' (EJ) – the fair distribution of environmental goods and bads [2,5].

Despite the compelling claim that unequal exposure to health damaging environments contributes to socioeconomic inequalities in health, this assertion has rarely

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been tested. Analyses of environment and health relationships often consider area-level social disadvantage only as a potential confounder (e.g., [6]). This approach assumes that environmental health risks are consistent across different social strata. The possibility of effect modification – different risks for different social groups – has been investigated less frequently [7]. Two pathways may be involved: differential exposure arises when populations with low socioeconomic status have more frequent or intense exposure to environmental hazards (i.e., environmental inequality), and differential susceptibility (i.e., effect modification) occurs when disadvantaged populations are more likely to be harmed by exposure to the same level of environmental hazard [8]. There has been little exploration of the pathways linking environmental inequality and health disparities, although the urgent need for such work has been highlighted by a number of researchers [4,9].

The present study responds to these calls to investigate the contribution of environmental inequality to health inequalities at the population level, by exploring differential exposure and susceptibility to air pollution in Europe. Air pollution in Europe is a transboundary issue: it is not only the regions producing the pollution that are exposed to it or suffer its health consequences [10]. Displacement of environmental hazards has been found at regional, national and international scales [11,12]. We therefore examine the geographical distribution of potentially hazardous levels of air pollution across Europe, and investigate whether environmental disparities are associated with population-level health inequalities.

In Europe, the air pollutant causing most deaths is particulate matter with an aerodynamic diameter ≤ 10 μm (PM_{10}) [13]. Exposure to PM_{10} has been associated with increased all-cause, respiratory and cardiovascular mortality [14]. This evidence has been used to develop air quality standards for health protection [15,16] although health effects can occur at lower concentrations [14]. Strong socioeconomic gradients have been found for causes of death linked to air pollution, [17,18] with deprived groups consistently suffering worse health.

International and national air quality policies have brought about significant improvements in air quality in Europe, although these improvements have not been spatially uniform [13]. Differential air pollutant exposure by either area or individual SES has been explored in eight Western European countries with inconsistent conclusions: disadvantaged groups were exposed to higher levels of air pollution in some studies, but the reverse was found in other work [19]. Fewer studies have explored differential susceptibility to air pollution by SES, and all have focussed on one or a few cities in single countries [20-24]. These studies consistently found that "irrespective of exposure, subjects of low socio-economic status experience greater health effects of air pollution" [19]; Hence, it is

feasible that differential exposure and susceptibility to air pollution may contribute to the continuance of health inequalities in Europe [25]. However, the existing European evidence is limited in scope, resulting in uncertainties about the generalisability of the results to other contexts, and particularly to Eastern Europe. We address this paucity of geographical coverage by undertaking a Europe-wide analysis at the level of sub-national regions, to facilitate comparisons both within and between nations.

We addressed the following research questions:

1. To what extent do potentially health-damaging levels of PM_{10} vary across the regions of Europe?
2. Are regions with lower average household income disproportionately exposed to lower air quality?
3. Are populations of regions with lower average household income disproportionately susceptible to the health effects of lower air quality?

Methods

We adopted an ecological study design to address our research questions. Such a design enables comparability across multiple nation states and generalisability. Additionally, individual-level data with sufficient Europe-wide coverage and sample sizes were not available. We used ambient PM_{10} concentrations within each region as an indicator of population 'exposure', and used regional differences in associations between PM_{10} and mortality to indicate 'susceptibility'.

Spatial units

We sought units that could be compared between countries and for which appropriate datasets were available. The Nomenclature of Territorial Units for Statistics (NUTS) geography was designed to provide units for statistical comparisons. We selected level 2 of the 2006 version of this geography (NUTS2 regions hereafter) which guidance states should contain between 0.8 and 3 million people.

Air pollution data

We obtained annual PM_{10} data for 2004 to 2008 from the European Environment Agency's (EEA) public air quality database 'AirBase'. As health impacts can vary with exposure time, we obtained indicators of short- and long-term exposure: the 36th highest *daily* mean concentration (μg.m^{-3}) and the *annual* average concentration (μg.m^{-3}), respectively. The AirBase data had been interpolated from air pollution monitoring data from the European Air Quality Monitoring Network (sites that meet specified data quality criteria), supplemented with altitude, meteorological and concentration modelling data, and were referenced to a 10 × 10 km grid [26]. These interpolated data, developed at

the European scale, may differ slightly from within-country assessments.

As populations and particulate pollution tend to be spatially correlated we calculated population-weighted regional averages to reflect the average air quality experienced by the population. This approach weighed pollutant concentrations for more populated parts of each region more heavily than those for sparsely populated places. This prevented an underestimation of PM_{10} concentration if a region had, for example, large areas of unpopulated land. First, the 2006 1 km^2 population distribution grid for Europe [27] was aggregated to give population counts for 10×10 km grid cells that were coincident with the air pollution dataset. Second, the PM_{10} concentration for each grid cell was extracted from the AirBase dataset. Third, the population-weighted average concentration for each region was calculated using the following equation:

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

In this equation P_r is the population-weighted PM_{10} concentration for NUTS2 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. If any grid cell was split between two or more regions, the cell's population was divided on the basis of land area (e.g., a region accounting for 75% of the land area of a grid cell would receive 75% of that cell's population).

Socioeconomic data

We used average primary household income for private households 2004 to 2008 to measure regional socioeconomic status [28]. Primary household income is the balance generated directly from market transactions – salaries, other income, interest, rent and mortgage payments – before the state's benefits and taxes are included. Household income has been used as an indicator of SES in health analyses in a wide range of European countries [29]. Average primary household income is estimated using Purchasing Power Consumption Standard units (PPCS) per capita, allowing for meaningful comparison between countries.

Health data

We selected three causes of death with a plausible aetiological link with PM_{10} – respiratory disease, circulatory disease and all causes – and one with no plausible link, chronic liver disease, for comparison. Age-standardised sex-specific premature (age < 65 y) mortality rates for all causes (International Classification of Disease (ICD) 10 A00-Y89 excluding S00-T98), respiratory diseases (ICD10 J00-J99), circulatory diseases (ICD10 I00-I99), and chronic liver disease (ICD10 K70, K73, K74) were obtained for NUTS2 regions [28]. Three-year moving average rates, standardised to the European standard population, were acquired for 2004–2006, the most recent averaging period with data for most regions. There was however insufficient temporal coverage to investigate trends over time. Separate male and female mortality rates were obtained because sex differences in exposure have been found in other studies [30]. To account for the potentially confounding influence of smoking rate differences between regions [6] we obtained country-level smoking rate estimates derived from the national Health Interview Surveys (2002 collection round) [31].

Data availability

Air pollution and population data were available for 268 regions of 31 countries between 2004 and 2008 (Austria, Belgium, Bulgaria, Croatia, Czech Republic, Denmark, Estonia, Finland, France, Germany, Hungary, Iceland, Ireland, Italy, Latvia, Liechtenstein, Lithuania, Luxembourg, Macedonia, Malta, Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, Switzerland, and United Kingdom). Continuous household income data (2004 to 2008) were not available for ten of these countries, reducing the SES analysis to 235 regions in 12 Western European and 9 Eastern European countries. The regional mortality data (average 2004–2006) were available for 210 regions in 17 countries (161 from the Western European countries of Austria, Finland, France, Germany, Ireland, Netherlands, Norway, Portugal, Spain, Sweden, and UK; and 49 from the Eastern European countries Bulgaria, Czech Republic, Hungary, Poland, Romania, and Slovakia).

As in previous work on health inequalities across Europe [25,32] we excluded certain non-mainland NUTS2 regions that were either atypical of their countries or had very small populations and missing or unreliable data: Åland, Finland; Ceuta, Melilla and the Canary Islands, Spain; French overseas territories; and Madeira and the Azores, Portugal.

Analyses

The analyses were undertaken in three stages. First, we assessed the spatial and temporal variation in PM_{10} concentrations across NUTS2 regions by mapping them in ArcMap 9.3.1 (ESRI, Redlands, CA). Second, in order to assess variability in pollution according to area-level SES, mean concentrations were calculated for regions grouped into quintiles by their average household income in each year. Summary statistics and correlations between SES and PM_{10} concentrations were calculated using the statistical software Stata/IC 11.0 (StataCorp, College Station, TX). Finally, the relationship between air pollution and health was assessed using ordinary

least-squares (OLS) regression analyses to model the relationship between PM_{10} concentrations and regional mortality rates. Models stratified by household income tertiles were run to test whether SES modified the relationship between regional air pollution and health – i.e., disproportionate susceptibility – and the Wald test was used as a formal test for interaction. Pollutant concentrations and household income data for the start year, 2004, were used in these models as proxies for conditions across 2004–2006. Country-level smoking rate estimates were included in all models as continuous percentages.

We investigated spatial autocorrelation in the OLS model residuals, because if the observations are not independent of each other this can lead to artificially small standard errors and false-positive conclusions [33]. We used the GeoDa software [34] to run models corrected for spatial autocorrelation but the results were not substantively different so are not presented here.

Results

The characteristics of the regions in the study are summarised in Table 1. The short- and long-term PM_{10} measures were highly correlated each year ($r > 0.97$), and analyses revealed virtually identical patterns, hence only results for annual average PM_{10} are presented.

Q1. How do potentially health-damaging levels of PM_{10} vary across the regions of Europe?

In order to identify 'potentially health-damaging' levels of particulate pollution we applied the EU and the World Health Organization (WHO) health standards. The EU Air Quality Directive mandates that annual average PM_{10} should not exceed 40 μg.m^{-3}, [15] whereas the WHO recommends a lower target of 20 μg.m^{-3} to significantly reduce health risks [16]. It should be noted that our PM_{10} variable was based on interpolated data produced for use at the European scale, hence may give results that differ from national assessments. Additionally, national compliance with the EU Air Quality Directive is assessed within reporting zones that are often smaller than NUTS2 regions.

Throughout the study period PM_{10} concentrations were greatest in the regions of Southern and Eastern Europe, although by 2008 the particulate pollution in these areas was markedly reduced (Figure 1). Breach of the EU's 40 μg.m^{-3} threshold was rare: this occurred in a maximum of 3% of the regions ($n = 7$) in any one year, and in none in 2008. However in 2006, the most polluted year between 2004–2008, 86% of Western European and 98% of Eastern European regions exceeded the WHO guideline.

Q2. Are regions with lower average household income disproportionately exposed to lower air quality?

There were significant negative correlations between household income and pollution across Europe (Table 2), with lower-income regions experiencing higher levels of PM_{10}. In each year the Europe-wide lowest-income quintile of regions experienced higher PM_{10} concentrations than all other regions, and significantly higher

Table 1 Demographic, socioeconomic, environmental and health characteristics of the NUTS2 regions in the study in 2004

Variable	n	Mean	Standard deviation	Minimum	Maximum
Population	268	1,848,263	1,462,705	26,347	11,350,290
Area (km^2)	268	17,552	21,094	160	154,191
Population density (per km^2)	268	346	835	3	9142
PM_{10}: population-weighted annual average (μg.m^{-3})	268	22.3	7.6	2.7	48.5
PM_{10}: population-weighted 36th highest daily mean (μg.m^{-3})	268	37.1	13.1	3.4	82.7
Mean household income (PPCS)	235	14,689	5,389	2,736	29,707
Mean smoking rate (%, country level)	29	32.0	1.18	18.6	45.1
Premature mortality rate (per 100,000, 2004–2006)					
All-cause male	210	305.3	124.2	103.2	706.6
All-cause female	210	145.6	40.9	78.3	279.5
Circulatory disease male	210	79.6	52.7	24.2	274.8
Circulatory disease female	210	27.2	19.5	7.8	104.3
Respiratory disease male	210	11.8	7.3	2.8	47.2
Respiratory disease female	210	6.0	3.4	1.5	20.4
Chronic liver disease male	210	16.5	12.9	1.8	80.6
Chronic liver disease female	210	5.9	4.6	0.6	26.2

Abbreviations: *NUTS2* Nomenclature of territorial units for statistics level 2, *PM₁₀* Particulate matter with an aerodynamic diameter ≤ 10 μm, *PPCS* Purchasing power consumption standard.
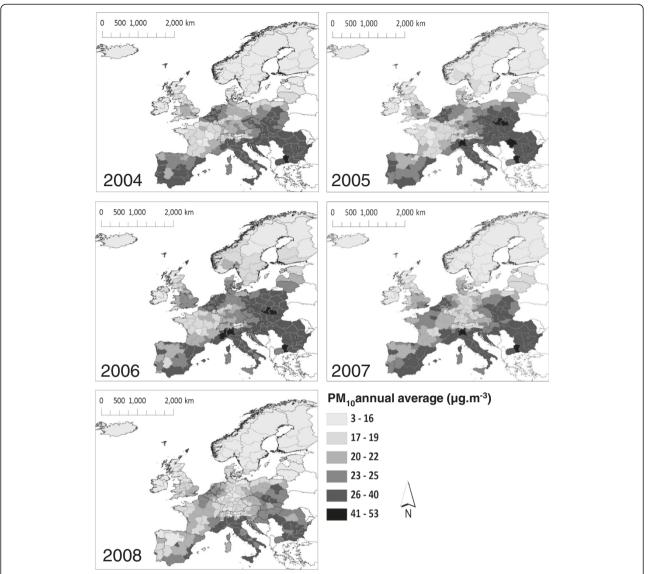
Figure 1 Regional population-weighted average concentrations of annual average PM$_{10}$ (µg.m^{-3}) between 2004 and 2008. Data sources: NUTS2 and country boundary data: GISCO [42]; PM$_{10}$: derived from EEA AirBase data [26].

values than the Europe-wide average (Table 2). Approximately 90% of the regions in this quintile were Eastern European. The two highest-income quintiles also tended to have higher PM$_{10}$ values than the overall average, while regions with an intermediate level of income experienced the lowest values.

Stratified correlation analyses revealed *positive* relationships between PM$_{10}$ and income within Western Europe (significant in 2005 and 2006): each year the highest-income regions experienced higher average concentrations of PM$_{10}$ than the lowest-income regions. PM$_{10}$ concentrations decreased over time for all quintiles, but improvements were greatest in the highest-income regions.

In Eastern European regions the highest PM$_{10}$ concentrations were experienced by the lowest-income regions, in each year except 2008. However, the lowest concentrations were experienced in middle-income regions which, together with the smaller number of regions, may explain why no significant correlations were found. Eastern European regions experienced the greatest improvement in overall air quality: by 2008 average PM$_{10}$ concentrations for these regions were 19% lower than in 2004 compared with 9% for Western Europe. Pollution levels in the lowest-income Eastern European regions fell by the greatest amount over the period (29%).

Across Europe, the 10% of regions with the highest pollutant values were identified. Eleven of these 23 most PM$_{10}$-polluted regions – from Romania, Hungary and Poland – were also among the 10% with the lowest household income. Four of the most PM$_{10}$-polluted regions –

Table 2 The relationship between regional average household income and population-weighted annual average PM$_{10}$ (µg.m^{-3}), 2004–2008

	(a) Correlation coefficients	(b) Pollutant means (µg.m^{-3}, CI)						Ratio Q1:Q5
			by household income quintile (year specific)					
		All regions	Q1 (lowest)	Q2	Q3	Q4	Q5 (highest)	
Whole sample								
n regions	235	235	47	47	47	47	47	
2004	−0.25**	21.7 (20.7 to 22.7)	27.5 (25.4 to 29.5)$^£$	21.4 (19.0 to 23.7)	18.7 (17.3 to 20.1)$^$$	22.2 (20.5 to 23.9)	23.1 (21.3 to 24.9)	1.2
2005	−0.35***	22.9 (21.9 to 24.0)	30.4 (28.3 to 32.6)$^£$	21.7 (19.8 to 23.6)	19.1 (17.6 to 20.6)$^$$	23.0 (21.2 to 24.8)	23.0 (21.3 to 24.7)	1.3
2006	−0.33***	24.7 (23.7 to 25.6)	31.4 (29.4 to 33.4)$^£$	23.8 (22.1 to 25.5)	20.7 (19.1 to 22.3)$^$$	25.5 (23.9 to 27.2)	24.7 (23.1 to 26.3)	1.3
2007	−0.20**	22.1 (21.3 to 22.9)	25.9 (24.3 to 27.6)$^£$	22.1 (20.5 to 23.6)	20.2 (18.9 to 21.6)	22.7 (20.9 to 24.6)	22.5 (20.9 to 24.1)	1.2
2008	−0.14*	19.4 (18.8 to 20.0)	22.3 (21.0 to 23.5)$^£$	19.4 (18.0 to 20.9)	18.3 (17.2 to 19.4)	20.0 (18.6 to 21.4)	20.2 (18.9 to 21.6)	1.1
2004 to 2008 change (% 2004)		*−10.7*	*−18.9*	*−9.0*	*−2.1*	*−10.1*	*−12.5*	
Western Europe								
n regions	187	187	38	37	38	37	37	
2004	0.10	21.2 (20.3 to 22.1)	21.9 (19.6 to 24.2)	18.0 (16.0 to 19.9)$^$$	20.8 (19.1 to 22.5)	22.2 (20.1 to 24.3)	23.1 (21.1 to 25.2)	0.9
2005	0.13*	21.5 (20.7 to 22.4)	21.5 (19.5 to 23.5)	18.8 (17.0 to 20.5)$^$$	20.9 (19.2 to 22.6)	23.0 (21.2 to 24.9)	23.6 (21.5 to 25.7)	0.9
2006	0.17*	23.5 (22.7 to 24.3)	23.1 (21.4 to 24.8)	20.9 (19.2 to 22.6)$^$$	23.4 (21.5 to 25.4)	25.0 (23.1 to 26.9)	25.1 (23.3 to 27.0)	0.9
2007	0.07	21.9 (21.1 to 22.7)	21.9 (20.1 to 23.8)	20.3 (18.7 to 21.9)	21.4 (19.5 to 23.2)	22.6 (20.8 to 24.4)	23.1 (21.2 to 25.1)	0.9
2008	0.08	19.4 (18.8 to 20.1)	19.6 (17.9 to 21.2)	17.8 (16.6 to 19.0)	19.5 (18.2 to 20.8)	20.0 (18.3 to 21.7)	20.1 (18.6 to 21.7)	1.0
2004 to 2008 change (% 2004)		*−8.5*	*−10.5*	*−0.8*	*−6.1*	*−10.0*	*−13.0*	
Eastern Europe								
n regions	48	48	10	10	9	10	9	
2004	−0.01	27.8 (25.8 to 29.9)	31.8 (28.1 to 35.4)	24.7 (20.2 to 29.1)	22.4 (17.4 to 27.4)	31.7 (25.8 to 37.6)	28.1 (25.6 to 30.6)	1.1
2005	−0.04	30.8 (28.7 to 32.9)	34.9 (31.6 to 38.2)	28.8 (23.5 to 34.0)	25.1 (20.6 to 29.5)	34.6 (28.3 to 41.0)	30.0 (27.4 to 32.6)	1.2
2006	−0.11	32.0 (30.1 to 33.9)	34.5 (32.3 to 36.7)	32.0 (27.6 to 36.5)	27.8 (23.9 to 31.7)	33.3 (27.0 to 39.7)	31.8 (26.6 to 37.0)	1.1
2007	−0.17	25.9 (24.3 to 27.5)	29.5 (26.8 to 32.3)	25.9 (22.3 to 29.5)	21.8 (19.2 to 24.4)	25.9 (21.0 to 30.8)	26.1 (21.5 to 30.8)	1.1
2008	0.06	22.4 (21.1 to 23.8)	22.5 (20.5 to 24.5)	24.0 (22.0 to 26.1)	18.4 (14.9 to 21.9)	23.6 (20.2 to 27.0)	23.4 (19.2 to 27.6)	1.0
2004 to 2008 change (% 2004)		*−19.4*	*−29.1*	*−2.5*	*−17.9*	*−25.6*	*−16.8*	

Results given for the whole sample and the Western and Eastern European subsamples: (a) correlation coefficients; (b) mean values (95% confidence interval, CI) for all regions combined and for household income quintiles.

Abbreviations: *CI* confidence interval, *PM$_{10}$* Particulate matter with an aerodynamic diameter ≤ 10 µm.

Correlation coefficients: *0.001 ≤ p < 0.1; **0.0001 ≤ p < 0.001; *** p < 0.0001.

Pollutant means: $^£$ indicates mean is significantly higher than Europe-wide average (*p* < 0.05), $^$$ indicates significantly lower (*p* < 0.05).

Lombardia and Emilia Romagna from Northern Italy, and Flemish Brabant and Walloon Brabant from Belgium – were among the 10% richest.

Q3. Are regions with lower average household income disproportionately susceptible to the health effects of lower air quality?

In Europe-wide models PM_{10} was related to elevated risk of chronic liver disease, suggesting residual confounding. However, separate analysis of Western and Eastern European regions revealed no relationship between liver disease and PM_{10} (Table 3). Hence we report on the separate analyses for respiratory and circulatory disease and all-cause mortality. In Western European regions PM_{10} was associated with a small increase in risk of respiratory disease mortality for males but not for females, and for no other cause of death. Against Western European mean prevalence the coefficient equated to a 16% increase in male respiratory disease mortality for each 10 $\mu g.m^{-3}$ increase in annual average PM_{10}. In Eastern Europe PM_{10} was associated with increased risk of circulatory disease and respiratory disease mortality for males and females, and all-cause mortality for females. The relative mortality increase related to a 10 $\mu g.m^{-3}$ increase in PM_{10} was modest for female all-cause mortality (9% of Eastern European mean prevalence), but was more substantial for circulatory disease (males 17% and females 27%) and respiratory disease (20 and 22%, respectively). For most causes of death significantly associated with PM_{10} the absolute 'effect' sizes found were twice as high for males as for females, due to differences in baseline prevalence, although in relative terms the associated increase in female deaths was greater.

We assessed whether the relationships between PM_{10} and mortality varied across regions grouped according to average household income (Figure 2). Many of the resulting associations were in the expected direction but lacked statistical significance due to small sample sizes. The lowest-income regions exhibited significantly elevated risks ($p \leq 0.03$) for male and female circulatory disease mortality in Eastern Europe ($R^2 = 0.62$ and 0.66 respectively) and male respiratory disease mortality in Western Europe ($R^2 = 0.18$). However, no significant interaction effects for household income tertiles in the relationship between PM_{10} and mortality were found.

Discussion

We investigated whether low income regions in Europe experienced the double jeopardy of exposure to poor air quality as well as social disadvantage. We also considered the associations between PM_{10} and related health outcomes to examine whether low-income areas were disproportionately susceptible to health effects.

Annual average PM_{10} was greatest in the regions of Southern and Eastern Europe, but declined in all regions between 2004 and 2008. Very few regions experienced annual average PM_{10} concentrations higher than those set by the EU Air Quality Directive for the protection of human health, but most exceeded the WHO's guideline value, indicating the potential for further Europe-wide improvement that would benefit health. Health effects have been shown for PM_{10} concentrations below the EU threshold, hence WHO have recently recommended that the regulations are amended [35].

We found clear evidence of environmental inequality when analysing Europe as a whole. However, the double disadvantage of low income and poor air quality was disproportionately concentrated in Eastern European regions and these were driving the Europe-wide association. Among Western regions only, we observed a positive relationship between income and PM_{10} levels. Such stark differences between associations highlights the importance of scale when addressing these research questions.

The East–West differences in ambient pollution are particularly notable because all countries included, except Norway and Croatia, are subject to the same EU pollution regulations. Eastern European countries were required to meet the EU Air Quality Directive by their accession in 2004 or 2007, although some concessions were made to aid their transition. Latvia, for example, had no system of hazardous waste management until 1995 [36]. But while air quality regulations are being harmonised across Europe, less wealthy Eastern European nations balance these new

Table 3 Regression coefficients (+ 95% confidence intervals) for the relationship between PM_{10} concentration and cause- and sex-specific age-adjusted mortality rate

Cause of death	Western Europe		Eastern Europe	
	Male	**Female**	**Male**	**Female**
All cause	0.74 (−0.28 to 1.77)	−0.30 (−0.78 to 0.18)	1.33 (−1.86 to 4.53)	1.74 (0.39 to 3.08)*
Circulatory disease	−0.16 (−0.51 to 0.19)	0.06 (−0.08 to 0.20)	2.67 (1.44 to 3.90)***	1.38 (0.80 to 1.96)***
Respiratory disease	0.15 (0.06 to 0.24)**	−0.01 (−0.08 to 0.05)	0.42 (0.17 to 0.67)**	0.19 (0.07 to 0.32)**
Chronic liver disease	0.08 (−0.10 to 0.25)	0.00 (−0.07 to 0.07)	0.68 (−0.04 to 1.40)	0.24 (−0.01 to 0.49)

Models were adjusted for regional-level household income and country-level smoking rate and run separately for Eastern and Western Europe.
PM_{10} concentration = 2004 population-weighted annual average ($\mu g.m^{-3}$). Mortality rates = 3-year average 2004–2006 (deaths per 100,000).
Abbreviations: PM_{10}, Particulate matter with an aerodynamic diameter $\leq$ 10 μm.
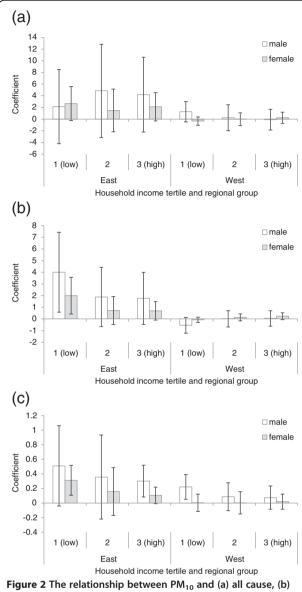* $0.01 \leq p < 0.05$; ** $0.001 \leq p < 0.01$; *** $p < 0.001$.

Figure 2 The relationship between PM$_{10}$ and (a) all cause, (b) circulatory disease, and (c) respiratory disease mortality, stratified by household income tertiles. Models were adjusted for household income and were run separately for Eastern and Western Europe. PM$_{10}$ concentration = 2004 population-weighted annual average (μg.m^{-3}). Mortality rates = 3-year average 2004–2006 (deaths per 100,000). Error bars indicate 95% confidence intervals.

pressures against those of continuing economic disadvantage [37]. These countries have taken financial advantage of opportunities for international trade, by exporting the products of heavy industry and importing hazardous wastes for disposal [38]. Both types of transaction have the potential for increasing the East-West disparity in environmental quality.

Contrary to expectations, the richest regions were rarely the least polluted; rather the lowest levels of pollution were found among regions with an intermediate level of household income. In Western Europe income and pollution were *positively* correlated: the highest PM$_{10}$ concentrations were consistently found in the highest income regions. High levels of pollution and wealth were co-located in the highly-populated commercial centres of Belgium and the Northern Italian regions involved in high-end automobile and machinery manufacture. In Eastern Europe, although the lowest-income regions were the most polluted in most years, concentrations were lowest in the middle-income regions, hence there was no overall income gradient in air quality. Dawson [36] observes that, in the transition economies of Eastern Europe, the economic benefits of polluting activities appear to have outweighed potential environmental quality and health concerns. Our finding of no clear relationship between income and air quality in these regions supports this claim.

The associations between PM$_{10}$ and health also demonstrated an East–West dichotomy. In Western Europe, out of three plausibly-related health outcomes, PM$_{10}$ was only related to increased risk of male respiratory disease mortality. In Eastern European regions we found significantly elevated risks for male and female circulatory and respiratory disease mortality, and female all-cause mortality. Air pollution is a major risk factor for respiratory disease, but circulatory disease has a number of more influential risk factors: smoking, physical inactivity, unhealthy diet, overweight and high blood pressure. Even though we adjusted for smoking rate differences, albeit crudely, it is possible that the effects of this and other determinants dwarf the contribution of air pollution to circulatory disease mortality rates in Western Europe, with its relatively low levels of pollution. In Eastern Europe, the PM$_{10}$ concentrations are perhaps high enough to contribute to population-level circulatory disease rates. Additionally, as respiratory diseases contribute less to overall mortality than circulatory diseases, the finding of no relationship with all-cause mortality in Western Europe is unsurprising. The significant association with male but not female respiratory disease mortality in Western Europe may be attributable to differential exposure patterns: individual exposure to and inhalation of air pollution is dependent on mobility, time spent indoors and outdoors, and the level of physical activity being undertaken [30]. It may alternatively indicate residual confounding by SES, as male deaths are likely to be more strongly associated with regional income (as seen in Figure 2).

Other work suggests that the relationship between air pollution and health does not differ between Eastern and Western Europe [39]. Both the minimum and maximum annual average concentrations were ~10 μg.m^{-3} higher in the Eastern than the Western European regions in our study (13 to 49 μg.m^{-3} in the East and 3 to 40 μg.m^{-3} in the West in 2004). Detectable health

associations were found for the concentrations spanned by the higher range, including for circulatory disease. We suggest that air pollution is a more important risk factor for circulatory diseases at the concentrations found in Eastern than in Western Europe.

We examined whether poorer regional populations were disproportionately susceptible to the health effects of ambient air quality, as indicated in other studies [8]. If the elevated risk among lower-income regions was attributable to PM_{10} we might again expect these effects to be found for respiratory disease mortality ahead of circulatory disease mortality. However, for respiratory disease, increased susceptibility within lower-income regions was only found for males in Western Europe. In Eastern Europe, populations in the lowest-income regions had disproportionately elevated risks of male and female circulatory disease, but not male respiratory disease, for an equivalent increase in annual average PM_{10}. Although we adjusted for regional income and smoking within each income grouping, it is possible that other circulatory disease risk factors which are also socially patterned – such as diet or physical activity – may have contributed to the disproportionate 'effect'. While some high-income regions also experienced high pollution, mortality in these regions was not related to PM_{10} concentrations.

Our study had limitations. First, the characterisation of 'exposure' to air pollutants is a clear problem for ecological analysis. Our air pollution measures captured 'typical' ambient air quality for each region, but this does not necessarily equate with the exposure experienced by the population. We did not consider indoor exposures or individual activity spaces. Nonetheless, our population-weighting technique aimed to reflect typical ambient conditions where the population was concentrated, hence it provides some improvement over discrete monitoring points or area averages. Second, and related, the ecological fallacy is a potential concern in an analysis of regional-level associations. Hence our findings cannot be assumed to translate into air pollution responses at the individual level. Future work could combine individual- and area-level data to explore these relationships. Third, as a cross-sectional study we cannot draw causal inference from this analysis – a key limitation is our inability to account for the accumulation of exposure across the lifecourse, particularly if exposure had occurred in regions other than the region of residence in 2004. Fourth, unmeasured regional variations may have affected our results. The strong positive associations between mortality rates and PM_{10} found among the poorest regions in Europe may reflect the impact upon health of other unmeasured aspects of socio-economic status (e.g., health behaviours). Also, our inclusion of a single environmental factor did not recognise the simultaneous multiple exposures experienced by populations [9]. Finally, there are additional implications

of our use of such large units of analysis, including the Modifiable Areal Unit Problem (MAUP) [40]. Other researchers have found that opposing results can be obtained by analysing the same data at different levels of aggregation, [41] hence our NUTS2-level analysis should be interpreted in this context. We used NUTS2 regions in order to maximise geographical and temporal coverage: if it had been possible to complete our analyses for a smaller geography it is likely that we would have found wider inequalities, largely due to the greater range in pollution and SES values.

Conclusions

The study confirmed that, while air quality is improving, most regions experience annual average PM_{10} concentrations that exceed those recommended by the WHO, and that stark East–West differences persist. The Europe-wide finding of higher pollution for lower-income regions was not borne out in separate Eastern and Western Europe analyses. Most notably, richer Western European regions tended to experience higher pollution levels than lower-income regions, owing to their wealth-generating industry and commerce.

Ambient particulate air pollution levels were more strongly related to mortality outcomes in Eastern than Western Europe, perhaps reflecting the higher concentrations in Eastern regions. The effects of air pollution may also be dwarfed by those of other non-communicable disease risk factors in Western Europe. We found some indication that the populations of lower-income regions were more susceptible to the health effects of PM_{10}, but the evidence varied between Eastern and Western Europe, and between mortality outcomes. Hence, understanding air pollution and its effects may assist our understanding of the geography of health inequalities within Europe, although the relationships may depend on the geographical scope of enquiry.

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