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Air quality and social deprivation in four French metropolitan areas – A localized spatiotemporal environmental inequality analysis

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Abstract

Several studies have documented that more deprived populations tend to live in areas characterized by higher levels of environmental pollution. Yet, time trends and geographic patterns of this disproportionate distribution of environmental burden remain poorly assessed, especially in Europe. We investigated the spatial and temporal relationship between ambient air nitrogen dioxide (NO_2) concentrations and socioeconomic and demographic data in four French Metropolitan Areas (Lille in the north, Lyon in the center, Marseille in the south, and Paris) during two different time periods. The geographical unit used was the census block. The dependent variable was the NO_2 annual average concentration (μg/m^3) per census block, and the explanatory variables were a neighborhood deprivation index and socioeconomic and demographic data derived from the national census. Generalized additive models were used to account for spatial autocorrelation. We found that the strength and direction of the association between deprivation and NO_2 estimates varied between cities. In Paris, census blocks with the higher social categories are exposed to higher mean concentrations of NO_2. However, in Lille and Marseille, the most deprived census blocks are the most exposed to NO_2. In Lyon, the census blocks in the middle social categories were more likely to have higher concentrations than in the lower social categories. Despite a general reduction in NO_2 concentrations over the study period in the four metropolitan areas, we found contrasting results in the temporal trend of environmental inequalities. There is clear evidence of city-specific spatial and temporal environmental inequalities that relate to the historical socioeconomic make-up of the cities and its evolution. Hence, general statements about environmental and social inequalities may not properly

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Competing interests

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characterize situations where people of higher social status find the benefits of living in a specific city outweigh the detriment of higher pollution.

Keywords

air pollution; environmental inequalities; generalized additive models; social determinants; spatial-temporal analysis

1. Introduction

Environmental justice first emerged in the United States and Canada where it is now an important part of environment and public health policy assessment (Jerrett et al., 2001; Bowen, 2002; Fairburn et al., 2009; Laurent, 2011). The concept draws attention to the questions of whether certain socioeconomic groups, including the economically and politically disadvantaged, bear a disproportionate burden of environmental externalities, and whether policies and practices that relate to sources of nuisances and pollution or, conversely, to wholesome environments (e.g., green spaces), are equitable and fair (Bowen, 2002; Braubach, 2013).

A number of ecological studies dealing with environmental equity (or justice) have investigated this topic and assessed population exposure to environmental pollution and socioeconomic characteristics using data collected at different geographic scales. As expected, many studies conclude that groups with a low socioeconomic status tend to be more highly exposed to air pollutants and toxicants, due especially to the proximity of their homes to pollution sources (e.g. high-traffic roads, industrial facilities and waste disposal sites) (Finkelstein et al., 2005; Chaix et al., 2006; Marshall, 2008; Briggs et al., 2008; Yanosky et al., 2008; Diekmann and Meyer, R, 2010; Viel et al., 2010; Brochu et al., 2011; Bell and Ebisu, 2012; Laurian and Funderburg, 2013).

More recently, the issue of uneven distribution of environmental pollution across populations with different socioeconomic status entered into discussions in Europe, specifically in The Netherlands (Kruize et al., 2007), Finland (Rotko et al., 2001), Sweden (Chaix et al., 2006), Germany (Kohlhuber et al., 2006), the UK (Namdeo and Stringer, 2008; Mitchell and Dorling, 2003; Fairburn et al., 2009; Walker, 2010; Jephcote and Chen, 2012), Italy (Forastiere et al., 2007), and France (Laurian, 2008; Havard et al., 2009; Laurian and Funderburg, 2013). In contrast with American studies, inconsistent results were obtained in Europe. For instance, while some report that populations with low socioeconomic status are more exposed to air pollutants (Kruize et al., 2007; Namdeo and Stringer, 2008), others find that populations with middle socioeconomic status experience higher levels of air pollution (Havard et al., 2009), or show an inverse relationship (Forastiere et al., 2007). The methodological diversity of these studies and the variety of their settings may partly explain the heterogeneity of their results. This heterogeneity might also express the diversity of the urban make-up both across and within European countries (Deguen and Zmirou-Navier, 2010). According to an Organization for Economic Co-operation and Development report (OECD Report, 2004), more studies are needed in Europe to improve our understanding of the underlying mechanisms of environmental inequality.

A decreasing trend of urban air pollution has been observed in most European countries during the last two decades, an effect of the important evolution of the general structure of the European economy, but also of national regulations, in compliance with the European directives (1999/30/EC, 2008/50/EC). Despite air quality improvements, air pollution remains a major public health research field, particularly in consideration of social justice. Some neighborhoods in urban areas are characterized by concentrations of socially and materially deprived populations. Additionally, previous studies demonstrate that trends in ambient air quality can create disparities across neighborhoods (O'Neill et al., 2003; Jerrett et al., 2005b).

In this context, our work concerns two issues. Firstly, we will identify whether urban neighborhoods are characterized by an uneven distribution of ambient air concentrations of nitrogen dioxide (NO_2) according to the level of deprivation in four large French metropolitan areas. Secondly, we will investigate the time trends of environmental inequalities by comparing two time periods during the last decade (2002–2005 vs 2006–2009) during which a general pattern of air pollution reduction was observed. We will address three underlying questions: (1) Are environmental inequalities comparable across the four French cities, with regards to air pollution? (2) How do environmental inequalities change over the time? (3) Do the socioeconomic markers of environmental inequalities differ between the two study periods?

Nitrogen dioxide was selected because it is known to be a good tracer of urban air pollution generated by traffic and because its spatial heterogeneity is recognized to be greater than for other air pollutants (Jerrett et al., 2004). It is also a pollution indicator for which exposure varies substantially among socioeconomic groups (Yanosky et al., 2008; Crouse et al., 2009; Diekmann and Meyer, R, 2010; Branis and Linhartova, 2012; Vrijheid et al., 2012). Strengths of the study include the small spatial scale of the analysis which reduces the residual autocorrelation between spatial units, the comprehensive modeling of the urban distribution of NO_2 concentrations, and the use of the same statistical methodology for the 4 major metropolitan areas.

2. Materials and Methods

2.1. Study area and setting

Our study is an ecological study using the smallest geographical level unit with available socioeconomic data in France. The statistical unit is the sub-municipal French census block (called IRIS "Îlot Regroupé pour l'Information Statistique") defined by the National Institute of Statistics and Economic Studies (INSEE, 2013). This geographical unit averages 2000 inhabitants and is constructed to be as homogenous as possible in terms of socio-demographic characteristics and land use. The census blocks' surface areas are 1.2 km^2 (± 2.1) for the Lille, North of France, 4.1 km^2 (± 6.3) for the Lyon, Center-East of France, 2.0 km^2 (± 4.6) for the Marseille, South of France and 0.3 km^2 (± 0.6) for the Paris metropolitan areas. The spatial analysis of environmental inequalities were stratified by two periods of 4 years (2002–2005 and 2006–2009) to assess trends over time within the four Metropolitan Areas.

Figure 1 presents the study areas with Lille, Marseille, Lyon and Paris. The Paris metropolitan area includes the city of Paris and three surrounding departments (named "petite couronne"). These four metropolitan areas have been chosen because they exhibit important differences regarding socioeconomic and demographic characteristics (Table 1).

2.2. Neighborhood socioeconomic variables

Socioeconomic and demographic data estimated from the 1999 (for the first period 2002–2005) and 2006 (for the second period 2006–2009) national census from The National Institute of Statistics and Economic Studies (INSEE, 2013) were used in two ways.

From these data, we constructed a composite neighborhood deprivation index at the census block level that measures the global level of deprivation. The methods have been presented in detail elsewhere (Lalloué et al., 2013). Briefly, principal-components analysis was used to synthesize the information from INSEE. Successive Principal Component Analyses were used to maximize the inertia of the first component by deleting all the variables weakly correlated with it and the variables with a contribution lower than the average. Following this procedure, the first component is composed of 20 variables which explain 63 % of the inertia of the initial variables for the Lille, 54% for the Lyon, 60% for the Marseille, and 59% for the Paris metropolitan areas, respectively. This index covers the different known domains of the socioeconomic deprivation including family and household, immigration status and mobility, employment and income, education, and housing. Because social disadvantage is a multidimensional concept, deprived population groups are often disadvantaged in more than one way (Braubach, 2013). Figure 2 shows the spatial distribution of the deprivation index classified by tertiles across the census blocks of the 4 metropolitan areas.

The variables included in the deprivation index common to all metropolitan areas, were then used to assess the spatial association between air quality and socioeconomic and demographic characteristics between two periods. We include the proportion of immigrants; variable related to the family and household: the proportion of single parents and economic variables related to job insecurity: the proportion of unemployment and of insecure jobs (such as contracts for limited periods or for apprenticeship). We also included the proportion of white collar jobs and the proportion of residents with a high level of education, based on the expectation that these variables influence the tradeoffs between housing prices and local positive and negative aspects of the environment. We included the proportion of subsidized housing, non-homeownership and median income because low income affects the capacity to choose one's place of residence. These variables were selected based on their associations with other environmental exposures (Jerrett et al., 2001; Brainard et al., 2002; Brochu et al., 2011b; Branis and Linhartova, 2012).

2.3. Air pollution: spatial and temporal patterns

Annual ambient air concentrations of NO_2 were modeled by the local air quality monitoring networks (Atmo Nord Pas-de-Calais for Lille metropolitan area, Air Rhône-Alpes for Lyon metropolitan area, Air PACA for Marseille metropolitan area, AirPARIF for Paris and 'petite couronne') for each census block throughout the entire study period (2002–2009).

The four air quality monitoring networks developed and tested a methodology to describe and characterize disparities in environmental exposures at a local scale for that period. They used different deterministic models: ADMS (Atmospheric Dispersion Modeling System) Urban for the Lille metropolitan area (McHugh et al., 1997; Carruthers et al., 2000), SIRANE for the Lyon metropolitan area (Soulhac et al., 2011, 2012), ESMERALDA for the Paris metropolitan area (Carruthers et al., 2000) and STREET for the Marseille metropolitan area (Carruthers et al., 2000). In 2010, Jerrett et al. demonstrated the effectiveness and reliability of these types of models for assessing air quality in health assessment research (Jerrett et al., 2010). These models integrate meteorological data (air temperature, wind speed and direction, relative humidity, barometric pressure, supplied by Météo France, the French meteorologic service), emission sources of air pollutants, and background pollution measurements, as input parameters. Selected emission sources were linear sources (main roads), surface sources (diffuse road sources, residential and tertiary emissions) and important point sources.

2.4. Regression analysis

Census blocks without socioeconomic information (for example, an industrial census block or a park) were excluded from the analysis; i.e., 2 blocks (0.4%) in Lille, 6 (1.1%) in Lyon, 11 (1.7%) in Marseille and 54 (1.9%) in Paris. We also excluded census blocks that had no information on air pollution: 24 (4.7%) in Lille, 13 (2.5%) in Lyon, 72 (11.4%) in Marseille and 3 (0.1%) in Paris. The final dataset included 476, 492, 545 and 2692 census blocks for Lille, Lyon, Marseille and Paris respectively.

We applied simple and multivariate regression analyses to assess associations between socioeconomic variables and air quality, all estimated at the census block level, adjusting for spatial autocorrelation.

We used generalized additive models (GAMs), a form of non-parametric regression with the ability to analyze area-based data adjusting for covariates and taking into account spatial autocorrelation (Hastie and Tibshirani, 1990; Wood, 2006, 2004; Kiffer et al., 2011).

We modeled location, a potential proxy measure of unknown exposure or uncontrolled risk factors, using a smooth (S) of longitude (X) and latitude (Y) with a gaussian link function.

$$\mathrm{Log}[\mathrm{p}(\mathrm{X},\mathrm{Y})]=\mathrm{S}(\mathrm{X},\mathrm{Y})+\gamma'\mathrm{Z} \quad \text{(equation 1)}$$

where the left-hand side is the logarithm of the NO_2 concentrations estimation at the census block's centroid (X,Y), and γ is a vector of parameters associated with Z, the vector of covariates.

In our study, Z represents the socioeconomic variables and γ, the coefficient associated with the covariates. The model is semi-parametric because it includes both nonparametric and parametric components. Without the smooth function, S(X,Y), the model becomes an ordinary linear regression on the covariates. GAMs can be applied with locally weighted regression smoothers (LOESS) to account for geographic location as a possible predictor of environmental inequalities. The amount of smoothing depends on the percentage of the data points in the neighborhood, referred to as the span size. The optimal amount of smoothing was determined by minimizing the Akaike's Information Criterion (AIC). The span we used was 0.15. Small span sizes produce bumpier variability and larger span sizes produce smoother variability. As the span size increases, the amount of bias in the fit increases and the variance decreases.

We used the GAM package of the R software, written by Trevor Hastie and is an implementation of the GAM framework of Hastie and Tibshirani (1990), to perform the generalized additive modeling, and the ArcView 9.3 software (ESRI, Inc., Redlands, California) to map the results of our analyses.

Results

3.1. Descriptive statistics

Table 1 summarizes the annual averages of the NO_2 concentrations for the periods 2002–2005 and 2006–2009, respectively, in the four metropolitan areas (Lille, Paris, Lyon and Marseille). The Lyon metropolitan area had the largest decrease of NO_2 concentrations between the two periods (−11.5%), from 43.6 $\mu g/m^3$ (SD=5.4) to 38. 6 $\mu g/m^3$ (SD=6.3). The Marseille metropolitan area had the smallest difference (−3.3%) with 33 $\mu g/m^3$ (SD=10.2) for the first period and 31.9 $\mu g/m^3$ (SD=9.8) for the second. The Paris metropolitan area had the highest level of NO_2 concentrations for both periods, with 47.4$\mu g/m^3$ (SD=9.3) for the first and 44.2$\mu g/m^3$ (SD=9.9) for the second (−6.8 %). In all the metropolitan areas, neighborhoods with the highest concentrations are downtown and along the major roads linking the cities (Figure 3).

Neighborhood socioeconomic variables present similar patterns between the two periods (Table 1). All metropolitan areas are characterized by an increased proportion of insecure jobs and of immigrants and a decreased proportion of single parent families. But there were also specific patterns depending on the metropolitan area. Marseille has the highest proportion of unemployment and the lowest rate of subsidized housing whereas Paris has the highest proportion of white collar jobs and non-homeownership. Figure 2 presents the spatial distribution of the deprivation index in tertiles and shows strong contrasts within each metropolitan area. In Lille and Marseille, the most deprived areas are located in the urban center and in the major cities (Lille and Roubaix for the Lille metropolitan area, and Marseille and Aix-en-Provence for the Marseille metropolitan area) (Figure 2). In Lyon, the East suburb is most deprived, whereas in Paris, the most deprived areas are concentrated in the north and the south-eastern part of the metropolitan area (Figure 2).

3.2. Levels of air pollution across social groups

Metropolitan patterns—Table 2-A shows average NO_2 concentrations ($\mu g/m^3$) in groups of contrasted socioeconomic deprivation areas. The most deprived areas correspond to the 80th percentile of the deprivation index distribution and the less deprived correspond to 20th percentile. In the Lille and Marseille metropolitan areas, the NO_2 concentrations ratios vary between 1.21 and 1.67 (Table 2-A). The most exposed census blocks in the Lille metropolitan area include the Lille city center and the towns of Roubaix and Tourcoing, in the north-east side; these areas exhibit high deprivation values. The poorer census blocks in the northern part of the city of Marseille and its very center show the same patterns. Connversely, in the Paris metropolitan area, NO_2 concentrations are higher in the most favored census blocks (Percentile 80 / Percentile 20 ratio=0.83). Central districts ('arrondissements') 1 to 8 in the city of Paris have low deprivation values whereas eastern peripheral districts 12, 13, 18, 19 and 20, are more deprived. In less favored census blocks in the Seine-Saint Denis department (north of Paris), the air residents breathe is of poorer quality than the wealthy inhabitants of the Western Haut de Seine department or the middle categories of the Southern Val de Marne department. The situation is different in the Lyon metropolitan area where census blocks of the medium deprivation category (between percentiles 60 and 40) show the highest NO_2 concentrations (43.8μg/m^3), with the lowest found in the wealthy West area.

Table 2-B compares the average NO_2 concentrations over the two study periods (period 1: 2002–2005, and period 2: 2006–2009), across the low, middle and high categories of the deprivation index for each metropolitan area. It shows a general decrease of NO_2 concentrations during the study period. However, this evolution depends on the deprivation categories. In the Lyon metropolitan areas, the reduction between the two periods is lower in the middle census blocks (with the highest exposure) and the most disadvantaged census blocks than in the most favored ones (−11.4%, −13.7% versus −16.8%). In contrast, for the Paris and Marseille metropolitan areas, the reduction is greater among the most deprived census blocks. This may reflect a change in traffic density away from the more deprived areas to those more favored, though further studies are needed to fully understand these patterns. The evolutions are similar between the two periods in the deprivation categories in the Lille metropolitan area (−9.3%, −9.5% and −10.3%).

3.3. Socioeconomic characteristics of environmental inequalities

Table 3-AB presents the regression coefficients from GAM models for simple and multivariate associations between the socioeconomic variables and average NO_2 concentrations adjusting for spatial autocorrelation for two time periods, in the Lyon, Lille, Paris and Marseille metropolitan areas. The results demonstrate a negative relationship between the proportion of white collar, the median income and the average concentrations of NO_2 for the Lyon and Marseille metropolitan areas. In other words, favored neighborhoods with high proportion of white collar and high median income were associated with lower exposures to air pollution. The results confirm that in the Marseille metropolitan area favored neighborhoods are located far from the major city (Marseille and Aix en Provence) and in Lyon, the favored neighborhoods are located in the west side of the metropolitan area where the pollution concentrations are low. Conversely, in Lille and Paris metropolitan areas, we found a positive relationship between the proportion of immigrants and the average concentrations of NO_2. In Lille metropolitan area, large portions of immigrants are located in the city of Lille, Roubaix and Villeneuve d'Ascq where the air pollution is highest. For the Paris metropolitan area, immigrants are, in large part, located in the Seine Saint Denis department in the North of the metropolitan where the pollution is higher in the first period. These associations were all in the expected direction and support that environmental inequities in the distribution of environmental burden exist in France.

Between the models of the two periods, the regression coefficients for the socioeconomic variables do change in direction, or significance. Three different findings are observed according to the metropolitan area and the time period. The first case is that of socioeconomic variables which are significantly associated with NO2 concentrations during the first period do not remain so during the second one: the proportion of immigrants in the Marseille and Paris metropolitan areas respectively, or the proportion of non-homeownership in the Lyon metropolitan area. The second is the reverse situation, where associations present in the second period had not been found in the first one: the proportion of insecure jobs in Marseille and Lille. Finally, in the Paris metropolitan area, the proportion of non-homeownership and the median incomes were significantly associated with NO_2 concentrations in both periods.

4. Discussion

Our study shows social inequalities at the census block level in the four largest French metropolitan areas, with respect to air pollution exposure at the place of residence. This is a recent research topic in Europe, but still limited in France (Laurian, 2009, 2008; Havard et al., 2009; Deguen and Zmirou-Navier, 2010; Laurian and Funderburg, 2013). We found an uneven distribution of NO_2 concentrations between census blocks where different social groups live. Our study also reveals differences in the strength and direction of the association between deprivation (using the deprivation index or the socioeconomic variables) and the evolution of NO_2 concentrations between two time periods, and changes in the socioeconomic markers of environmental inequalities between the two periods.

Our results in Paris reveal that the most socioeconomically advantaged census blocks experience higher levels of NO_2. A study in Rome, Italy (Forastiere et al., 2007) has also described this situation. Air pollution is no longer dominated by industrial emissions but by movement of goods, commuter transportation and associated traffic tail pipe emissions. Industrial activities have moved to outer areas of the capital region, to other French regions and, predominantly, to other countries in Eastern Europe or emerging and developing countries. The city of Paris now hosts professionals, mainly in the tertiary sector (management and administration, bank, insurance, culture and academia), representing 42% of the resident population (Le Floch, 2013). Although the city of Paris has a very dense public transport network, it hosts 726 000 cars, not counting those passing through and duty vehicles, and more than 2 million inhabitants in a very limited surface area of 105 km^2.

Our results for the **Lyon** metropolitan area support previous observations from the area of Strasbourg (North-East France) where the relationship between the deprivation index and air pollution was shown to be non-linear, with the midlevel deprivation areas being the most exposed to traffic-related air pollution (Havard et al., 2009). Due to its valleys in the west side of the Saône and Rhône rivers, historically, the dense housing sectors have developed in the more deprived Eastern part of the metropolitan area where the housing market is less expensive. While the close East and South suburbs host the most deprived neighborhoods, intermediate social categories reside in the city districts where the traffic is dense and NO_2 concentrations is higher. The favored population mostly dwells in the valleys of the West side of the Saone and Rhône rivers, which are less polluted areas, with large green spaces and rather easy access to the city center. Lyon is an attractive metropolitan area with major industries in pharmacy, mechanics and automotive, textile and more recently the environment sector (Fabriès-Verfaillie et al., 2000).

Our findings in the **Lille** and **Marseille** metropolitan areas show higher NO_2 concentrations in deprived sectors. Crouse et al. (2009), in Montreal, found specific neighborhoods that were characterized by a double burden of higher level of deprivation and high concentrations of NO_2. Yanosky et al (2008), in Massachusetts, found that, after controlling for spatial autocorrelation, deprived areas were significantly associated with traffic related air pollutants, including nitrogen dioxide. In both Rijnmond (The Netherlands), according to Kruize et al. (2007) and in Leeds (UK), according to Mitchell and Dorling et al. (2003) and Namdeo et al. (2008), lower income groups live in places with higher levels of NO_2 compared to higher income groups. The Lille metropolitan area also has a strong industrial history, based on coal, steel and textile. People live in the major cities close to their workplace. Since the postwar period, the region has faced serious infrastructural problems and an acute economic and social crisis, with only the textile industries remaining active. Presently, Lille is heading towards a tertiary future, taking advantage of its position close to the Benelux and the UK (Fabriès-Verfaillie et al., 2000). The port of Marseille is the largest in France and in the Mediterranean area and steel and petrochemical industries are present, with a relatively large proportion of blue collars and poor employees in the workforce.

Despite a general reduction in NO_2 concentrations over the study period in the four metropolitan areas, we found contrasting results in the temporal trend of environmental inequalities. In the Lille and Lyon metropolitan areas, the reduction over the two periods is somehow weaker in the most disadvantaged census blocks compared to the most favored one. Major deprived neighborhoods located in the cities of Villeurbanne, Vaux en Velin and Bron, in the Lyon metropolitan area, show a persistence of poorer air quality between the two periods; the main reason relates to the traffic increase in the East, where important highways circle the metropolitan area. To a lesser extent, similar results are found in the Lille metropolitan area, in particular, in the deprived neighborhoods in the cities of Lille, Loos and Mons-en-Baroeul. By contrast, in Paris and Marseille, the air quality improvement was more beneficial to the deprived census blocks; nevertheless, the difference in air quality between deprived and more well off areas in Marseille remains large. These finding are consistent with results from Tonne et al in 2008 who showed in London a greater reduction in air pollution in deprived areas than in the most affluent ones after the introduction of the Congestion Charging Zone (Tonne et al., 2008). Comparing the trend of NO_2 levels between 1993 and 2005 in Leeds, Mitchell et al. demonstrated that the average difference between deprived and affluent communities declined from 10.6 mg/m^3 in 1993 to 3.7 mg/m^3 in 2005. City-wide improvements in air quality were driven by transport strategies with the usage of newer vehicles and road user charging (Mitchell, 2005).

Many hypotheses have been proposed in the literature to explain environmental inequalities based on the socioeconomic status. In the Unites States and Canada, this phenomenon is attributed mainly to racial and ethnic segregation, employment status, housing market dynamics, and income (Jerrett et al., 2001; Morello-Frosch and Shenassa, 2006). In Europe, socioeconomic disparities, notably those related to social and racial segregation, are less marked than in the United States. Yet, social and economic resources (income, material living conditions, housing) explain some part of the environmental inequalities (Brainard et al., 2002; Havard et al., 2009; Mitchell, 2005) but factors related to the local urban design also play a role.

The housing market impacts the choices people make in terms of the tradeoffs between proximity to amenities and local positive and negative aspects of the environment. In Lille and Marseille, the cost of purchasing housing in deprived areas (corresponding to more polluted areas) ranges on average between 1935 and 1325 euros/m^2, and between 2479 and 2172 euros/m^2 in the favored areas (corresponding to less polluted areas), respectively (source: chamber of notary, personal communication). The metropolitan area of Lyon shows a gradient, with higher housing costs in the West side than in the East side. In the city of Paris - except for districts 18 and 19 (which are poorer and experience high air pollution close to the high traffic-dense circular highway) – favored and well educated populations make the individual choice to live in expensive and polluted areas because they are closer to other benefits/amenities, such as living close to where they work and being able to walk to restaurants and shopping. Figure 4 presents the spatial distribution of the housing market in euros per m^2 in the (A) Paris and (B) Lyon metropolitan areas.

The interpretation of our findings must also consider some weaknesses, notably in the exposure assessment. First, our study has a higher proportion of census blocks (72/628: 11.4%) without estimation of annual ambient air concentrations of NO_2 in Marseille Metropolitan area. These municipalities do not belong to the administrative jurisdiction of the local monitoring network. The proportions of the socioeconomic variables are similar between the municipalities included and those excluded.

This study has several strengths. The study of environmental inequalities requires methodological and analytical choices to be robust (Laurian, 2009). According to Jerrett (2004), NO_2 modeling provides a powerful method to estimate pollutant concentrations over a fine spatial scale. It gives acceptable results and shows high correlations between the model’s predictions and the measured NO_2 values obtained from the monitoring stations. The same methodology was used to assess intra urban exposure in each metropolitan area and to compare the environmental inequalities between them. In order to minimize the ecological biases and take into account the dependency of spatial units we used validated models. Bowen et al (2002) reviewed the empirical research on environmental justice and concluded that published studies fail to consider important methodological issues about choice of geographic units, analytical methods and exposure estimates and taking into account spatial autocorrelation among observations. Lastly, the heterogeneity of the methods used may in part explain discrepancies in the results.

The strength of the associations between air quality and social characteristics from our results are weak irrespective of the metropolitan area. This could be due to the consideration of spatial autocorrelation in models which reduces the strength of the association (Yanosky et al., 2008; Havard et al., 2009). In a study in Switzerland, Diekmann and Meyer (2010) also found a weak association and explained that environmental injustice may be less accentuated in Switzerland than in countries with a higher degree of socioeconomic segregation like in the United States. Differences in the size of the areas considered in the studies may also influence the strength of the association. Stroh et al. (2005) and Briggs et al. (2008) concluded that small area associations between socioeconomic status and environmental pollution become stronger with an increased level of spatial aggregation.

5. Conclusion

Despite a general reduction in ambient air NO_2 concentrations over the study period in the four French metropolitan areas, we found contrasting results in the temporal trend of environmental inequalities. There is clear evidence of city-specific spatial and temporal environmental inequalities that relate to the historical socioeconomic make-up of the cities and its evolution. Hence, general statements about environmental and social inequalities may be inappropriate. Traffic related air pollution is an important contributor to environmental inequalities and to associated risks. This work calls for further examination of the role of socioeconomic characteristics in air pollution epidemiology and risk assessment. Such evidence may inform local or country-wide policies that would aim to cope with environmental health inequalities.

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	Number of Census Blocks	Number of municipalities	Population in 2008 (inhabitants)
Lille	504	85	1.193.244
Paris	2749	412	10.354.675
Lyon	511	58	1.281.971
Marseille	628	52	1.715.096

Figure 1.
Location of the four metropolitan areas in France.

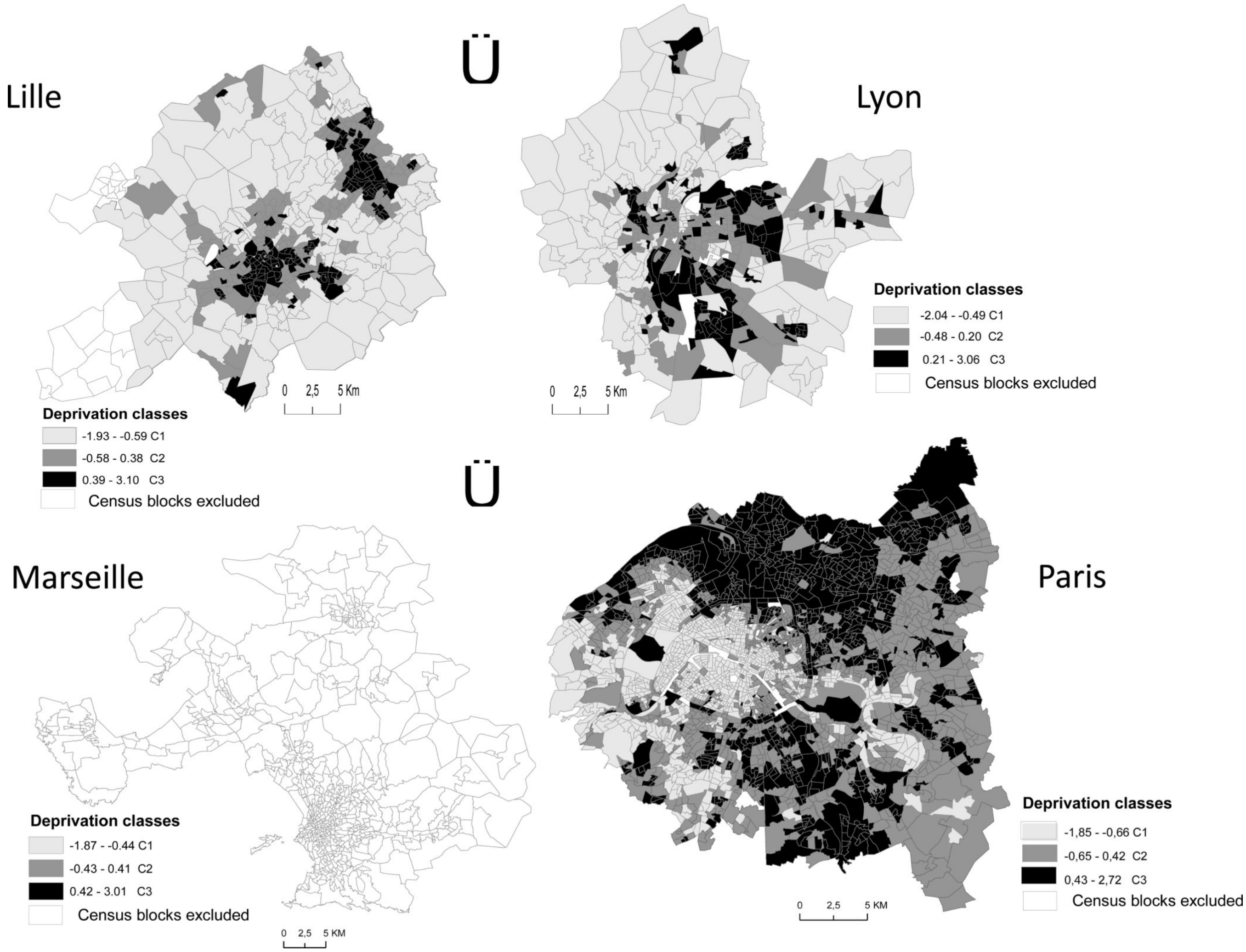

Figure 2.

Spatial distribution of the deprivation index of 2006 in tertiles: Lille, Lyon, Marseille and Paris Metropolitan areas.

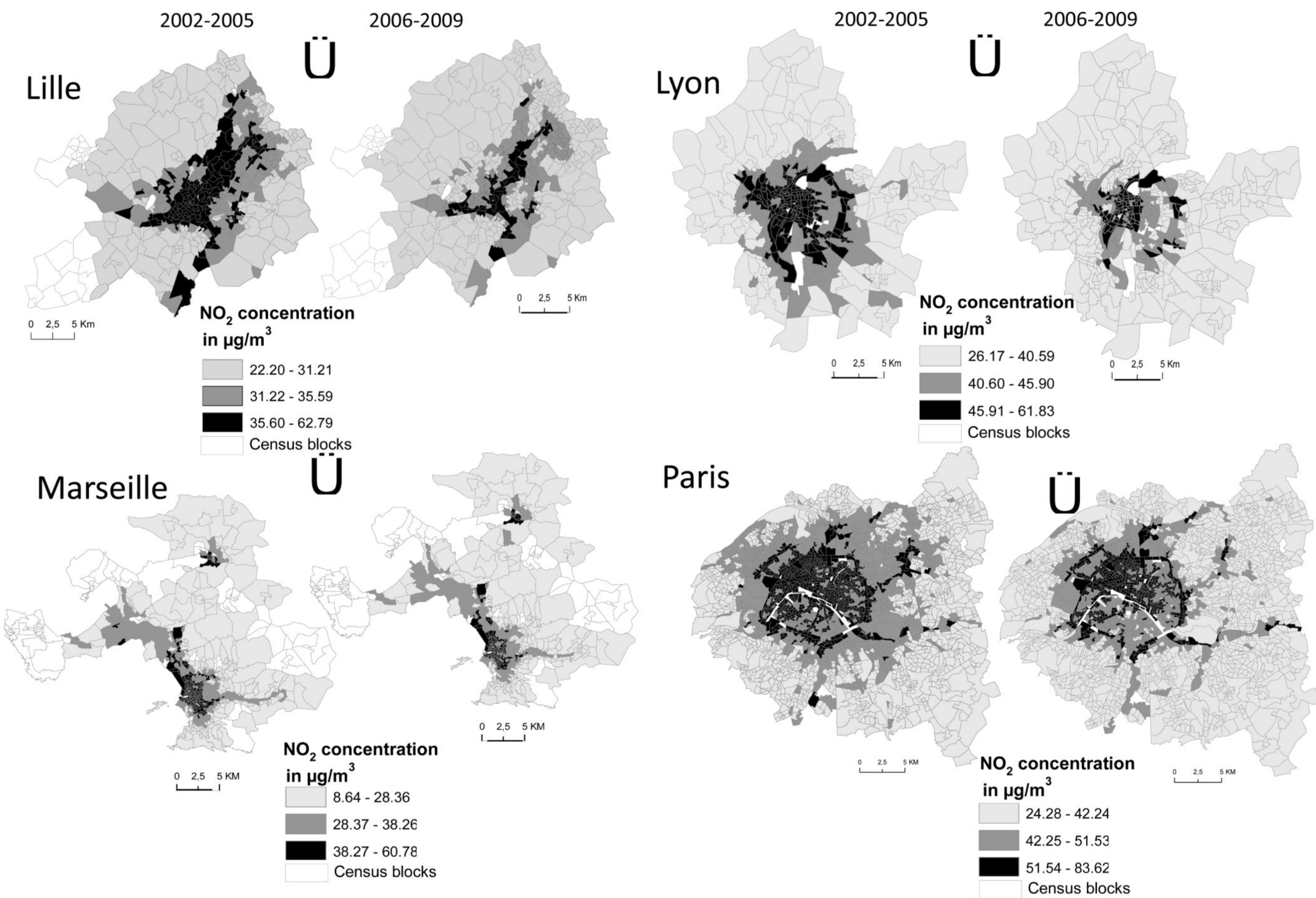

Figure 3.
Maps of the spatial distribution of the average of NO_2 concentrations in $\mu g/m^3$ in tertiles for 2002 – 2005 and 2006 – 2009 for Lille, Lyon, Marseille, Paris Metropolitan areas.

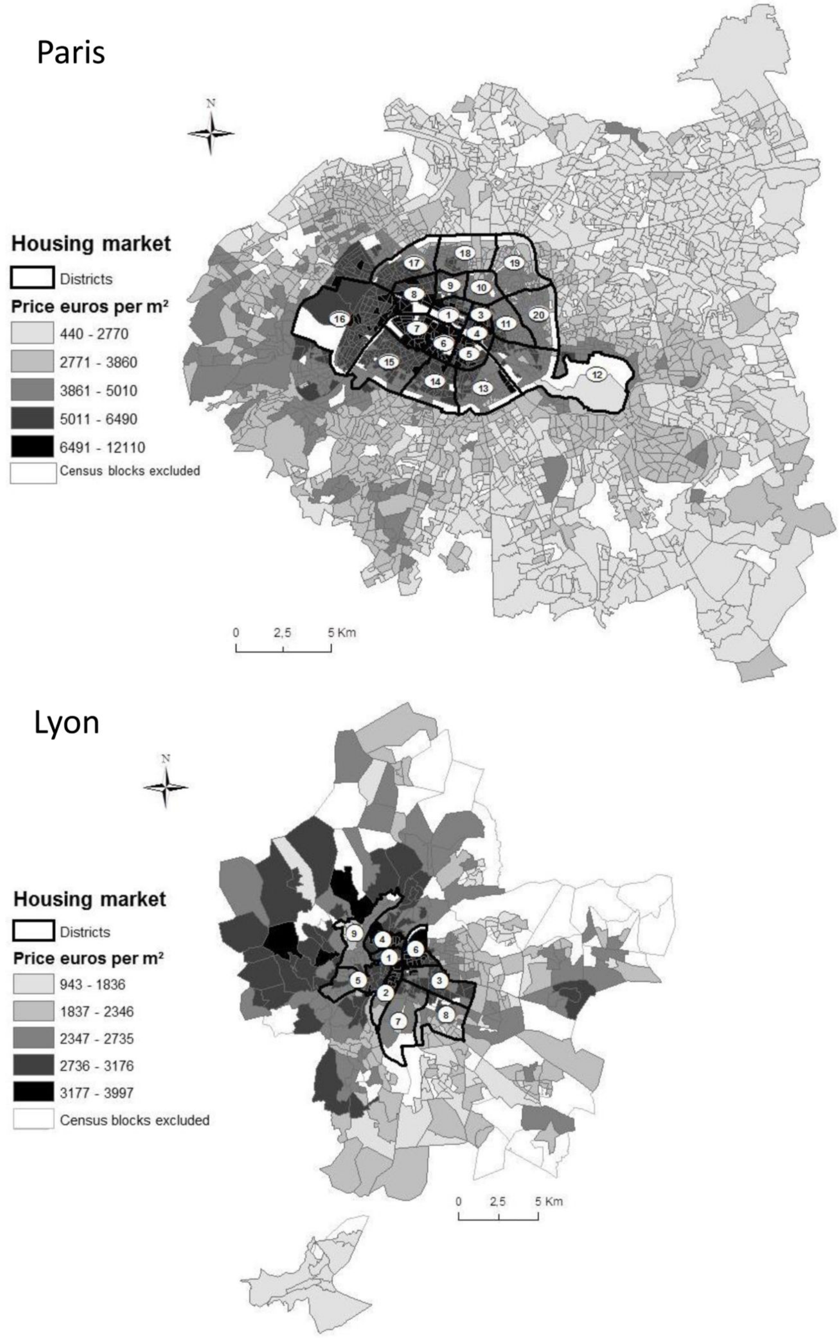

Figure 4.
Spatial distribution of the housing market in euros per m^2 in the Paris and Lyon metropolitan areas.

Table 1

Descriptive statistics of the distribution of the socioeconomic variables and NO_2 concentrations according to periods and MAs, Mean and standard deviation for all MA

	LILLE (504 census blocks)			LYON (511 census blocks)			MARSEILLE (628 census blocks)			PARIS (2749 census blocks)		
	2002–2005	2006–2009	p†	2002–2005	2006–2009	p	2002–2005	2006–2009	p	2002–2005	2006–2009	p
NO_2 concentrations (μg/m3)	33.7±6.04	30.5±4.6	***	43.6±5.4	38.6±6.3	***	33.0±10.2	31.9±9.8	0.27	47.4±9.3	44.2±9.9	***
% unemployment	16,2±9,6	14,7± 9,1	***	12,7±6,6	11,6±6,4	***	21.6±11.7	16.2±9.8	***	12.7±5.8	11.9±5.5	***
% single parent	15,3± 7.1	10,8± 5,5	***	14,2±6	9,2±4,5	***	18.7±8.4	12.1±5.8	***	16.2±6	9.9±5	***
% insecure job	12.1±4,2	27.2±7,6	***	11,6±3,6	27,4±7,9	***	10.6±3.2	25.2±6.9	***	10.7±3.2	22.7±5.5	***
% white collar	13.2±11.1	11,4± 8,4	**	15.4 ±10.7	14±9	**	12.6±10.6	10.6±7.4	***	22.7±14.8	21.8±13.3	***
% highereducation	8.1±3.5	9.9± 3.7	**	9.3±3.6	11± 3.9	**	7.8± 3.5	9.5±4.3	**	9.4± 2.9	10± 3.4	*
% non-owner	48,7±25,9	47,9±26,4	*	56,4±21,8	53,7±22,8	***	53.3±22.2	52.7±23.8	0.90	64±20.5	61±22	***
% subsidized house	21,5±26,8	23.4±24.5	***	24,4±29,8	21,2± 25	***	19.3±28.1	17.5±25.3	*	29.2±32.5	24.8±28.3	***
% immigrants	4,8±4.5	8.2 ±6,3	***	7,7±6,6	13,3± 8,9	***	5.4±5.7	11.0±8.7	***	12.3±6.8	20.3±9.1	***
Medianincome (euro)	21952±7130	16339±5411	***	23751±6558	18691±5194	***	21534±7383	16302±5672	***	27636±7823	21638±8343	***

† p values for Student Paired test between periodsfor each MA.

p<0.05,

** p<0.01,

*** p<0.001

Table 2

A: Average NO_2 concentrations (μg/m^3) in groups of contrasted socioeconomic categories of the deprivation index in the 4 metropolitan areas, France, 2002 to 2009.

Metropolitan areas	Number of census blocks by groups	NO_2concentrations more than the percentile 80†	NO_2 concentrations between percentile 80 and 60	NO_2 concentrations between percentile 60 and 40	NO_2 concentrations between percentile 40 and 20	NO_2 concentrations less than the percentile 20‡
Lille	96/476	34.6±5.4	33.4±4.3	32.3±4.5	31.6±5.5	28.7±4.8
Lyon	98/492	40.2±6.0	44±4.5	43.8±5.1	41.7±6	36.5±5.1
Marseille	109/545	37.4±8.7	36.9±9.5	36.1±8.8	29.7±6.5	22.3 ±6.7
Paris	532/2692	42.1±7.9	44.1±8.7	44±9.1	48.3±10.3	50.5±8.9

B: Evolution of average NO_2 concentrations (μg/m^3) across the low, middle and high categories of the deprivation index between two periods in the 4 metropolitan areas, France

Metropolitan areas	NO_2 concentrations in percentile 80 areas at		NO_2 concentrations between percentile 60 and 40		NO_2 concentrations in percentile 20 areas at		Evolution(%)** percentile 80	Evolution (%) percentile 60–40	Evolution (%) percentile 20
	P1*	P2*	P1*	P2*	P1*	P2*			
Lille	36.3±6.3	32.9±4.7	33.7±5.4	30.5±3.9	30.8±5.8	27.6±4.3	−9.3%	−9.5%	−10.3%
Lyon	43.4±4.9	37.5±5.5	46.4±5.3	41.1±5.6	40.1±4.9	33.4±5.1	−13.7%	−11.4%	−16.8%
Marseille	39.8±8.3	36.7±8.6	37.2±9.2	36.5±9.3	22.5±6.6	22.1±6.6	−7.5%	−1.8%	−1.8%
Paris	44.4±8.4	40.6±8.1	47.4±9.6	42.8±9.4	50.8±9.4	49.1±9.6	−8.6%	−9.7%	−3.3%

† (percentile 80): The most deprived census blocks, corresponding to the 80th percentile of the deprivation index distribution

‡ (percentile 20): The less deprived census blocks, corresponding to 20th percentile of the deprivation index distribution

* P1: first period 2002–2005, P2: second period 2006–2009

** ((NO_2 concentrations at P2 – NO_2 concentrations at P1)/ NO_2 concentrations of P1) *100. Example: −9.3% = ((32.9–36.3)/36.3)*100

Table 3

Regression coefficients from GAM models for simple and multivariate associations between the socioeconomic variables and average NO_2 concentrations adjusting for spatial autocorrelation for two periods A) 2002–2005 period, B) 2006–2009 period in Lyon, Lille, Marseille and Paris metropolitan areas. For an increase of 1 unit of the socioeconomic variable or for an increase of 1000 euros of median income

A) 2002–2005 period	**Models Lyon N=492**		**Models Lille N=476**		**Models Marseille N=545**		**Models Paris N=2692**	
	[a]Simple (μg/m^3)	**[b]Multivariate (μg/m^3)**	**[a]Simple (μg/m^3)**	**[b]Multivariate (μg/m^3)**	**[a]Simple (μg/m^3)**	**[b]Multivariate (μg/m^3)**	**[a]Simple (μg/m^3)**	**[b]Multivariate (μg/m^3)**
% immigrants	0.22	--	0.15*	0.141*	−0.002	−0.069*	0.023	0.045*
% single parent	0.023	--	0.070	−0.007	0.029	--	0.031*	--
% insecure job	0.034	--	0.018	−0.087	0.119	--	0.066*	--
% unemployment	0.007	--	0.072*	0.010	0.027	--	−0.009	−0.093*
% white collar jobs	−0.024*	−0.026*	−0.020	−0.004	−0.063*	−0.056*	−0.016*	--
% higher education	−0.058	--	−0.032	0.081	−0.135	--	−0.077	--
% subsidized housing	−0.004	−0.022*	0.021*	0.012	0.002	−0.009	0.003	--
% non-homeownership	0.008*	0.028*	0.020	0.007	0.009	--	0.011*	0.012*
median Income (euro)	−0.003*	--	−0.056	−0.005	−0.123*	−0.130*	−0.039*	−0.039*

B) 2006–2009 period	**Models Lyon N=492**		**Models Lille N=476**		**Models Marseille N=545**		**Models Paris N=2692**	
	[a]Simple (μg/m^3)	**[b]Multivariate (μg/m^3)**	**[a]Simple (μg/m^3)**	**[b]Multivariate (μg/m^3)**	**[a]Simple (μg/m^3)**	**[b]Multivariate (μg/m^3)**	**[a]Simple (μg/m^3)**	**[b]Multivariate (μg/m^3)**
% immigrants	0.002	--	0.10*	0.116*	0.012	--	0.034*	--
% single parent	−0.036	−0.080*	0.029	--	−0.035	−0.094*	−0.005	−0.093*
% insecure job	0.016	--	−0.036	−0.049*	−0.042*	−0.061*	−0.007	--
% unemployment	0.011	--	0.038	--	−0.005	−0.051	0.037	--
% white collar jobs	−0.021	--	0.0007	--	−0.104*	−0.090*	−0.023*	--
% higher education	0.004	--	−0.048	--	−0.083	--	0.071	--
% subsidized housing	−0.001	--	0.014	--	0.003	--	0.005	--
% non-homeownership	0.009*	--	0.014	--	0.007	--	0.012*	0.013*
median Income (euro)	−0.006*	−0.010*	−0.07	--	−0.125	−0.236*	−0.065*	−0.076*

[a] Coefficient denotes the simple regression coefficients adjusting for location,

[b] denotes the multivariate regression coefficient adjusting for location

* Anova test is significant $p<0.05$