Environmental Pollution 249 (2019) 345–353

Contents lists available at ScienceDirect

Environmental Pollution

journal homepage: www.elsevier.com/locate/envpol

Spatial variability in air pollution exposure in relation to socioeconomic indicators in nine European metropolitan areas: A study on environmental inequality☆

E. Samoli [a,*], A. Stergiopoulou [a], P. Santana [b], S. Rodopoulou [a], C. Mitsakou [c], C. Dimitroulopoulou [c], M. Bauwelinck [d], K. de Hoogh [e,f], C. Costa [b], M. Marí-Dell'Olmo [g,h,i], D. Corman [j], S. Vardoulakis [c,k], K. Katsouyanni [a,l], on behalf of the EURO-HEALTHY Consortium

[a] Department of Hygiene, Epidemiology and Medical Statistics, Medical School, National and Kapodistrian University of Athens, Greece
[b] Centre of Studies in Geography and Spatial Planning, Department of Geography and Tourism, University of Coimbra, Portugal
[c] Environmental Hazards and Emergencies Department, Centre for Radiation, Chemical and Environmental Hazards, Public Health England, UK
[d] Interface Demography – Department of Sociology, Vrije Universiteit Brussel, Belgium
[e] Swiss Tropical and Public Health Institute, Basel, Switzerland
[f] University of Basel, Basel, Switzerland
[g] Agència de Salut Pública de Barcelona, Barcelona, Spain
[h] CIBER Epidemiología y Salud Pública, Madrid, Spain
[i] Institut d'Investigació Biomèdica (IIB Sant Pau), Barcelona, Spain
[j] Department of Public Health Sciences, Karolinksa Institute, Stockholm, Sweden
[k] Institute of Occupational Medicine, UK
[l] Department Population Health Sciences and Department of Analytical, Environmental and Forensic Sciences, School of Population Health & Environmental Sciences, King's College London, UK

ARTICLE INFO

Article history:
Received 7 November 2018
Received in revised form
12 February 2019
Accepted 13 March 2019
Available online 17 March 2019

Keywords:
Air pollution
EURO-HEALTHY
Nitrogen dioxide
Socio-economic indicators

ABSTRACT

A limited number of studies have addressed environmental inequality, using various study designs and methodologies and often reaching contradictory results. Following a standardized multi-city data collection process within the European project EURO-HEALTHY, we conducted an ecological study to investigate the spatial association between nitrogen dioxide (NO_2), as a surrogate for traffic related air pollution, and ten socioeconomic indicators at local administrative unit level in nine European Metropolitan Areas. We applied mixed models for the associations under investigation with random intercepts per Metropolitan Area, also accounting for the spatial correlation. The stronger associations were observed between NO_2 levels and population density, population born outside the European Union (EU28), total crimes per 100,000 inhabitants and unemployment rate that displayed a highly statistically significant trend of increasing concentrations with increasing levels of the indicators. Specifically, the highest vs the lowest quartile of each indicator above was associated with 48.7% (95% confidence interval (CI): 42.9%, 54.8%), 30.9% (95%CI: 22.1%, 40.2%), 19.8% (95%CI: 13.4%, 26.6%) and 15.8% (95%CI: 9.9%, 22.1%) increase in NO_2 respectively.

The association with population density most probably reflects the higher volume in vehicular traffic, which is the main source of NO_2 in urban areas. Higher pollution levels in areas with higher percentages of people born outside EU28, crime or unemployment rates indicate that worse air quality is typically encountered in deprived European urban areas. Policy makers should consider spatial environmental inequalities to better inform actions aiming to lower urban air pollution levels that will subsequently lead to improved quality of life, public health and health equity across the population.

☆ This paper has been recommended for acceptance by Dr. Payam Dadvand.

* Corresponding author. Department of Hygiene, Epidemiology and Medical Statistics, Medical School, National and Kapodistrian University of Athens, 75 Mikras Asias street, 115 27, Athens, Greece.

E-mail address: esamoli@med.uoa.gr (E. Samoli).

https://doi.org/10.1016/j.envpol.2019.03.050
0269-7491/

1. Introduction

Environmental inequality, that re-emerged as an issue a few years ago (Fairburn et al., 2005; Jerrett, 2009; WHO, 2010), is a concept investigating whether people suffering socioeconomic deprivation (including ethnic minorities) are exposed to worse conditions of environmental stressors such as air pollution, noise or excessive heat, but also landfill proximity, water quality and green spaces. As air pollution has been classified among the top 10 factors that affect health worldwide (Global Burden of Disease Project), it is of vital importance to identify those most exposed in order to properly inform public health policies targeting to reduce pollution levels. This is particularly important in urban areas with strong socioeconomic and air quality gradients, where local action on air pollution can reduce or unintentionally exacerbate inequalities (Vardoulakis et al., 2018).

A limited number of studies have addressed environmental inequality, using various study designs and methodologies and often reaching contradictory results (Fecht et al., 2015; Hajat et al., 2015; King and Steadman, 2000; McLeod et al., 2000; Temam et al., 2017; Wheeler 2005). The few studies in Europe that explored socio-economic determinants of environmental exposures showed that the association depends on the city, but also the geographical scale of the analysis and differs across cities and countries. (Fecht et al., 2015; King and Steadman, 2000; McLeod et al., 2000; Temam et al., 2017; Wheeler 2005). Studies conducted in the U.K. used the deprivation index as a socioeconomic strata (SES) indicator and reported that in urban areas the more socioeconomically deprived certain population groups are, the more exposed they are to environmental stressors, e.g. to air pollution (Fecht et al., 2015; King and Steadman, 2000; Wheeler 2005), although the association was inverse in rural areas (Wheeler 2005) or Glasgow (King and Steadman, 2000). Temam et al. (2017) using data from three multicenter epidemiological European cohorts reported that the middle socioeconomic strata were more exposed to high air pollution levels as reflected by nitrogen dioxide (NO_2) concentrations.

With a focus on air pollution health effects, some studies, mostly in the U.S.A., have investigated the synergistic effects of SES variables and air pollution on various outcomes and reported evidence of higher effects among the most deprived social groups (Bell et al., 2013; Vishnevetsky et al., 2015; Chi et al., 2016; O' Lenck et al., 2017). Furthermore, policy measures targeting on reducing air pollution levels have been reviewed to assess whether they promote equality. Wang et al. (2016) reviewed four types of such measures, namely general regulations on air quality control, road traffic related emission control, energy generation related emission control and greenhouse gas emission control interventions, and reported that these interventions led to lower levels of urban air pollution (particles and NO_2). Three out of the 15 studies included in their review indicated that the related policies could reduce health inequality associated with air pollution, although no consistent impact on health equality was found.

EURO-HEALTHY (Shaping European Policies to promote Health Equity, http://www.euro-healthy.eu), a research project funded by the EU, built a multidimensional and multilevel Population Health Index to evaluate population health of the EU regions in a wide range of areas of concern, dimensions and indicators, including economic conditions, demographic change, physical environment and built environment. The findings have uncovered that the spatial distribution of the multiple determinants of population health is heterogeneous. When looking within the European Union (EU28) countries, at the geographical level 2 of the EU28 regions (often referred as NUTS 2), Santana et al. (2017) found that regions where the country's capital is located systematically presented better value-scores when compared with the remaining ones, namely regarding economic conditions. Nevertheless, the same study demonstrated that capital regions face higher levels of air pollution, concluding that EU28 capital regions concentrate better economic conditions but worse pollution levels. Regarding within-city inequalities, the city scale statistics often mask differences within capital regions and their surroundings, failing to identify deprived areas.

Using the wealth of SES indicators collected in the EURO-HEALTHY project and in response to the limited and inconsistent evidence on the characterization of the spatial variability of air pollution according to SES area characteristics, we conducted an ecological study to investigate the association between NO_2 as a surrogate for traffic related air pollution and several SES indicators in small areas, defined at Local Administrative Units (LAU) within nine metropolitan areas (MA) throughout Europe.

2. Data and methods

We collected data on environmental and socioeconomic indicators in the framework of the European project EURO-HEALTHY that aimed to characterize health equity across Europe using a standardized protocol procedure under an ecological study design. Data were collected at a comparable administrative spatial level, roughly corresponding to municipalities. Following the EUROSTAT's hierarchical system of Local Administrative Units (LAU) focal points from each MA collected the data for one of the following levels: the upper LAU level (LAU level 1) and the lower LAU level (LAU level 2). For most European countries, LAU-2 corresponds to municipalities (Sohn and Stambolic, 2013). Therefore, we collected data at municipality level for nine MA across Europe for the period 2001–14 (Fig. 1) considering the following LAU level: Athens, Greece, including 40 LAU 1; Barcelona, Spain, including 23 LAU 2; Berlin-Brandenburg, Germany, including 23 LAU 1; Brussels, Belgium, including 91 LAU 2; Lisbon, Portugal, including 18 LAU 1; London, UK, including 33 LAU 1; Paris, France, including 150 LAU 2); Stockholm, Sweden, including 26 LAU 2 and Turin, Italy, including 49 LAU 2.

Concentrations of NO_2 for 2010 were derived for Europe from a previously developed Land Use Regression (LUR) model, incorporating chemical transport model estimates, road data and land use (de Hoogh et al., 2016). The original $100\,m \times 100\,m$ gridded NO_2 data was intersected with the municipality's boundaries and aggregated to calculate an average of the annual mean NO_2 concentration at the municipality level.

For the present analysis, we only considered SES indicators with available data from at least five MA in 2001–14. These are presented in Table 1 and included: unemployment and youth (aged 15–24 years old) unemployment rate, disposable income of private households per capita, number of crimes per 100,000 inhabitants, population aged 25–64 with upper secondary or tertiary education attainment, early leavers from education and training and population born in non EU28 countries. We further considered daily smokers aged above 15 years and population density as indirect SES indicators and finally the area's ageing index as an indicator of the health susceptibility and vulnerability of the population. Different MA collected data for different years, within the period 2001–14, depending on the indicator and its availability from the census or other sources of data, such as police records (for crimes) and representative population surveys (for smoking prevalence data). Furthermore, some indicators were provided annually, while others in 3- and 4-years intervals. We only considered indicators that were available for the period 2010–14 in order to have a time correspondence with NO_2 data availability but also because data for this period were more complete compared to previous years. When

Fig. 1. Metropolitan areas included in the study.

indicators were provided annually, we assigned to each LAU the average of the indicator's levels for the available years within 2010–14. In cases that an indicator was not available at LAU level, the value of an upper administrative level was assigned to all LAUs within that city for descriptive purposes but the MA was excluded from further analysis of the specific variable (as was the case for the income and crimes indices in Athens, or percent of daily smokers in Paris).

We initially performed the analysis separately by MA. We calculated the Spearman correlation coefficients between NO_2 and SES indicators and applied linear regressions, accounting for each indicator separately. We estimated the spatial autocorrelation of the residuals by Moran's I to assess model assumptions (Havard et al. 2009). In the second stage of the analysis, data from all MA were pooled and analyzed together by applying mixed models for the associations under investigation with random intercepts per MA and accounting for the spatial correlation by the introduction of a bivariate thin plate regression spline for the centroid's geographic coordinates of each LAU, as implemented by Wood (2003). In all analyses NO_2 was log-transformed as its original distribution deviated from the normal. The indicators were entered in the models one at a time using MA-specific quartiles to account for linearity deviations. We tested the sensitivity of our findings by using quartiles for the indicators as estimated by the overall distribution across the 9 MA, acknowledging as drawback in this analysis that in the overall distribution different MA contribute to different levels. Finally we assessed the consistency of the associations in models adjusting for population density.

All analyses were performed using the R v3.3.2 statistical package (R Foundation for Statistical computing 2016).

3. Results

Table 2 presents the distribution of NO_2, SES indicators and other characteristics used in the analysis. There was large spatial variability both between and within cities. For example the unemployment rate ranged from 3.1% in Stockholm to 26.7% in Barcelona with the highest standard deviation (SD) in Brussels (SD = 6.7%); while the percent of inhabitants born out of the EU28 ranged from 2.5% in Turin to 27.0% in London with the highest intra-city variability in Brussels (SD = 8.6%). NO_2 concentrations also displayed spatial variability (both inter and intra-city) with the least polluted city being Stockholm and the most polluted Paris (Table 1 and Fig. 2). Boxplots of the MA-specific and pooled distribution for NO_2 and the selected indicators are presented in Supplementary Fig. S1.

Table 3 presents the correlations of NO_2 and SES or other characteristics per MA indicating variability between cities and among indicators. For example, the correlation of NO_2 with unemployment ranged from 0.05 in Stockholm to 0.65 in Berlin-Brandenbourg. For

Table 1
List of socio-economic indicators considered in the analysis for the period 2010–14.

Indicator	Definition	Units	Number of Metropolitan areas (MA) with data at local administrative unit level	Time-frame of data availability
Unemployment rate	% unemployed of adult work force	%	9	Data for all MA for 2011, except for: Paris data for 2012; Berlin and Stockholm annual data for 2010–2014; Brussels annual data for 2010–2013.
Youth unemployment rate	% unemployed in the age group 15–24 years old	%	9	Data for all MA for 2011, except for: Paris for 2012; Berlin, Brussels & Stockholm annual data for 2010–2014.
Disposable income of private households per capita	Household income	Euros per inhabitant	6 (not available for Athens, Lisbon, Turin)	Annual data for: Barcelona for 2010–2014; Berlin and London for 2010–2013; Brussels for 2010–2012; Paris for 2010–2011; Stockholm for 2012.
Crimes per 100,000 inhabitants	As recorded by the police	Number	6 (not available for Athens, Barcelona, Turin)	Annual data for all MA for 2010–2014 except for London that data were provided for 2-years intervals
Population aged 25–64 years with upper secondary or tertiary education attainment	% of the total population	%	9	Data for all MA for 2011, except for: Paris for 2012; Berlin for 2011, 2013; Stockholm annual data for 2010–2014.
Early leavers from education and training	% of the total population	%	8 (not available for Barcelona)	Data for all MA for 2011, except for: Paris for 2012; Berlin for 2011, 2013; Stockholm for 2011, 2012.
Population born in non EU28 countries	% of the total population	%	8 (not available for Paris)	Data for all MA for 2011, except for: Barcelona, Berlin and Stockholm annual data for 2010–2014.
Ageing index	number of persons ≥60 years per hundred persons under age 15	Ratio	9	Annual data for all MA for 2010–2014, except for: Athens and Turin data for 2011; Paris for 2012; Stockholm for 2013.
Daily smokers aged ≥15 years	% of the population ≥15 years	%	9	Annual data for Barcelona for 2011; Berlin, Brussels, Turin for 2013; Athens, Lisbon for 2014; Paris for 2010,2014; London for 2010–2014; Stockholm provided data for 2011–2014 overall.
Population density	inhabitants/km^2	inhabitants/km^2	9	Annual data for all MA for 2010–2014, except for Athens data only for 2011.

all cities except London, the highest correlation across the indicators was observed with population density, ranging from 0.70 in Turin to 0.96 in Berlin-Brandenbourg. In London the highest correlation was observed with the crime rate ($r = 0.85$). Negative correlations were also observed, which were especially high in Berlin-Brandenbourg for the association with income ($r = -0.69$) and population aged 25–64 years with upper secondary or tertiary education ($r = -0.68$).

MA-specific linear regression models indicated low to moderate spatial autocorrelation for the great majority of the indicators, ranging from 0.07 in Athens for most indicators to 0.42 in Brussels for the association with the aging index. In all analyses, we addressed this spatial autocorrelation by adding a smooth bivariate term for each municipality's geographic coordinates in the mixed models analysis with the pooled data over all MAs (Table 4). All indicators presented positive associations with NO_2 concentrations indicating increases for levels above the lowest quartile of the indicator distribution. Among the indicators analyzed, the stronger associations were observed between NO_2 levels and population density, population born outside the EU28, crimes per 100,000 inhabitants, and unemployment rate, which displayed a highly statistically significant trend of higher NO_2 concentrations with increasing levels of the indicators. Specifically, the highest vs the lowest quartile of each of these four socioeconomic indicators was associated with 48.7% (95% confidence interval (CI): 42.9%, 54.8%), 30.9% (95%CI: 22.1%, 40.2%), 19.8% (95%CI: 13.4%, 26.6%) and 15.8% (95%CI: 9.9%, 22.1%) increase in NO_2 respectively. A statistically significant increasing trend was observed for areas with a higher ageing index, where the areas at the highest quartile of the ageing index had 11.9% higher NO_2 levels. The association with youth unemployment rate and the percentage of smokers over 15 years indicated that the middle levels of the indicators presented the highest increases in NO_2 levels, rather than the highest. Income and higher education attainment indices were not significantly associated with NO_2 levels.

The models using pooled data quartiles for the indicators identified the same statistically significant indicators that followed the same patterns as in the analysis with the MA-specific quartiles (Supplementary Table S1), while the magnitude of the effects increased in all cases except for the population born in non EU28 (decreased) and the ageing index (identical). Models adjusting for population density also revealed the same patterns although the magnitude of the effects decreased (Supplementary Table S2).

4. Discussion

We analyzed various direct and indirect SES indicators in relation to NO_2 spatial variability in nine European MAs within the framework of the EURO-HEALTHY ecological study. We found higher levels of NO_2 concentrations in LAU areas with higher levels of population density, percentage of population born outside the EU28 countries, crimes per 100,000 inhabitants and unemployment rate. We considered one variable at a time as all analyzed indicators reflect the same i.e. SES under different perspectives. As our aim is not the investigation of a causal association (under which several variables may act as confounders and/or mediators and/or effect modifiers) or the construction of a prediction model, the joint consideration of variables does not add value to our research. The

Table 2
Descriptive statistics for the population, NO_2 levels and the analyzed indicators for the local administrative units by metropolitan area (MA) for the period 2010–2014.

Indicator	MA	Min	25%	Median	Mean	75%	Standard Deviation	Max
Number of inhabitants	Athens	25,389	39,199	61,919	77,263	73,355	98,478	664,046
	Barcelona	13,531	33,817	46,667	134,955	84,758	320,181	1,611,822
	Berlin-Brandenburg	58,018	11,9506	182,259	195,701	259,822	85,160	371,438
	Brussels	2160	9920	15,428	24,854	29,654	26,722	176,545
	Lisbon	17,569	68,693	140,718	156,771	174,860	124,898	547,733
	London	7648	215,671	263,386	255,047	310,516	70,725	372,752
	Paris	1701	19,668	32,202	46,663	55,391	43,290	235,357
	Stockholm	9331	30,985	42,328	80,440	69,289	158,750	864,315
	Turin	1200	4920	8856	33,051	19,074	124,093	886,837
Annual mean NO_2 mean (μg/m^3)	Athens	18.8	29.2	37.5	35.7	41.4	7.3	46.5
	Barcelona	20.2	30.5	36.4	36.9	44.0	8.2	48.9
	Berlin-Brandenburg	10.8	12.1	17.6	19.2	24.6	7.6	34.0
	Brussels	19.9	22.6	25.6	28.1	31.9	7.2	47.0
	Lisbon	11.5	14.4	19.0	19.9	22.9	6.8	34.8
	London	30.7	34.3	38.2	38.8	41.3	5.4	53.1
	Paris	21.6	34.4	40.4	39.7	45.8	7.3	54.0
	Stockholm	4.3	7.2	8.8	11.4	15.4	5.4	23.2
	Turin	12.6	21.3	25.6	24.8	28.3	6.3	40.9
Unemployment rate (%)	Athens	3.3	11.5	14.2	14.6	18.4	4.5	25.3
	Barcelona	16.9	23.2	26.7	25.9	29.1	4.8	36.6
	Berlin-Brandenburg	5.4	7.3	7.7	9.2	11.6	3.0	15.1
	Brussels	3.0	5.3	8.6	10.2	11.6	6.7	33.1
	Lisbon	9.1	12.1	13.1	13.2	14.3	2.0	17.9
	London	3.9	6.4	6.9	7.5	9.0	2.0	11.7
	Paris	6.3	9.2	11.1	12.6	15.1	4.5	26.8
	Stockholm	1.4	2.4	3.1	3.8	4.9	1.9	9.9
	Turin	4	7	8.2	7.9	9	1.5	11.2
Youth unemployment rate (%)	Athens	16.5	49.4	53.4	52.8	58.6	9.0	67.2
	Barcelona	31.7	48.1	50.9	51.1	54.9	7.6	70.3
	Berlin-Brandenburg	12.4	12.4	14.9	13.7	14.9	1.3	14.9
	Brussels	13.9	15.0	25.6	22.9	25.6	9.2	38.2
	Lisbon	7.7	9.6	11.3	11.6	13.4	2.5	16.3
	London	0.6	1.3	1.6	1.7	2.0	0.5	2.9
	Paris	2.0	8.0	10.7	10.9	13.8	3.7	19.7
	Stockholm	2.2	4.0	5.2	5.2	6.1	1.6	9.2
	Turin	0.9	2	2.5	2.3	2.8	0.6	3.5
Disposable income of households per capita (Euros per inhabitant)	Athens[a]	13,348	13,348	13,348	13,348	13,348	–	13,348
	Barcelona	8782	12,153	13,181	14,116	15,406	3177	22,787
	Berlin-Brandenburg	16,079	17,288	17,288	17,598	18,135	767	19,655
	Brussels	15,833	18,167	18,867	18,579	19,967	1544	19,967
	Lisbon[a]	14,508	14,508	14,508	14,508	14,508	14,508	14,508
	London	20,065	22,400	24,204	27,143	25,368	8895	48,838
	Paris	6666	12,449	16,277	18,091	21,219	8639	54,654
	Stockholm	27,735	32,861	35,346	35,164	37,686	3469	42,876
	Turin	–	–	–	–	–	–	–
Crimes recorded by the police per 100,000 inhabitants	Athens[a]	902	902	902	902	902	0	902
	Barcelona[a]	4895	4895	4895	4895	4895	0	4895
	Berlin-Brandenburg	317	344	548	536	651	196	947
	Brussels	2879	4776	6189	7561	8955	4620	32,687
	Lisbon	2759	3353	3814	3998	4400	1084	7596
	London	5644	7077	9183	11,632	11,232	11,581	72,092
	Paris	5785	6316	6676	7788	9152	1705	10,937
	Stockholm	6186	9970	11,750	11,949	14,178	3558	22,108
	Turin	–	–	–	–	–	–	–
Population aged 25–64 years with upper secondary or tertiary education attainment (%)	Athens	54.6	70.9	75.8	76.5	86.1	10.4	94.9
	Barcelona	39.9	51.2	54.2	56.5	60.0	9.2	80.4
	Berlin-Brandenburg	71.3	85	91.8	89.0	93.7	6.6	96.5
	Brussels	49.8	69.3	75.1	73.8	78.6	7.3	86.3
	Lisbon	29.2	35.0	36.3	38.3	38.9	6.0	52.5
	London	37	50	55	55.7	63	10.0	81
	Paris	12.1	25.9	36.1	38.0	51.6	15.7	69.8
	Stockholm	74.2	82.9	86.1	85.5	88.7	4.8	94.2
	Turin	32.5	41.0	44.7	46.9	49.7	8.7	75.6
Early leavers from education and training (%)	Athens	1.8	3.6	5.1	6.4	8.5	3.8	18.4
	Barcelona[a]	25.2	25.2	25.2	25.2	25.2	–	25.2
	Berlin-Brandenburg	5.2	5.2	8.2	6.7	8.2	1.5	8.2
	Brussels	4.3	8.4	11.4	12.5	15	5.5	32
	Lisbon	1.2	1.5	1.7	1.8	2.0	0.3	2.4
	London	9	13	14	14.5	16	2.5	19
	Paris	9	13	14	14.5	16	2.5	19
	Stockholm	5	7.3	8.4	8.5	9.9	1.9	12.3
	Turin	0	0.4	0.8	0.8	1.2	0.6	2.7

(*continued on next page*)

Table 2 (*continued*)

Indicator	MA	Min	25%	Median	Mean	75%	Standard Deviation	Max
Population born in non EU28 countries (%)	Athens	5	6.7	8.6	9.1	10.6	3.2	19.4
	Barcelona	4.1	5.7	7.7	8.8	9.8	4.2	19.4
	Berlin-Brandenburg	2.3	4.9	7.5	8.8	12.7	5.0	18.3
	Brussels	1.2	3.4	6.3	9.2	12	8.6	40.7
	Lisbon	2.0	3.8	4.6	5.1	6.0	2.0	9.5
	London	7.0	23.6	27.0	26.4	30.8	8.2	42.5
	Paris	–	–	–	–	–	–	–
	Stockholm	2.6	4.9	7.6	9.2	13.4	5.1	19.1
	Turin	1.6	2.2	2.5	2.8	2.8	1.4	9.8
Ageing index (ratio)	Athens	0.8	1.1	1.3	1.3	1.6	0.3	1.9
	Barcelona	0.5	0.8	0.9	1.0	1.1	0.3	1.7
	Berlin-Brandenburg	0.8	1.4	1.7	1.7	2.0	0.4	2.5
	Brussels	0.7	1.0	1.1	1.1	1.2	0.3	2.5
	Lisbon	0.8	0.9	1.1	1.1	1.3	0.3	2.0
	London	0.3	0.5	0.6	0.6	0.7	0.3	1.7
	Paris	0.2	0.5	0.7	0.7	0.8	0.3	2.0
	Stockholm	0.6	0.7	0.8	0.9	0.9	0.2	1.7
	Turin	0.9	1.2	1.4	1.4	1.6	0.2	2.0
Daily smokers aged 15 and over (%)	Athens	32.1	33.7	33.8	34.5	34.8	1.7	38.4
	Barcelona	18.5	23.0	23	22.8	23.0	0.9	23.0
	Berlin-Brandenburg	16.9	20.3	23.5	23.0	25.6	3.4	28.1
	Brussels	13.9	13.9	18.3	18.2	23.4	3.9	23.4
	Lisbon	18.7	18.7	18.7	18.7	18.7	18.7	18.7
	London	13.3	16.4	18.1	18.2	19.8	2.6	23.3
	Paris[a]	25.0	25.0	25.0	25.0	25.0	–	25.0
	Stockholm	3.3	7.8	9.7	9.9	14	3.6	15.1
	Turin	19.6	22.0	22.0	22.0	22.0	0.3	22.0
Population density (inhabitants/km^2)	Athens	1077	5293	8944	9055	12,979	4936	20,917
	Barcelona	1464	2015	3882	6916	10,355	5819	20,635
	Berlin-Brandenburg	71	89	1449	2806	4931	3438	13,181
	Brussels	109	339	620	2641	1882	4794	23,721
	Lisbon	136	270	1201	2029	2457	2213	7376
	London	2095	4256	5362	6827	9809	3528	14,191
	Paris	382	4716	7583	10,354	13,992	8478	42,918
	Stockholm	28	120	368	1355	1208	1355	4738
	Turin	85	326	518	946	1198	1113	6833

[a] City-value assigned to all local administrative units for descriptive purposes.

investigation of the association with multiple indicators was intended to test the consistency of the results regardless of the indicator used to represent SES.

Our results on the association with population density presumptively indicates the higher volume of vehicular traffic, which is the main source of NO_2 in urban areas. On the other hand, higher pollution levels in LAUs with higher percentages of people born outside the EU28, crime or unemployment rates indicate that higher NO_2 levels occur more likely in deprived European urban areas.

The associations of NO_2 concentrations with youth unemployment rate (among 15–24 years old), as well as the percentage of daily smokers, although less strong than those discussed above, indicate that the middle SES strata were associated with higher NO_2 levels. This finding is not in perfect agreement with our results related to population density, unemployment rate, and percentage of population born outside the EU28 countries, but we consider that the youth unemployment rate and the percentage of smokers are more prone to misclassification. The former due to the different recording systems of youth employment among EU countries and the latter because the data on smoking were not provided by the census or official registries, but in most cases were estimated from population surveys.

Our findings add to previous literature by presenting a variety of indicators and are in accordance with reports indicating higher air pollution levels for those suffering social deprivation. Clark et al. (2014) investigated environmental injustice and inequality in residential outdoor NO_2 exposure of the US population and reported greater inequality in average NO_2 concentrations than in average income by area. They also reported that people of a non-Caucasian race experienced 38% higher residential outdoor NO_2 concentrations than Caucasians. Temam et al. (2017) used data from cohorts in 16 European areas (mainly urban) participating in the ESCAPE study, to show that participants with a lower individual SES were less exposed to NO_2, while those living in neighborhoods with a higher unemployment rate were more exposed. They contributed these conflicting findings to the hypothesis that individual- and neighborhood-SES indicators capture different aspects of the association between SES and exposure to air pollution. Wheeler and Ben-Shlomo (2005) used an air quality index based on NO_2, particulate matter (PM_{10}), sulphur dioxide (SO_2) and benzene to assess combined effects of SES and local air quality on respiratory health among the Health Survey participant households in England and also reported that lower social class urban households were more likely to be located in areas of poor air quality. Ncess et al. (2007) studied the effect of $PM_{2.5}$ and social deprivation markers (at individual and neighborhood level) on mortality in an adult cohort in Oslo, Norway. They reported that socially deprived neighborhoods had higher exposure to air pollution, while deprivation at both individual and neighborhood level accounting for some of the excess mortality associated with air pollution. Although the authors did not report results on NO_2, the high correlation between $PM_{2.5}$ and NO_2 in their study ($r = 0.87$) implies that comparable results are expected if NO_2 would have been the exposure of interest, as in our current study.

The findings of our study may be limited by the different reporting systems among European countries that may have affected certain indices such as unemployment. Nevertheless other indicators, such as the ageing index, population density, and country of birth, are not expected to be affected in a similar way. We

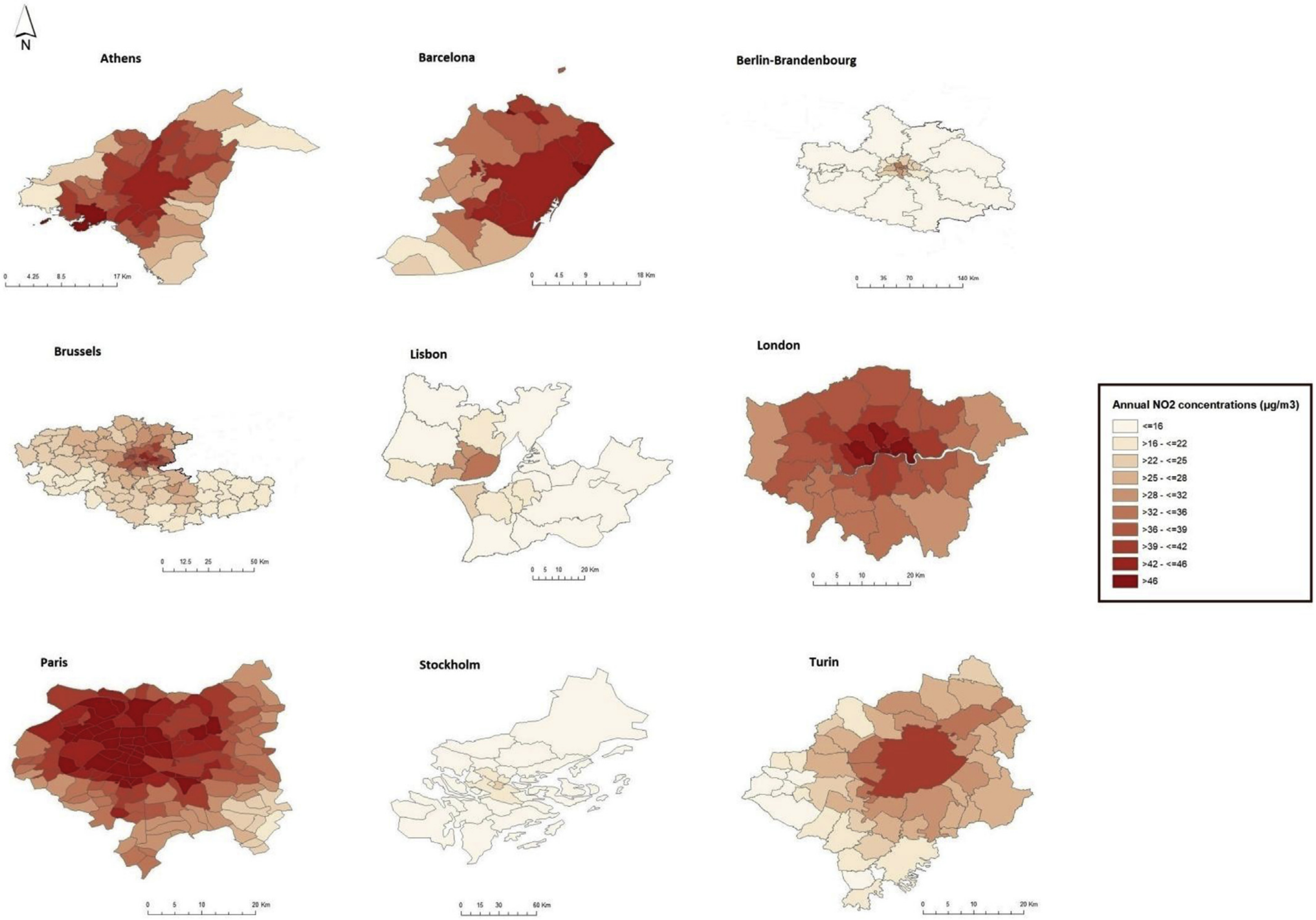

Fig. 2. Spatial distribution of NO_2 concentrations ($\mu g/m^3$) at local administrative unit level by Metropolitan Area (2010).

Table 3
Spearman Correlation coefficients between NO_2 and socio-economic indicators per metropolitan area.

Metropolitan area	Unemployment rate	Youth unemployment rate	Household Income	Crimes per 100,000 inhabitants	Population 25–64yrs with upper education	Early education leavers	Born in non EU-28	Ageing index	Smokers >15yrs	Population Density
Athens	0.287^{b}	0.005	–	–	−0.119	0.257	0.490^{a}	0.309^{b}	0.063	0.740^{a}
Barcelona	0.502^{a}	0.556^{a}	−0.191	–	0.167	–	0.423^{a}	0.482^{a}	−0.129	0.765^{a}
Berlin-Brandenbourg	0.647^{a}	0.866^{a}	−0.687^{a}	0.841^{a}	−0.683^{a}	0.866^{a}	0.734^{a}	−0.374^{b}	0.359^{b}	0.963^{a}
Brussels	0.375^{a}	0.295^{a}	−0.263^{a}	0.659^{a}	−0.157	0.351^{a}	0.733^{a}	−0.244^{a}	−0.399^{a}	0.923^{a}
Lisbon	0.063	0.075	–	−0.088	0.197	−0.027	0.651^{a}	0.746^{a}	–	0.932^{a}
London	0.381^{a}	−0.013	0.243	0.850^{a}	0.507^{a}	0.254	0.642^{a}	−0.339^{b}	0.435^{a}	0.769^{a}
Paris	0.236^{a}	0.224^{a}	0.126	0.335^{a}	0.346^{a}	−0.251^{a}	–	0.133	–	0.824^{a}
Stockholm	0.045	−0.240	0.316	0.265	0.478^{a}	−0.324	0.503^{a}	0.030	−0.319	0.939^{a}
Turin	0.421^{a}	0.258^{b}	–	–	0.010	0.182	0.251^{b}	0.249^{b}	−0.245^{b}	0.697^{a}

$^{A}p<0.05$, $^{b}p<0.1$.

did not proceed with the construction of a combined SES indicator that has the potential to summarize any underlying association as this is hindered by the varying spatio-temporal characteristics of the available data across countries. More importantly our conclusions are limited by the modifiable areal unit effect, as the size of the LAU varied greatly both within and between MA and this impacts the estimation of the various indicators with the potential to mask or bias associations. The magnitude of this potential impact cannot be estimated but is addressed up to one level by the interpretation of the mixed models' estimates as within MA results obtained by accounting for both within and between MA variability and considering that most SES indicators are reported as rates allowing for spatial comparisons. Finally the focus on the analysis of NO_2 as a marker of traffic pollution is justified by the fact that vehicular traffic is the major source of air pollution in urban centers and has been more consistently associated with air pollution effects (HEI, 2010). The strengths of our study include the wide spatial distribution of the metropolitan areas across Europe, the standardized data collection of a large number of area indicators at a rather small area level (municipality), as well as the resulting large sample size that enhances the statistical power of the study.

In conclusion, our results show that higher NO_2 levels are

Table 4
Percent change (and associated 95% confidence intervals (CIs)) in NO_2 levels (μg/m^3) per metropolitan area-specific quartile level of socio-economic (SES) indicators compared to the lowest category. Results from mixed models with random intercept per Metropolitan Area (MA).

SES indicator	Quartile level of SES indicators	% change (95%CI) in NO2 concentrations	p-value	p-value for trend
Unemployment rate *(n = 453; MA = 9)*	2nd	7.3 (2.4, 12.3)	0.003	<0.001
	3rd	13.7 (8.2, 19.4)	<0.001	
	4th	15.8 (9.9, 22.1)	<0.001	
Youth unemployment rate *(n = 453;MA = 9)*	2nd	15.6 (10.5, 20.9)	<0.001	0.022
	3rd	12.6 (6.9, 18.7)	<0.001	
	4th	7.5 (1.6, 13.7)	0.012	
Disposable income of private households per capita *(n = 346[a];MA = 6)*	2nd	1.3 (−2.9, 5.7)	0.539	0.117
	3rd	2.8 (−2.5, 8.4)	0.312	
	4th	4.9 (−1.2, 10.1)	0.125	
Crimes recorded by the police per 100,000 inhabitants *(n = 341[b];MA = 6)*	2nd	5.5 (0.7, 10.8)	0.026	<0.001
	3rd	5.8 (0.3, 11.6)	0.040	
	4th	19.8 (13.4, 26.6)	<0.001	
Population aged 25–64 years with upper secondary or tertiary education *(n = 453;MA = 9)*	2nd	2.6 (−2.2, 7.7)	0.290	0.126
	3rd	0.1 (−4.7, 5.1)	0.973	
	4th	5.1 (−0.1, 10.7)	0.053	
Early leavers from education and training *(n = 430[c];MA = 8)*	2nd	6.5 (1.6, 11.7)	0.010	0.084
	3rd	4.9 (−0.1, 10.2)	0.054	
	4th	4.9 (−0.4, 10.5)	0.073	
Population born in non EU28 countries (*n = 292 [d];MA = 8***)**	2nd	8.0 (1.7, 14.8)	0.013	<0.001
	3rd	13.7 (6.2, 21.5)	<0.001	
	4th	30.9 (22.1, 40.2)	<0.001	
Ageing index *(n = 453;MA = 9)*	2nd	1.8 (−2.6, 6.4)	0.431	<0.001
	3rd	6.3 (1.5, 11.3)	0.010	
	4th	11.9 (6.8, 17.2)	<0.001	
Daily smokers aged > 15 years *(n = 449;MA = 9)*	2nd	14.0 (6.6, 21.9)	<0.001	0.054
	3rd	12.3 (3.6, 21.7)	0.005	
	4th	4.9 (−3.0, 13.5)	0.228	
Population density *(n = 453, MA = 9)*	2nd	12.0 (8.0, 16.0)	<0.001	<0.001
	3rd	25.7 (21.1, 30.6)	<0.001	
	4th	48.7 (42.9, 54.8)	<0.001	

Missing for: [a]Athens, Lisbon, Turin; [b] Athens, Barcelona, Turin; [c] Barcelona; [d] Paris.

observed in socioeconomically deprived areas of European Metropolises, as these are reflected by higher levels of population density, population born outside the EU28, crime and unemployment rates. Epidemiological investigations on the health effects of air pollution should carefully consider the characterization of area-level SES characteristics in their design as according to our findings these may act as potential confounders and/or effect modifiers considering that deprivation is also related to health. Policy makers should consider spatial environmental inequalities to better inform actions aiming to lower urban air pollution levels in Europe that will subsequently lead to improved quality of life, public health and health equity across the population.

Acknowledgements

The authors acknowledge the Hellenic Statistical Authority for the provision of Athens data; the National Statistics Institute, Portugal for the provision of Lisbon data.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2019.03.050.

Funding

Research was partly supported by the European Union's Horizon 2020 research and innovation program under grant agreement No 643,398 (Euro-Healthy project).

References

Bell, M.L., Zanobetti, A., Dominici, F., 2013. Evidence on vulnerability and susceptibility to health risks associated with short-term exposure to particulate matter: a systematic review and meta-analysis. Am. J. Epidemiol. 178 (6), 865–876.
Chi, G.C., Hajat, A., Bird, C.E., Cullen, M.R., Griffin, B.A., Miller, K.A., Shih, R.A., Stefanick, M.L., Vedal, S., Whitsel, E.A., Kaufman, J.D., 2016. Individual and neighborhood socioeconomic status and the association between air pollution and cardiovascular Disease. Environ. Health Perspect. 124, 1840–1847.
Clark, L.P., Millet, D.B., Marshall, J.D., 2014. National patterns in environmental injustice and inequality: outdoor NO_2 air pollution in the United States. PLoS One 9 e94431.
de Hoogh, K., Gulliver, J., Donkelaar, A.V., Martin, R.V., Marshall, J.D., Bechle, M.J., Cesaroni, G., Pradas, M.C., Dedele, A., Eeftens, M., Forsberg, B., Galassi, C., Heinrich, J., Hoffmann, B., Jacquemin, B., Katsouyanni, K., Korek, M., Künzli, N., Lindley, S.J., Lepeule, J., Meleux, F., de Nazelle, A., Nieuwenhuijsen, M., Nystad, W., Raaschou-Nielsen, O., Peters, A., Peuch, V.H., Rouil, L., Udvardy, O., Slama, R., Stempfelet, M., Stephanou, E.G., Tsai, M.Y., Yli-Tuomi, T., Weinmayr, G., Brunekreef, B., Vienneau, D., Hoek, G., 2016 Nov. Development of West-European PM2.5 and NO2 land use regression models incorporating satellite-derived and chemical transport modelling data. Environ. Res. 151, 1–10.
Fecht, D., Fischer, P., Fortunato, L., Hoek, G., de Hoogh, K., Marra, M., Kruize, H., Vienneau, D., Beelen, R., Hansell, A., 2015. Associations between air pollution and socioeconomic characteristics, ethnicity and age profile of neighborhoods in England and The Netherlands. Environ. Pol. 198, 201–210.
Fairburn, J., Walker, G., Smith, G., 2005. Investigating Environmental Justice in Scotland: Links between Measures of Environmental Quality and Social Deprivation. Final Report. http://eprints.staffs.ac.uk/1828/1/1828.pdf. (Accessed 4 October 2018).
Hajat, A., Hsia, C., O'Neill, M.S., 2015. Socioeconomic disparities and air pollution exposure: a global review. Curr Environ Health Rep 2, 440–450.
Havard, S., Deguen, S., Zmirou-Navier, D., Schillinger, C., Bard, D., 2009. Traffic-related air pollution and socioeconomic status. Epidemiology 20, 223–230.
HEI Panel on the Health Effects of Traffic-Related Air Pollution, 2010. Traffic-related Air Pollution: a Critical Review of the Literature on Emissions, Exposure, and Health Effects. Health Effects Institute, Boston, 2010. Special Report 17. https://www.healtheffects.org/publication/traffic-related-air-pollution-critical-review-literature-emissions-exposure-and-health. (Accessed 7 September 2018).
Jerrett, M., 2009. Global geographies of injustice in traffic-related air pollution exposure. Epidemiology 20, 231–233.
King, K., Stedman, J., 2000. Analysis of Air Pollution and Social Deprivation. Report AEAT/R/ENV/0241. Didcot. AEA Technology Environment.
McLeod, H., Langford, I.H., Jones, A.P., Stedman, J.R., Day, J.R., Lorenzoni, I., Bateman, I.J., 2000. The relationship between socio-economic indicators and air pollution in England and Wales: implications for environmental justice. Reg.

Environ. Change 1 (2), 78–85.
Ncess, O., Piro, F.N., Nafstad, P., Smith, G.D., Leylan, A.H., 2007. Air pollution, social deprivation, and mortality a multilevel cohort study. Epidemiology 18, 686–694.
O' Lenick, C.R., Winquist, A., Mulholland, J.A., Friberg, M.D., Chang, H.H., Kramer, M.R., Darrow, L.A., Sarnat, S.E., 2017. Assessment of neighbourhood-level socioeconomic status as a modifier of air pollution–asthma associations among children in Atlanta. J. Epidemiol. Community Health 71, 129–136.
Santana, P., Costa, C., Freitas, Â., Stefanik, I., et al., 2017. Atlas of Population Health in European Union Regions. Imprensa da Universidade de Coimbra, Coimbra, Portugal. https://doi.org/10.14195/978-989-26-1463-2.
Sohn, C., Stambolic, N., 2013. The urban development of European border regions: a spatial typology. Eur. Reg. 21, 177–189.
Temam, S., Burte, E., Adam, M., Antó, J.M., Basagaña, X., Bousquet, J., Carsin, A.E., Galobardes, B., Keidel, D., Künzli, N., Le Moual, N., Sanchez, M., Sunyer, J., Bono, R., Brunekreef, B., Heinrich, J., de Hoogh, K., Jarvis, D., Marcon, A., Modig, L., Nadif, R., Nieuwenhuijsen, M., Pin, I., Siroux, V., Stempfelet, M., Tsai, M.Y., Probst-Hensch, N., Jacquemin, B., 2017. Socioeconomic position and outdoor nitrogen dioxide exposure in Western Europe: a multi-city analysis. Environ. Int. 101, 117–124.
Vardoulakis, S., Kettle, R., Cosford, P., Lincoln, P., Holgate, S., Grigg, J., Kelly, F., Pencheon, D., 2018. Local action on outdoor air pollution to improve health. Int. J. Public Health 63, 557–565.
Vishnevetsky, J., Tang, D., Chang, H.W., Roen, E.L., Wang, Y., Rauh, V., Wang, S., Miller, R.L., Herbstman, J., Perera, F.P., 2015. Combined effects of prenatal polycyclic aromatic hydrocarbons and material hardship on child IQ. Neurotoxicol. Teratol. 49, 74–80.
Wang, L., Zhong, B., Vardoulakis, S., Zhang, F., Pilot, E., Li, Y., Yang, L., Wang, W., Krafft, T., 2016. Air quality strategies on public health and health equity in Europe- a systematic review. Int. J. Environ. Res. Public Health 13, 1196.
Wheeler, B.W., Ben-Shlomo, Y., 2005. Environmental equity, air quality, socioeconomic status, and respiratory health: a linkage analysis of routine data from the Health Survey for England. J. Epidemiol. Community Health 59 (11), 948–954.
Wood, S.N., 2003. Thin plate regression splines. J.R.Statist.Soc.B 65 (1), 95–114.
WHO, 2010. Environment and health risks: a review of the influence and effects of social inequalities. WHO Regional Office for Europe.