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**Air Pollution and Urban
Structure Linkages:
Evidence from European
Cities**

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AIR POLLUTION AND URBAN STRUCTURE LINKAGES: EVIDENCE FROM EUROPEAN CITIES - ENVIRONMENT WORKING PAPER No. 96

By Miguel Cárdenas Rodríguez (1), Laura Dupont-Courtade (1) and Walid Oueslati (1)

(1) OECD, Environment Directorate

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ABSTRACT/ RÉSUMÉ

This paper investigates the relationship between local air pollution and urban structure with an emphasis on urban fragmentation. Using a unique dataset of 249 Large Urban Zones (LUZ) across Europe, a Bayesian Model Averaging selection method is employed to empirically identify the determinants of within-LUZ concentration of three air pollutants: NO₂, PM₁₀ and SO₂ for the year 2006. Several indices of land use are considered among possible determinants. These are supplemented by a dataset on various economic, demographic and meteorological variables that can explain the variation of air pollution. The results of this econometric analysis support the hypothesis that urban structure has significant effects on pollution concentration. In particular, they suggest that fragmented urban areas experience higher concentrations of NO₂ and PM₁₀ and that densely populated urban areas suffer from higher SO₂ concentration. The findings suggest that policies favouring continuous urban areas may result in environmental improvements.

JEL Classification: Q52, Q58, R52

Keywords: urban sprawl, air pollution, fragmentation, artificial area, spatial planning, Bayesian Model Averaging

Ce rapport s'intéresse à la relation entre la pollution atmosphérique locale et la structure des villes en s'attachant plus particulièrement à la fragmentation urbaine. On applique une méthode d'analyse bayésienne des modèles pour identifier, à partir d'un ensemble de données unique couvrant 249 zones urbaines élargies (LUZ) d'Europe, les facteurs qui déterminent les concentrations de trois polluants atmosphériques (NO₂, PM₁₀ et SO₂) dans ces zones, pour l'année 2006. Plusieurs indices d'occupation des sols figurent parmi les possibles déterminants. Ils sont complétés par un ensemble de données sur différentes variables économiques, démographiques et météorologiques qui pourraient expliquer les variations de la pollution atmosphérique. Les résultats de cette analyse économétrique confirment l'hypothèse selon laquelle la structure du tissu urbain a des effets importants sur les concentrations de polluants. En particulier, les résultats indiquent des concentrations plus élevées de NO₂ et de PM₁₀ dans les espaces urbains fragmentés et des concentrations plus élevées de SO₂ dans les zones urbaines densément peuplées. Ces résultats donnent à penser que la mise en œuvre de politiques favorisant la continuité de l'espace urbain pourrait être bénéfique pour l'environnement.

Classification JEL: Q52, Q58, R52

Mots-clés: étalement urbain, pollution atmosphérique, fragmentation urbaine, territoire artificialisé, aménagement de l'espace, méthode d'analyse bayésienne des modèles

FOREWORD

The paper has been authored by Miguel Cárdenas Rodríguez, Laura Dupont-Courtade and Walid Oueslati (OECD Environment Directorate). The authors are grateful to delegates to the Working Party on Integrating Environmental and Economic Policies for helpful comments on earlier drafts of this paper. They would also like to thank Alexandros Dimitropoulos, Daniel Sanchez-Serra and Monica Brezzi for comments on previous versions of the paper and Natasha Cline-Thomas for editorial assistance. The authors are responsible for any remaining omissions or errors. Work on this paper was conducted under the overall responsibility of Shardul Agrawala, Head of the Environment and Economy Integration Division.

ACRONYMS AND ABBREVIATIONS

BMA	Bayesian Model Averaging
CLC	CORINE Land Cover
EKC	Environmental Kuznets Curve
GIS	Geographic Information Systems
LUZ	Large Urban Zone
NO₂	Nitrogen Dioxide
PM₁₀	Particulate Matter with a diameter greater than 10 micrometers
SO₂	Sulphur Dioxide
UMZ	Urban Morphological Zone
WHO	World Health Organization

GLOSSARY

Artificial area	Following the definition of Corine Land Cover (CLC), artificial areas include: (1) urban fabric, (2) industrial, commercial and transport units, (3) mine, dump and construction sites, and (4) artificial non-agricultural vegetated areas (green urban areas and sport/leisure facilities).
Agricultural area	Following the definition of CLC, agricultural areas include: (1) arable land, (2) permanent crops, (3) pastures, and (4) heterogeneous agricultural areas (OECD, 2012).
Compact urban area	Urban area characterised by: (1) dense and proximate development pattern, (2) urban area linked by public transport; (3) accessibility to local service and jobs (OECD, 2012).
Continuous urban area	Urban area characterised by a continuous urban tissue development.
Core city	Urban area delimited by its administrative boundary.
Fragments	Isolated urban patches.
Large Urban Zone	Defined by the Urban Audit (a Eurostat project) as the core city plus the surrounding municipalities in which at least 10% of inhabitants work in the city. This threshold ranges between 10% and 20% according to regional and national characteristics.
Urban sprawl	Uncontrolled expansion of urban development characterised by low density, segregated land use and insufficient infrastructure provision. Urban sprawl can take the form of leapfrog development whereby development leaps over undeveloped land (OECD, 2012).
Urban Morphological Zones	Urban tissue classes defined by CLC (continuous urban, fabric, discontinuous urban fabric, industrial or commercial units and green urban areas).
Wetland	Defined by CLC as inland and coastal wetlands.

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EXECUTIVE SUMMARY

Local air pollution has adverse effects on humans, ecosystem services and the economy. In particular, concerns for its impact on public health are highlighted as a key issue for urban areas (OECD, 2014). Pollution concentration is affected by the structure of urban areas, in particular by their size, shape and composition. Urban patterns are driven by location (of residence and workplace), mobility and consumption choices made by individuals. A good understanding of the determinants of pollution at the urban scale is therefore essential.

This study investigates the impact of urban morphology on air pollution concentration. A unique dataset of 249 European large urban areas is exploited to analyse the impact of various urban form components on the concentration of three pollutants: Nitrogen Dioxide (NO₂), Particulate Matter (PM₁₀) and Sulphur Dioxide (SO₂). Linear regression models are used to identify the relationship between urban fragmentation and air pollutant concentrations. The models control for the effects of other factors influencing pollution, such as the size of local economy, industrial and agricultural activity, local climate conditions, as well as other land cover indicators. The relationship between population density and the concentration of specific air pollutants is also analysed.

Air pollution is generated by different types of economic activities. PM₁₀ is mainly emitted by road transportation, household heating and industrial processes, NO₂ emissions are largely attributed to road transportation, whereas SO₂ is mainly produced by electricity generation processes.¹ Due to these differences in emission sources, urban areas do not face the same patterns of concentration of different air pollutants.

As pollutants emanate from different sources, different empirical specifications may be required to analyse the impact of urban structure on the concentration of each pollutant. The choice of the appropriate empirical specifications is hereby guided by a state-of-the-art econometric model selection method (Bayesian Model Averaging – BMA). Specifically, a core model linking the level of pollution concentration and urban area fragmentation is first specified on the basis of insights from relevant literature. The explanatory potential of different control variables is then tested, to arrive at the subset of explanatory variables maximising the predictive power of the model. BMA supports the hypothesis that different models need to be used to analyse the concentrations of different pollutants.

The results suggest that urban fragmentation is associated with higher PM₁₀ and NO₂ concentrations, i.e. pollutants driven by road transportation, among other activities. Empirical results further indicate that population density is positively related to the concentration of SO₂. In contrast to PM₁₀ and NO₂, the majority of SO₂ emissions in Europe originate from fuel combustion in power stations and domestic heating systems. Therefore, denser urban areas may produce higher residential SO₂ emissions and, therefore, concentrations. Finally, the results suggest that high-income urban areas experience lower concentrations of PM₁₀ and SO₂. This may result from tighter environmental regulations or higher public expenditure to improve air quality in high income areas.

These findings reveal that concerns about increased levels of NO₂ and PM₁₀ concentration stemming from further expansion of urban areas in Europe, could be partially addressed by spatial policies aimed at

¹ It is important to note, however, that the share of different economic activities and combustion processes in PM₁₀, NO₂ and SO₂ emissions may vary substantially across countries, depending on the level of activity and emission intensity of specific industries and the fuel mix used for electricity and heat generation and road transportation.

the reduction of urban fragmentation. Continuous urban areas enhance connectivity, reduce travel needs and car dependency, and facilitate the use of non-motorised transport modes, such as biking and walking. In addition to environmental improvements, continuous urban areas may induce energy savings, reduce maintenance costs for energy and transport systems, improve the quality of life through local services and jobs and allow efficient infrastructure investments (OECD, 2012).

In addition to the reduction of urban fragmentation, spatial policies leading to decreases in population density could partially alleviate concerns about the impact of urban expansion on SO₂ emissions. Overall, the findings of the study suggest that instruments aiming at increasing continuity and reducing population density are worth considering in the policy mix used to avoid further air quality degradation by the expansion of urban areas in Europe. Such instruments can complement other policies used for the reduction of urban air pollution, such as vehicle emission standards.

This exploratory analysis is a first step towards more comprehensive studies of the effects of urban development on the environment in OECD countries. It would be interesting to extend the analysis beyond Europe and test whether the identified relationships also hold in other settings. In addition, a greater coverage of urban areas would provide more variation and stronger evidence on the impact of urban form and socio-economic variables on air quality and could allow for the study of non-linear effects of air quality determinants. Likewise, data over several years might spur causal inferences. For further research, it would be of interest to analyse the extent to which land-use policies shape urban areas, affect environmental quality and determine human exposure to pollution.

1. INTRODUCTION

Adverse effects of air pollution have been extensively documented. Annually, approximately 3.7 million people die prematurely due to outdoor air pollution worldwide (WHO, 2014). Moreover, air pollution contributes to respiratory, cardiovascular diseases and lung cancer. This incidence generates considerable economic impacts, manifested through increases in medical costs and the number of deaths and a reduction of productivity through lost working days. Moreover, air pollution not only harms people, materials and buildings, but has a clear environmental impact as well. Nitrogen oxides, sulphur dioxide and ammonia contribute to the acidification of soil, lakes and rivers, causing losses of animal and plant life and crop yields. Therefore, understanding the factors influencing pollution concentration is essential.

Air pollution is released from various processes (e.g. industrial production and road transportation) which are driven by different socio-economic phenomena such as consumption decisions, transportation mode choices, and housing and workplace location choices. In this context, the structure of urban areas can have a strong influence on pollution emissions; this is particularly evident for transport-related pollutants. For instance, fragmented development may translate into car-dependent urban areas, and thus, worsen air quality. Better knowledge of the relationship between urban structure characteristics and air pollution may help to improve air quality through better spatial planning and transport policies (Brezzi and Sanchez-Serra, 2014).

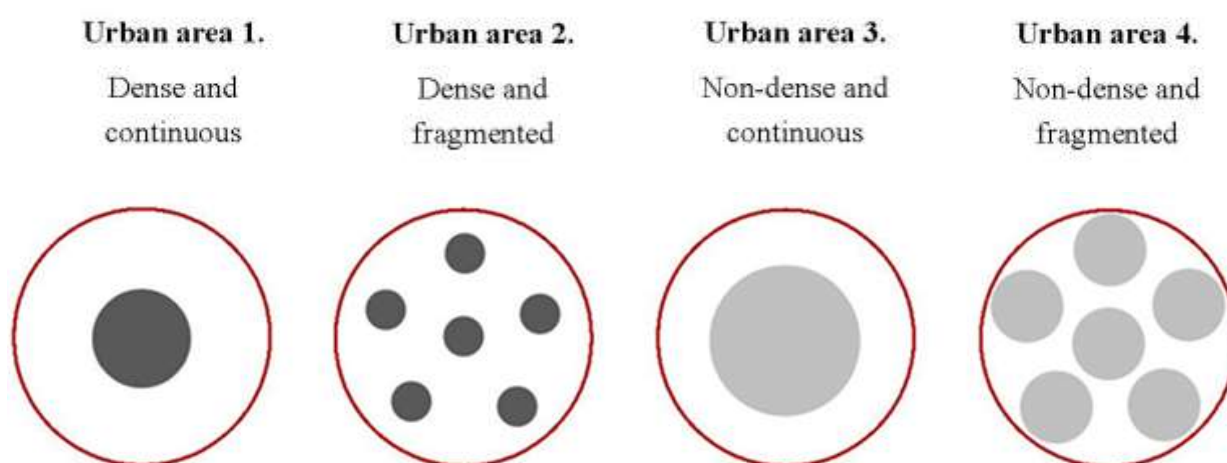
The effects of pollution have been extensively studied in various disciplines. Particular emphasis has been placed on the study of the harmful effects of pollution on health. On the other hand, the analysis of determinants of pollution concentration is gaining recognition. In economics, most of the pollution-related studies focus on the effects of transport and transport regulation policies on the environment. As an example, Davis (2008) empirically studies the effect of a driving restrictions program on air quality in Mexico City.

A growing number of studies provide evidence for the impact of urban structure on the environment and highlight the role of land use policies for achieving more environmentally friendly urban areas. In the urban economics literature, the impact of urbanisation on air quality has been studied through different urban structure indicators. One can distinguish between two categories of such indicators: (i) indicators related to the internal composition of the urban area and (ii) urban area morphology indicators.² Urban area morphology refers to the spatial disposition of the urban tissue (e.g. dispersed urban plots, linearity of urban areas) while internal composition refers to tissue composition (e.g. wetland, green spaces). Various urban structure indicators are analysed in the literature such as artificial areas (Bart, 2010), connectivity, density, scattering, availability of open space, land-use mix, agricultural land (Arribas-Bel, Nijkamp and Scholten, 2011), centeredness (Stone, 2008), decentralisation (Tolley and Cohen, 1975) and fragmentation (Burchfield et al., 2006). More generally, many studies look into the role of city compactness on air pollution (Cho and Choi, 2014; Manins et al., 1998; Martins et al., 2012; Neuman, 2005).

Recent literature on urban area shape and its impacts on the environment discusses the concept of compact urban areas. As defined by the OECD, a compact urban area pattern encompasses the following features: (i) dense and proximate development patterns, (ii) urban area linked by public transport; and (iii) accessibility to local services and jobs (OECD, 2012a). Figure 1 illustrates different patterns of urban areas. The ongoing debate on the environmental benefits of compact urban areas partly originates from the fact that the notion of compactness covers various dimensions. Findings and conclusions may well vary with the studied urban structure indicator, air pollutant, and measure of pollution (i.e. concentration or emission levels).

² Arribas-Bel, Nijkamp and Scholten (2011) introduced a categorisation of urban sprawl components relying on: (i) urban morphology (e.g. scattering), and (ii) internal composition (e.g. density).

Figure 1. Density and Fragmentation - Four city patterns



Note: Urban areas with different population densities (the darker, the denser) and different levels of fragmentation.

Concerning fragmentation, non-fragmented urban areas (e.g. *Urban area 1* and *Urban area 3*, Figure 1) enhance connectivity, reduce mobility needs and car dependency, and facilitate the use of non-motorised transport modes, such as biking and walking. In addition to environmental improvements, continuous urban areas may induce benefits such as energy savings, lower costs of maintenance for energy and transport systems, improvement of quality of life through local services and jobs, and more efficient infrastructure investments (OECD, 2012a). In this respect, a compact urban area, given its proximate development, is expected to produce lower emissions of transport-related pollutants compared to a fragmented urban area (e.g. *Urban area 2* and *Urban area 4*).

In turn, dense development, in terms of population and buildings (e.g. *Urban area 1* and *Urban area 2*), may have various effects on air quality. On the one hand, dense urban areas may reduce travel needs, stimulate more efficient infrastructure and better public transport systems and, thus, lead to a decrease in overall emissions per capita (Newman and Jeffrey, 2006). They also require less land and consequently have less adverse effects on biodiversity compared to more extensive development. On the other hand, dense urban areas expose a higher proportion of the population to pollution. In addition, air emissions can be more easily trapped by dense urban construction and thereby lead to higher pollution concentrations (Gaigné et al., 2012).

Concerns about air pollution and urban sprawl raise questions about the possible trade-off between economic development and the harmful impacts of pollution. The environmental Kuznets' curve (EKC), which gained recognition during the 1990s, is at the heart of this debate. Selden and Song (1994) were the first to study the environmental Kuznets' curve empirically. While this initial analysis was performed at the country level, Grossman and Krueger (1994) empirically examined the impact of GDP per capita on SO₂ and PM pollution concentration at the urban area level.³ They found evidence that economic growth initially leads to environmental deterioration, reverting into improvements when a certain level of per capita income is attained. More recently, Lamla (2007) examined the relationship between GDP and

³ A discussion about the environmental Kuznets' curve can be found in Dinda (2004).

pollution by employing Bayesian Model Averaging. In that study, the results suggest an EKC relationship for SO₂ and a non-decreasing concave relationship between GDP per capita and CO₂ emissions.

Using a sample of 249 European Large Urban Zones (LUZs),⁴ this study explores the relationship between urban structure indicators and the concentration of three air pollutants: Nitrogen Dioxide (NO₂), Sulphur Dioxide (SO₂) and Particulate Matter up to 10 micrometres (PM₁₀). While the study mainly focusses on the relationship between urban area fragmentation and pollution concentration, insights are also provided into the relationship between population density and the concentration of specific pollutants.

The pollutants studied are generated by different processes. For example, while transportation produces a major part of NO₂, a large share of SO₂ comes from electricity generation. PM₁₀ emissions mainly originate from transportation and manufacturing. These differences have to be taken into account when analysing determinants of pollution concentration. In this context, this paper develops different models for each pollutant using the Bayesian Model Averaging selection method.

On the basis of existing empirical literature, a core model linking the level of pollution concentration and urban area fragmentation is specified. It controls for GDP per capita and a number of land cover indicators. Then, a Bayesian Model Averaging method is employed to select the empirical model which best identifies the determinants of the concentration of different pollutants. For each pollutant, the influence of economic sector composition, population density and factors related to internal urban composition and road transport are tested. The study does not consider factors of pollution that occur outside urban areas, such as inter-city transport or activities in rural areas.

Overall, economic, socio-demographic and land cover variables have different effects across pollutants; this supports the insight that different empirical specifications need to be used for different pollutants. The findings suggest that urban fragmentation is positively correlated with PM₁₀ and NO₂ concentrations, which result to some extent from transportation activity. Second, higher population density is found to be associated with higher SO₂ concentrations. Overall, the findings of the study suggest that the expansion of urban areas in Europe should aim at increasing continuity and reducing population density to avoid further air quality degradation (as measured by PM₁₀, NO₂ and SO₂ concentrations). Finally, the results of this analysis show a negative correlation between GDP per capita and the level of concentration of PM₁₀ and SO₂.

This study's contribution to the literature linking urban structure with air pollution is manifold. First, urban area-level data are exploited, enabling accounting for the spatial context of the problem and controlling for detailed urban area characteristics. Second, the analysis is conducted on several air pollutants, which allows us to provide some insights into inherent differences across pollutants that need to be taken into account when analysing air pollution concentrations. Third, the paper exploits information on several urban structure variables: fragmentation, artificial area, agricultural land, distribution of population across the LUZ and population density. Finally, it provides a cross-country analysis of whether urban structure affects air pollution concentration.

The remainder of this paper is structured as follows. Section 2 describes the empirical model and the estimation approach undertaken. Section 3 presents the data used, along with some methodological issues. Section 4 discusses the econometric results, while the final section concludes and draws implications for urban planning and environmental policy.

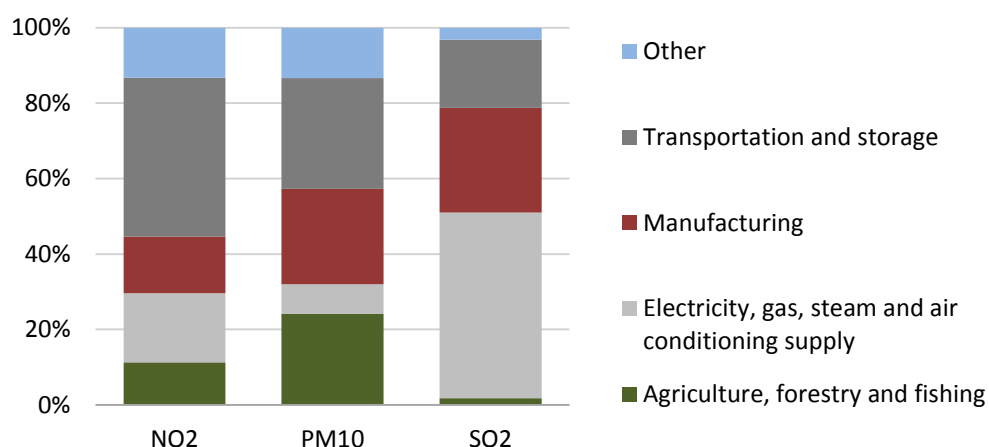
⁴ A LUZ is defined by the Urban Audit (Eurostat project) as the administrative city plus the surrounding municipalities whose at least 10% of inhabitants work in the city. This threshold ranges between 10% and 20% according to regional and national characteristics.

2. METHODOLOGY

The aim of this study is to investigate how different dimensions of urban sprawl can explain variations in air pollution concentrations for NO₂, PM₁₀ and SO₂. First, the analysis is conducted at the LUZ-level (OECD 2012b). This unit is larger than the administrative definition of a city (i.e. the core city) and enables accounting for urban sprawl observed beyond these boundaries. In the absence of a theoretical model linking air pollution and urban pattern, the choice of the explanatory variables relies on a model selection method.

A priori, there are no clear reasons to believe that concentrations of NO₂, PM₁₀ and SO₂ would have the same determinants. In this regard, Figure 2 highlights the share of emission discharged by five different economic sectors for the three pollutants.⁵ Important differences can be noticed. For example, while the majority of nitrogen oxide emissions stem from the transportation and storage sector (42%), half of sulphur oxide emissions are produced by energy generating processes. Emissions of PM₁₀ originate from various sources: transportation and storage (30%); agriculture, forestry and fishing (25%), and manufacturing (25%).

Figure 2. Air pollution emissions by activity



Source: Calculated by the authors on the basis of Eurostat's Air Emissions Accounts data

Thus, the model of interest should take into account the sources of each pollutant and other factors which may impact the level of concentration. Formally and according to the literature, for each pollutant, the empirical model is the following:

$$Poll_i = \beta_0 + \beta_1 Fragments_i + \beta_2 Sources_i + \beta_3 LandCover_i$$

⁵ Data come from Eurostat's Air Emissions Accounts which collects data on emissions by industries whose categories correspond to the Statistical Classification of Economic Activities in the European Community (NACE - http://ec.europa.eu/eurostat/statistics-explained/index.php/Business_economy_by_sector_-_NACE_Rev._2). Data for NOX and SOX concern the EU28 countries, and PM10 data cover EU28 countries without Ireland, Malta and Cyprus; and with Switzerland and Norway added. This graph is based on 2009 data. Data were extracted on November 2014.

$$+ \beta_4 \text{GeoMeteo}_i + \beta_5 \text{Surf} + \beta_6 \text{GDP/cap}_i + \varepsilon_i \quad (1)$$

where $i \in \{1, \dots, I\}$ indexes the LUZs. The dependent variable, *Poll*, denotes the level of pollution concentration (see Section 3 for details), *Fragments* is the variable of interest. *Sources* is a vector of variables controlling for the sources of the pollutant, it may comprise variables relative to: population, transportation, manufacturing and agriculture (cf. Figure 2). Moreover, model (1) includes land cover controls (*LandCover*) which are of interest to test and geo-meteorological variables (*GeoMeteo*) which may impact the level concentration (Elminir, 2005; Kerrie et al., 2000; Pearce et al., 2011). Finally, model (1) includes GDP per capita (*GDP/cap*) and the size of the LUZ (*Surf*) to account for disparities between LUZs and scale effects. The remaining variation in the dependent variable is subsequently represented as an error term, assumed to be normally distributed.

Based on this model, the control variables are tested to find the empirical specification that best explains the pollution patterns of the LUZs by employing Bayesian Model Averaging (BMA) as a model selection method. This method has been employed in a similar context by Oueslati et al. (2014) to study the impact of increasing population density and fragmentation on farm return. It has also been used by Lalma (2007) to examine the relationship between GDP and pollution.

BMA, introduced by Raftery et al. (1997), is suited for estimation and inference where there exists uncertainty in the choice of the model specification, either for empirical or theoretical reasons, as it is the case here. BMA is applied in a framework with two subsets of explanatory variables: (a) *core variables* for which we have good reasons, theoretical or empirical, to believe that they affect the dependent variable and (b) *auxiliary variables*, the variables we want to test because of the uncertainty of their explanatory power. BMA of linear models outperforms other conventional methods such as stepwise regression or adjusted R^2 in selecting the "true" model (Raftery et al., 1997). Instead of choosing among many specifications, BMA estimates are obtained as a weighted average of the estimates from each of the possible models in the model space with weights proportional to the marginal likelihood of the dependent variable in each model. The resulting average model has better predictive accuracy than single models (Hoeting et al., 1999).

BMA is employed for the three dependent variables: NO_2 , PM_{10} and SO_2 concentrations, with *Fragments*, *Surf* and *GDP/cap* as core variables and *GeoMeteo* and *Sources* and *LandCover* as auxiliary vector variables.⁶ BMA outcomes, presented in Section 5, support the hypothesis that different models need to be used to analyse different pollutants. Once the explanatory variables are identified via BMA, an ordinary least squares estimation⁷ with robust standard errors is used. The next section presents the data used to implement the estimation strategy.

⁶ The introduction of squared terms in order to study non-linearities unfortunately induces multicollinearity due to the small sample size.

⁷ Once the different models are specified, a Box-Cox regression is run in order to check the log-linearity of the dependent variables.

3. DATA

This paper studies a sample of European urban areas obtained by combining various existing data sources. Information on urban structure and other covariates restricts the analysis to 249 urban areas in 26 countries for the year 2006.⁸

Air pollution

The measures of air pollution concentration are constructed from the AirBase database.⁹ In the estimation sample, LUZs have an average of 3.62 monitoring stations, 49.4% of such stations are defined as background stations, 42.4% as traffic stations, 7.5% are industrial measuring stations and the remaining 0.7% of stations have an unknown classification. The average of concentrations registered by all monitoring stations is computed within a predefined LUZ. The objective is twofold: first, to fully capture pollution concentration in all types of areas, and second, to increase the number of urban areas in the sample.¹⁰ Table 1 presents the descriptive statistics of pollution concentration variables and Figures 3-5 illustrate the concentration of NO₂, PM₁₀ and SO₂ for the studied LUZs sample.

Table 1. Summary statistics of dependent variables

	Obs.	Mean	Std. Dev.	Min	Max
NO ₂ (in µg/m ³)	236	33.682	12.975	4.377	80.091
PM ₁₀ (in µg/m ³)	238	33.273	11.492	14.192	79.070
SO ₂ (in mg/m ³)	218	6.531	4.876	0.363	27.727

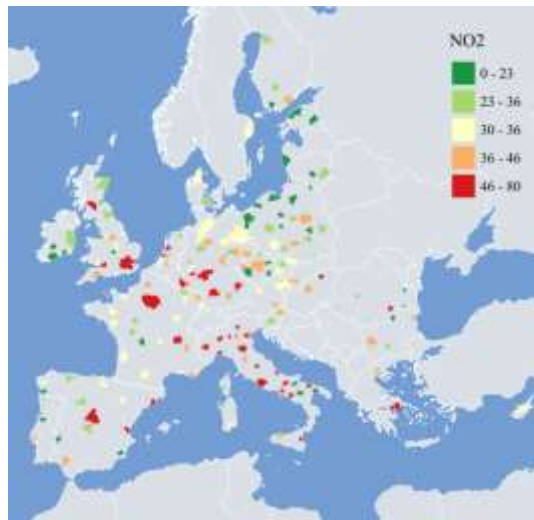
Figure 3 presents the NO₂ concentrations in the LUZs sample. Mediterranean LUZs (e.g. Barcelona, Valencia, Rome and Genoa) seem to experience higher levels of NO₂ concentration than Baltic ones (e.g. Tartu, Vilnius, Liepaja). Overall, LUZs of European capital urban areas seem highly polluted by NO₂. The WHO's guidelines suggest that the concentration of NO₂ should not exceed an average of 40 µg/m³ over a year; 27% of the urban areas of the sample are above this threshold (i.e. 65 urban areas).

⁸ The characterisation of urban structure is based on GIS data, obtained from European Environment Agency's Corine Land Cover database. The year 2006 was the most recent year for which Corine Land Cover data were available at the time of the study. Possible caveats arising from the lack of more recent data or relevant time series are discussed later in the text.

⁹ Airbase is the European air quality database maintained by the European Environment Agency containing data from individual stations monitoring air pollution throughout Europe. AirBase v8 extracted on 19/05/2014 from the European Environment Agency data portal.

¹⁰ By computing the average over all monitoring stations within a LUZ (regardless of the type), we seek to avoid excluding monitoring stations that have sometimes been classified ex-post on the basis of registered pollution concentrations. This restriction could impose a censorship in the variable; and excluding them will imply non-random missing values (e.g. as traffic, industrial or background).

Figure 3. Pollution concentration of Nitrogen Dioxide (in $\mu\text{g}/\text{m}^3$)

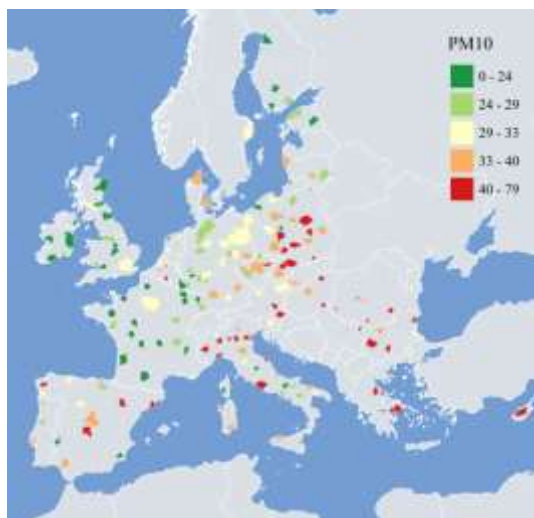


Source: Calculated by the authors on the basis of CORINE Land Cover data and Airbase monitoring data from a sample of 236 urban areas, average 2006 NO₂ concentration.

Reading: Pollution concentration (from dark green to red) is classified into 5 levels, each containing 20% of the LUZs sample, e.g. Paris and Madrid are among the 20% most polluted LUZs of the sample in terms of NO₂ concentration

Figure 4 reveals that Northern LUZs (e.g. Bristol, Leicester, Tartu, Gottingen, Lille) are on average less affected by PM₁₀ pollution than Southern countries. In Poland, however, many LUZs (e.g. Warsaw, Radom, Kalisz) belong to the last quantile of polluted LUZs. The WHO recommends achieving the lowest concentration possible, because any level of PM₁₀ has adverse effects on health.

Figure 4. Pollution concentration of Particulate Matter (in $\mu\text{g}/\text{m}^3$)



Source: Calculated by the authors on the basis of CORINE Land Cover data and Airbase monitoring data, from a sample of 238 urban areas, average 2006 PM₁₀ concentration.

Reading: Pollution concentration (from dark green to red) is classified into 5 levels, each containing 20% of the LUZs sample, e.g. Rome is among the 20% most polluted LUZs of the sample in terms of PM₁₀ concentration

Figure 5, SO₂ concentration appears to be higher in Eastern countries (Baltic countries excluded) than in Western Europe (Spain excluded). In particular, Poland (e.g. Krakow, Radom, Kalisz), Italy (e.g. Modena, Genoa, Bologna, Naples) and Bulgaria (e.g. Varna, Vidin, Ruse, Plovdiv) host many highly polluted urban areas. According to the WHO, the level of SO₂ should not exceed 50µg/m³ annually. Note the LUZs being classified in highest category of pollution are still considerably far away from reaching this threshold.

Figure 5. Pollution concentration of Sulphur Dioxide (in µg/m³)



Source: Calculated by the authors on the basis of CORINE Land Cover data and Airbase monitoring data, from a sample of 219 urban areas, average 2006 SO₂ concentration.

Reading: Pollution concentration (from dark green to red) is classified into 5 levels, each containing 20% of the LUZ sample, e.g. Athens and Madrid are among the 20% most polluted LUZs of the sample in terms of SO₂ concentration.

Overall, European LUZs rank differently across different pollutants. For example, Italian LUZs (e.g. Roma, Turin, Pescara) are part of the most polluted LUZs in terms of NO₂ concentration (Figure 3), while appearing among the least SO₂ polluted LUZs (Fig 5). The opposite phenomenon is observable for a number of Polish LUZs. Yet, Madrid experiences high levels of concentration for each type of pollutant as opposed to Estonia which records a low level of pollution. Figures 3, 4 and 5 highlight the importance of understanding the differences across pollutants as some areas are very affected by one pollutant and much less by others. Furthermore, Table 2 below shows that the correlations between pollutants do not exceed 0.5 which is relatively low.

Table 2. Correlation of pollutants

	NO ₂	PM ₁₀	SO ₂
NO ₂	1		
PM ₁₀	0.2397***	1	
SO ₂	-0.0359	0.4740***	1

Note: Pearson correlation. *** p<0.01, ** p<0.05, * p<0.1

Urban structure

Data on urban land - Urban Morphological Zones (UMZ) data - are compiled by the European Environment Agency (EEA). Derived from CORINE Land Cover (CLC), UMZ data covers the whole EU-27 at 200-meters resolution for those urban areas that are considered to contribute to urban tissue and function. Geospatial data on land-use for each urban area are obtained by superimposing the LUZ boundaries and the UMZ spatial data. For each LUZ, data collected on urbanisation allow the study of different components of urban form: number of fragments, share of artificial area, share of agricultural area, share of wetland, share of forest area, population density, population decentralisation (with respect to the core city) and the LUZ surface. Descriptive statistics are presented in Table 3.

Table 3. Summary statistics of explanatory variables

Explanatory variables	Obs.	Mean	Std. Dev.	Min	Max
Number of fragments	225	87.053	106.3305	2	898
GDP per cap	249	24593.050	14033.44	2894.496	149681
Surface (ln)	249	7.236	0.930	3.729	9.768
Median altitude (ln)	249	4.301	1.194	0.693	6.615
Temperature	249	21.435	4.052	14.6	35.5
Highway density	249	26.123	29.003	0.1	186
Road access	199	87.302	56.122	4	207
Pop density	213	583.529	700.574	14.614	6284.228
Decentralisation	206	0.438	0.193	0	0.834
Share of agriculture in value added	210	0.029	0.034	0	0.241
Share of industry in value added	210	0.274	0.082	0.112	0.547
Share of artificial area	249	0.137	0.117	0	0.597
Share of agricultural area	246	0.531	0.198	0	0.918
Wetland share	246	0.008	0.022	0	0.181
Forest share	246	0.280	0.190	0	0.877

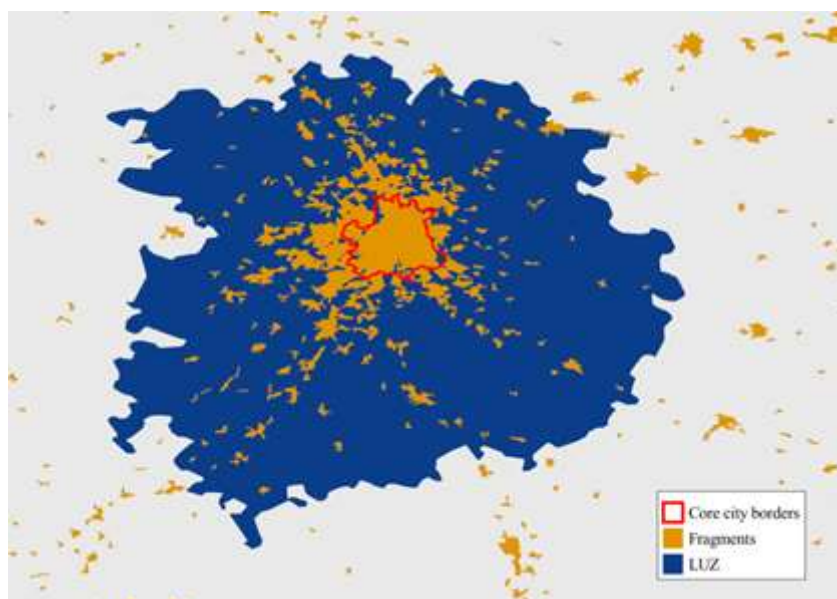
The variable *Number of fragments* refers to the number of discrete parcels of urban settlement in each LUZ. Figure 6 shows an example of the fragmentation of Toulouse, France. Regarding *LandCover* variables, the *Share of artificial area* shows the percentage of artificial area in total LUZ surface.¹¹ This simple measure reflects the share of the urbanised pattern in a given area independently of urban

¹¹ According to the CLC nomenclature, artificial surfaces comprise: (1) urban fabric, (2) industrial, commercial and transport units, (3) mine, dump and construction sites and (4) artificial non-agricultural vegetated areas (green urban areas and sport/leisure facilities).

See http://effis-viewer.jrc.ec.europa.eu/documents/general/land_cover.pdf.

morphology (e.g. the scattered nature of the urban area). Moreover, the analysis includes *Wetland share*, *Forest share* and *Share of agricultural area*¹², also defined at the LUZ level, each representing the share of a land type in the total LUZ area. Other things being equal, the correlation of the wetland and forest shares with pollution concentration is expected to be negative, while the share of agricultural area is likely to be associated with higher concentrations of agriculture-related pollutants.

Figure 6. Large Urban Zone, core city and fragments: Toulouse - France



Source: Calculated by the authors on the basis of CLC, UMZ and OpenStreetMap data.

Other variables

Other variables include economic sector-composition indicators of the LUZ such as the shares of industry and agriculture in total value added. These variables are retrieved from ESPON¹³. Then, different proxies for transportation intensity are included, retrieved from Urban Audit and ESPON. *Highway density* is measured as the number of km² of highway per km² of LUZ. Its expected impact on pollution concentration is not straightforward. While it may have a negative effect if road density translates into shorter and more efficient transport, it could also have a positive effect if it induces greater use of private vehicles resulting in more emissions. Consequently, this transport variable could be a proxy of connectivity efficiency or alternatively capture the level of car use. A second proxy for transportation intensity is *Road access*, an indicator of the connectivity of an urban area. This composite index is retrieved from ESPON. Its expected sign is unclear for the same reasons as *Highway density*.

The variable *Decentralisation* is measured as the share of people living outside the core city in total LUZ population. The higher the indicator, the more the population is spread out. One may

¹² CLC nomenclature defines agricultural area as: (1) arable land, (2) permanent crops, (3) pastures, (4) heterogeneous agricultural areas. See http://effis-viewer.jrc.ec.europa.eu/documents/general/land_cover.pdf.

¹³ ESPON is a European research programme providing information on European territorial structures. For further details, see <http://database.espon.eu/>.

expect a negative impact of decentralisation on the concentration of transport-related pollutants. The more the population is concentrated in the core city, the less car-dependent it is, and thus the lower road transportation emissions are. *Population density* is measured as the number of inhabitants per km² in the LUZ. This variable seeks to capture the agglomeration effect of population on pollution concentration. Both population-related variables are from the Urban Audit database.¹⁴

The geo-meteorological variables used in the study comprise the annual mean *Temperature* and the median city centre *Altitude* above sea level.¹⁵ The median altitude of the city is expected to have a positive impact on air pollution because higher altitude might translate into a lower boundary layer trapping pollution, as well as higher temperatures that can exacerbate air pollution (Elminir, 2005; Pearce et al., 2011; Hu et al., 2008). These variables are obtained from the European Climate Assessment & Dataset project.¹⁶ Finally, data on *Surface* (in km²) are taken from the UMZ dataset and are log-transformed to reduce the correlation with other covariates. *GDP per capita*, from ESPON, is measured in 2006 euros adjusted for purchasing power.

¹⁴ The Urban Audit database is a project by Eurostat which provides a wide range of socio-economic and environmental indicators for European urban areas.

¹⁵ The number of days of rain per year and wind speed have also been tested while expecting a negative impact on pollution concentration as precipitations washes off pollution in urban areas but they could not be included in the analysis due to missing values (Escobedo, 2013).

¹⁶ The European Climate Assessment & Dataset project provides daily datasets on weather and climate. More information on <http://eca.knmi.nl/>.

4. RESULTS

As expected, the model selection procedure reveals significant differences in variables selection across pollutants.¹⁷ Table 4 presents the selected explanatory variables.

Table 4. BMA-selected variables

Auxiliary variables	NO ₂	PM ₁₀	SO ₂
Highway density	no	no	no
Road access	no	no	no
Pop density	no	no	yes
Share of agriculture in value added	yes	yes	yes
Share of industry in value added	no	yes	no
Share of artificial area	yes	yes	no
Share of agricultural area	no	no	no
Wetland share	no	no	no
Forest share	no	no	no
Decentralisation	no	no	no
Median altitude (ln)	no	no	no
Temperature	yes	yes	no

BMA consistently identifies *Population density*, *Share of agriculture in the value added*, *Share of artificial area* and *Temperature* as important determinants of the concentration of several pollutants. *Share of agricultural area* and *wetland share* are not selected, which could be due to the fact that the analysed urban areas comprise few wetlands and agriculture areas. Neither *Highway density* nor *Road access* have been selected for any of the pollutants. This may be due to a large number of missing values for these variables. A weakness of the present analysis is, thus, that it does not include any transportation variables, even though transportation activities represent a major source of pollution emissions.¹⁸ *Forest share*, *Decentralisation* and *Median altitude* are not selected by BMA either.

The results of the estimation are presented in Table 5.¹⁹ LUZ fragmentation appears to be significantly and positively correlated with NO₂ and PM₁₀, the pollutants originating mostly from transportation. The effect of *GDP per cap* is negative and significant for PM₁₀ and SO₂

¹⁷ Following Raftery (1995), the best model specification is selected by including variables having a posterior inclusion probability equal to or above 0.5 (i.e. the probability that the covariate explains indeed the dependent variable is at least 50%)

¹⁸ Other variables from Eurostat have also been tested, i.e. the number of registered cars (stock of cars per 1000 inhabitants) and motorcycles, the share of population using public transportation for commuting, and a composite indicator of air access. Unfortunately, the large number of missing values for these variables prevents their inclusion in the analysis. Furthermore, despite applying multiple imputation methods to address the missing value problem, imputed variables were not selected by BMA.

¹⁹ The elasticity estimates are computed for selected variables in order to ease coefficient interpretation.

concentrations and insignificant for NO₂ concentrations. More precisely, a 1% increase in *GDP per capita* is associated with a decrease of 0.2% in PM₁₀ and 0.5% in SO₂. A closer look at the marginal effect shows that the negative effect on pollution concentration is stronger at higher levels of GDP per capita. This might be due to tighter environmental regulations, the use of cleaner energy, or more energy efficient transportation in LUZs with relatively higher GDP.

Nitrogen Dioxide

Turning into air pollutant specific results, BMA identifies *Population density*, *Share of agriculture in value added* and *Share of artificial area* as relevant factors explaining NO₂ concentration. *Number of fragments* is highly significant and positively correlated with the level of NO₂ concentration, indicating that urban fragmentation is associated with higher NO₂ concentration. In particular, an increase of 1% in the number of fragments is associated, on average, with a 0.08% increase in NO₂ concentration (column (1)). A positive relationship between the *Share of artificial area* and NO₂ concentration is also found; an increase of one percentage point in the share of artificial land is associated with a 1% increase in NO₂ concentration. *Temperature* is also significantly and positively correlated with NO₂ concentration. Interestingly, the relationship between the share of agriculture in the value added of LUZ's economy and NO₂ concentration is negative.

Particulate Matter

Share of industry in value added, *Share of agriculture in value added*, *Share of artificial area* and *Temperature* are chosen by the selection method. First, results show a positive and significant correlation between the LUZ fragmentation and PM₁₀ concentration, i.e. a 1% increase in the number of fragments is found to be associated with a 0.04% increase in PM₁₀ (column (2)). Similarly to the results above, this finding is consistent with the fact that PM₁₀ is produced to some extent by road transportation. The *Share of artificial area* is found to be positively correlated with the concentration of PM₁₀, an additional percentage point in the share of artificial area is correlated to a 0.9% increase in PM₁₀ concentration. As expected, the *Share of industry in value added* is positively correlated with PM₁₀ concentration. In particular, results reveal that a one percentage point increase in the *Share of industry in value added* is associated, on average, with a 0.1% increase of PM₁₀ concentration. Results show a positive and significant relationship between *Temperature* and PM₁₀ concentration.

Sulphur Dioxide

Determinants of Sulphur Dioxide concentration selected by BMA are *Population density* and *Share of agriculture in value added*. As expected, they are significantly and positively correlated with SO₂ concentration. In particular, results suggest that a rise of 1% in *Population density* is associated, on average, with a 0.2% increase in SO₂ concentration. Moreover, a 1% increase in the *share of agriculture in value added* is associated with an increase of 0.11% in SO₂ concentration. In contrast to other pollutants, the degree of fragmentation of an urban area does not appear to affect SO₂ concentration. This might be due to the fact that SO₂ is mainly produced by energy generation processes rather than by road transportation.

Table 5. OLS estimation results

	(1)	(2)	(3)
	NO ₂ (ln)	PM ₁₀	SO ₂
Number of fragments	0.000828*** (0.00677)	0.0132* (0.0612)	0.000683 (0.789)
GDP per cap	3.60e-06 (0.292)	-0.000272** (0.0239)	-0.000130*** (0.00880)
Surface (ln)	-0.0414 (0.354)	1.223 (0.475)	0.186 (0.764)
Share of agri. in value added	-6.359*** (5.31e-06)	47.99 (0.498)	30.43** (0.0407)
Share of ind.in value added		32.90*** (0.00651)	
Share of artificial area	0.915*** (0.000747)	28.83*** (0.00522)	
Temperature	0.0312*** (3.86e-06)	0.731*** (0.00478)	
Pop density			0.00205*** (0.000919)
Constant	2.967*** (0)	-0.763 (0.968)	5.698 (0.194)
Obs.	178	179	135
Adj R ²	0.480	0.144	0.206
BIC	118.5	1404.2	792.5

Note: p-values in parentheses: *** p<0.01, ** p<0.05, * p<0.1.
Robust standard errors.

5. CONCLUSIONS AND POLICY IMPLICATIONS

The exploratory analysis presented in this report reveals that urban fragmentation is significantly correlated with the concentrations of air pollutants emitted, among others, by road transportation. In particular, this study presents evidence that urban fragmentation is correlated with higher concentrations of NO₂ and PM₁₀, when controlling for economic factors and climate conditions. Moreover, the results suggest that densely populated urban areas are associated with higher SO₂ concentrations. The analysis also highlights that concentrations of NO₂, SO₂ and PM₁₀ are affected differently by urban characteristics due to differences in emission sources. The results also reveal that high-income urban areas experience lower concentrations of PM₁₀ and SO₂. This may be a result of tighter environmental regulations or higher public expenditure to improve air quality in high income areas.

These findings suggest that concerns about increased levels of NO₂ and PM₁₀ concentration stemming from further expansion of urban areas in Europe could, to some extent, be addressed by spatial policies aiming at the reduction of urban fragmentation. Continuous urban areas enhance connectivity, reduce travel needs and car dependency, and facilitate the use of non-motorised modes of transport, such as biking and walking. Further to the reduction of urban fragmentation, spatial policies leading to decreases in population density could partially alleviate concerns about the impact of urban expansion on SO₂ emissions. Overall, the findings of the study suggest that instruments aiming at increasing continuity and reducing population density are worth considering in the policy mix used to avoid further air quality degradation by the expansion of urban areas in Europe (see *Urban Area 3* in Figure 1 for an illustrative example). Such instruments can complement other policies used for the reduction of urban air pollution, such as vehicle emission standards.

The lack of recent GIS data and data on economic indicators at the city level restricts this cross-country analysis to cover only the year 2006. This results in a number of limitations for this study. First, causal interpretations of the identified relationships may be invalid, as the effect of time-invariant city characteristics is not controlled for. Second, the analysis cannot shed light on whether the identified relationships change over time. Even though changes in urban structure are relatively slow, changes in air pollution and the relative contribution of different sources in total emissions (e.g. road transport, manufacturing, electricity generation) may be more rapidly evolving over time. For example, the evolution of motor vehicle technology towards the production of cars with lower average emissions of NO₂ and PM₁₀ implies that one might expect that the link between urban fragmentation and air pollution would become weaker over time. In addition, it is important to consider other types of air pollution determinants such as inter-city transportation or activities in adjacent rural areas.

Continuity and density are among the characteristics of compact urban areas. The concept of urban area compactness has seen a growing interest in environmental economics literature. Nevertheless, the effects of compactness have not been examined thoroughly and the impact of anti-sprawl policies and measures favouring urban area compactness are still debated (Neuman, 2005). The results of this analysis indicate competing effects of the different dimensions of compactness on pollution concentration. This argument motivates the conduct of further empirical studies of the effects of these different dimensions on environmental quality.

More generally, empirical analyses of the relationship between urban form and environmental quality are still scarce. This exploratory analysis is a first step towards more comprehensive studies of the relationship between urban structure and the environment. The problem of missing data is particularly acute for spatially granulated information. In this respect, this analysis would benefit

from the use of more precise transportation indicators, and the inclusion of additional urban areas in the estimation, especially from non-European countries. A greater coverage of urban areas can provide more variation and perhaps more robust evidence of the impact of urban structure and socioeconomic variables on air quality. It may also allow the study of non-linear effects of the covariates and thus investigate the existence of the Environmental Kuznets Curve at the urban area level. Likewise, data over several years may allow the derivation of causal inferences.

Another important step forward would be to empirically analyse the effects of land-use policies on the concentrations of air pollutants and population exposure to pollution. Cross-country, multi-year empirical set-ups would be required for such analyses. These studies would provide stronger policy recommendations, and more accurately inform policy-making about the potential consequences of spatial planning decisions on air quality and human health.

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ANNEX I

Table 6. Correlations

	Number of fragments	GDP/cap	Surface (ln)	Median altitude (ln)	Temperature	Highway density	Road access	Pop density	Sh. of agri. in the add. val.	Sh. of ind. in the add. val.	Sh. of artificial area	Sh. of agricultural area	Wetland share	Forest share	Decentralisation
Number of fragments	1														
GDP per cap	0.249	1													
Surface (ln)	0.672	0.327	1												
Median altitude (ln)	0.104	-0.095	0.076	1											
Temperature	-0.275	-0.194	-0.332	0.050	1										
Highway density	0.228	0.497	0.048	-0.194	-0.152	1									
Road access	0.300	0.507	-0.028	0.114	-0.309	0.579	1								
Pop density	-0.156	0.092	-0.364	-0.135	0.202	0.258	0.146	1							
Sh. of agri. in add. val.	-0.280	-0.659	-0.338	0.026	0.136	-0.420	-0.454	-0.180	1						
Sh. of indus. in add. val.	-0.143	-0.250	-0.064	0.183	-0.149	-0.247	-0.160	-0.191	0.258	1					
Sh. of artificial area	-0.124	0.189	-0.479	-0.247	0.004	0.443	0.420	0.785	-0.229	-0.154	1				
Sh. of agricultural area	0.095	-0.113	0.019	-0.046	0.042	-0.086	0.054	-0.207	0.203	0.144	-0.164	1			
Wetland share	-0.071	0.013	0.167	-0.405	-0.112	-0.071	-0.237	-0.109	0.074	0.107	-0.137	0.032	1		
Forest share	0.012	-0.032	0.224	0.280	-0.044	-0.164	-0.248	-0.250	-0.061	-0.032	-0.420	-0.753	-0.124	1	
Decentralisation	0.262	0.561	0.348	-0.074	-0.127	0.335	0.375	0.148	-0.494	-0.183	0.106	0.066	0.029	-0.125	1