EXTENDED ABSTRACT

Title: Social status or environmental quality? A socio-ecological approach to air quality in Barcelona.

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Abstract Air pollution and air quality issues have been widely discussed in the scientific literature and by major international institutions (e.g. Samoli et al., 2019; WHO, 2021; EEA, 2021). Among the most commonly analysed air pollutants are carbon monoxide (CO), nitrogen dioxide (NO2), ozone (O3), sulphur dioxide (SO2) and

particulate matter of less than 2.5 μm (PM2.5) and 10 μm (PM10) aerodynamic diameter (Nowak et al., 2018). This interest in the study of air quality is linked to the increasing process of urban growth worldwide and evidence of the consequences and relationships associated with climate change (Lu et al., 2018; McDonald et al. 2020). In turn, air quality and increased pollution have been linked by numerous studies to increased mortality and physiological vulnerability in a region or area (e.g. EEA, 2020; Jerrett et al., 2004, Finkelstein et al., 2005; Forastiere et al., 2007). Thus, it is obvious that it is essential for any administration to know the distribution of the air pollution gradient in order to efficiently plan strategies to alleviate unequal access to health services (Marmot, 2007).

The high level of pollution and the complex interrelationship between the different variables related to air quality make this problem particularly important in mediterranean urban areas (Galindo et al., 2019; Selmi, et al., 2016). The latest available estimates determine that 96 % of the population living in urban areas in the EU would be exposed to high levels of air pollution (Targa et al., 2022). Based on the idea of urban ecosystems as a complex mosaic of climates, land uses, biophysical and socio-economic variables (Escobedo & Nowak, 2009), urban air quality can now be considered more fragile due to unsustainable urban development and building patterns since the late 20th century (Thunis, 2018).

Based on all these considerations and the diversity of results, our research develops a socioecological approach (Afriyanie et al., 2020; Cook et al., 2012; McHale et al., 2013) at the census tract level to correlate air quality, as measured by the most commonly used pollutants (NO2, PM10, PM2.5), with a series of socioeconomic, ecological and building contextual variables. With this approach we aim to generate a holistic explanation for air quality in the city of Barcelona in 2019. We have opted for an ecological design as they are the most widely used when relating the socioeconomic situation and pollution in the city. Although pollution and its effect on health is an individual matter, the contextual analysis developed by ecological studies allows us to determine the role of poverty in the area of residence. In this sense, using a unit of analysis such as the census tract, which usually has an average demographic size of around 1,500 inhabitants, allows us to consider that we start from the basis of very uniform socio-economic contexts. In fact, an analysis at the local and micro scale improves the understanding of the effects of the urban forest on pollution removal and, consequently, on the well-being of residents (Escobedo & Nowak, 2009). In turn, the spatial analysis at this micro scale allows us to uncover the spatial heterogeneity inherent to ecological studies, and smooth the modifiable areal unit problem (Anselin, 1988). This last aspect, together with the divergences in the results obtained in other studies, is mitigated in our case by the type of analysis used in our research, a Geographically Weighted Regression (GWR) approach (Fotheringham et al. 2001) following the strategy of specification proposed recently by Comber et al., (2022) at census tract level. By means of this research design we want to answer the following research questions:

RQ1: How does the presence of vegetation and building density affect air quality in Barcelona, and does it vary according to the pollutants analysed?

RQ2: Is the population with a higher degree of socio-health vulnerability exposed to a higher amount of air pollutants?

RQ3: Is there a relationship between socio-economic status and air quality in the city?

Through these research questions and the development of a methodology based on spatial statistics, we make an innovative contribution to the state of the art in two ways: (i) the holistic nature of the socio-ecological approach chosen. In this way, the variables used allow us to analyse the relationship between the physical and social factors that explain air quality in Barcelona. (ii) the spatial focus of the analysis developed through the use of the GWR techniques at census tract level and its comparison with classical non-spatial statistical methods such as the OLS model. Although recently some studies have started to use the GWR model for air quality studies (e.g. Li et al., 2022), our study is particularly innovative in that it contrasts the analyses of spatial and non-spatial statistics and produces more robust results specified at the census tract level. In turn, the implementation of the results at the census tract level provides practical tools for local policy makers to take specific measures to address air pollution in the city. This is essential when working with variables of territorial implementation in order to achieve rigorous results that show the diversity of situations in the area analysed, but which studies dealing with air quality have not done so far.

The city of Barcelona is located on the central coast of Catalonia, at the northeast of Spain, with an extension of 102.16km2 and a population of 1,608,746 inhabitants. It comprises 4.7km of linear beach extension on the southeast and a hill on the northwest with of 2.6 km2 of forest parcs, and 8.9 km2 of urban parcs within the city. In 2018, the City of Barcelona's gross domestic product (GDP) was €46,600 per inhabitant. In 2019, Catalonia generated a GDP of €250,597 million, representing 20.1% of Spain's total GDP. In the same year, Catalonia's per capita GDP exceeded the European Union's GDP by 12%.

The city has a street network which extends to 1,368 km long, overlaying an area with 11.3 km2 of streets, roads, and highways, and 9.8 km2 of sidewalks (Institut d'Estadística de Catalunya). Barcelona is the most densely populated city in Spain experiencing a mostly centralized growth during the last decades (Ciommi et al., 2018), with a moderately polycentric and dense metropolitan organization. Subcenters, with an important historical background, located out of the classical center took over the urban expansion. In this context, the immigration is particularly relevant in the city where the total proportion of immigrants has increased significantly within a very short period (2.90% in 2000 to 15.11% in 2019) and has concentrated in two types of zones: the historical center, where housing is of poor quality, and the peripheral districts close to public transport and where housing is relatively cheap, resulting in segregation and the emergence of ethnic enclaves (Martori et al., 2016).

In order to develop a socio-ecological approach firstly data about air contamination levels in the city of Barcelona have been collected through the Open Data BCN Portal (Ajuntament de Barcelona, 2022), the Barcelona's Town Hall's open data service, managed by the Department of Statistics and Data Dissemination of the Municipal Data Office. The service offers a catalogue of different datasets where users may find all information opened by Barcelona City Council in reusable formats. Regarding contamination, the air quality immission maps provide a set of detailed information on the quality of the environment that the city of Barcelona is subject to. Specifically, the data, on annual average at street section level, of the main atmospheric pollutants (Gómez-Moreno et al., 2019; Rodríguez et al., 2016) in Barcelona namely, nitrogen dioxide (NO_2), fine particulates ($PM_{2.5}$) and coarse particulates (PM_{10}), measured according to the evaluation criteria of Directive 2008/50/EC (European Union, 2015).

We use the census tracts as a proxy for all the data at local scale (i.e. Barceló et al., 2009) to study, from an ecological approach, the relationship between the pollutants and different characteristics of each census tract. The city of Barcelona is divided into 1068 census tracts. According to the theoretical framework, we collected data describing various dimensions, at local scale, from many different publicly available data sources. We gathered the socio-economic and socio-health data at the census tract level from the Spanish National Statistics (INE, 2022): income level (e.g. Nowak et al., 2006), percentage of people from non-EU countries (e.g. Carrier et al., 2014); population under four years old and population over eighty years old (e.g. Moreno-Jiménez et al., 2016)

and population density (e.g. Bartholomew & Ewing, 2008). The information about land use and vegetation for the city of Barcelona is also publicly available and we assembled our dataset from two different sources, the Open Data BCN Portal, and the Geologic and Cartographic Institute of Catalonia. Precisely, for each census tract, we computed the areas covered by green spaces (urban and forest parcs), the number of trees (inside and outside parcs), the normalized difference vegetation index average (NDVI), the built surface, and some more data regarding land use, i.e., number of parcels, shops surface, number of dwellings, number of parking slots. We transformed some variables with natural logarithm because they violated the assumption of normality and moreover, were highly skewed. Once the dataset was assembled, we performed some tests to measure the statistical association between the three pollutants, NO2, PM2.5 and PM10 –the dependent variables– and the socio-economic, socio-health, vegetation, and land use variables available.
We started the analysis following a standard approach, as in most empirical work, starting with non-spatial Ordinary Least Squares (OLS) linear regression models to interpret, globally, the influence of each possible predictor variable. We estimated several models applying OLS regressions following a stepwise procedure, to clarify the global relationship between the dependent and the explanatory variables. We used the Variance Inflation Factor (VIF) values (O'brien, 2007) to assess the OLS models by multicollinearity and the Corrected Akaike Information Criterion (AICc) (Akaike, 1973) to assess the relative quality of the models.

This study has proposed a socio-ecological analysis based on the use of spatial statistics using a variety of GWR modelling techniques, applied to the highest level of spatial desegregation possible at the administrative level for the city of Barcelona. The results that have just shown allow us to offer a series of reflections articulated on the basis of the answers to the research questions that have been posed and the advantages that the methodology developed provides for this type of study.
Firstly, our results support the findings of studies in Barcelona that highlight the relationship between higher population density and building density with poorer air circulation, greater heat island and higher air pollution (Yang et al., 2020). Broadly speaking, it can be considered that the areas of Barcelona with higher building density and population density are characterised by higher levels of pollution in the three types of pollutants analysed. This aspect is also related to the higher level of traffic in areas with higher building density and the lower dispersion of pollutants (Vance & Hedel, 2007; Bartholomew & Ewing, 2008). Although the results are significant in the spatial and non-spatial models, they are reinforced at the high and medium levels of the GWR and MS GWR models. If we focus the analysis on the role of tree mass, our results show that larger areas of tree mass, urban parks, are clearly related to lower pollution in line with what has been shown in numerous studies (e.g. Escobedo et al., 2011). However, these results show an inverse relationship when analysing the effect of isolated street trees on pollution. In these cases, as some studies have also shown, either because of the insufficient and isolated nature of the trees (McPherson et al., 1999), the excessive accumulation of pollen particles (Salmond et al., 2013) or the canyon-like layout of the streets (Wania et al., 2012), the presence of isolated street trees in Barcelona is associated with a higher level of concentration of the three types of pollutants analysed, regardless of the statistical model used. This aspect leads us to the reflection that municipal measures to improve air quality, rather than focusing on planting street trees in areas close to traffic, should prioritise the design of larger green zones.
The analysis of the most vulnerable population groups from a socio-health point of view, i.e. the migrant population from non-EU countries, children under four years of

age and those over 80 years of age, leads to different conclusions depending on each group analysed. In general terms, both the OLS model and the GWR model in their mean levels show a significant relationship between higher pollution levels and the presence of migrant population in the same line as already shown for Barcelona (Moreno Jiménez et al., 2016; 2022) and for other areas outside Spain (e.g. Ard et al., 2021; Carrier et al., 2014; Fecht et al., 2015). However, if vulnerability groups are analysed by age, the relationships are no longer so clear. Broadly speaking, the population under four years of age does not show a relationship with the highest degree of pollution and is therefore not significantly exposed to the three pollutants analysed. However, the older population alternates between areas with an inverse relationship with pollution in the north of the city, while a significant positive relationship with pollutants is found in the central area of the city, in the oldest and most socio-economically advanced neighbourhoods (e.g. Sarria and Ciutat Vella). In this case, the GWR models show a much more complete and complex reality that relativises the validity of the OLS model for this variable.

Finally, the analysis of income level and the presence of pollutants shows that the higher the income level, the worse the air quality. In this sense, the case of Barcelona shows the same trend as other European cities where it has been shown that certain sectors of middle and high social status experience greater exposure to pollutants in the city (Goodman et al., 2011; Santana et al., 2017). This relationship between better social status and higher exposure to particulate pollutants has been explained as collateral damage that is bearable compared to the advantages of living in urban areas (Buzzelli & Jerrett, 2007). In the case of Barcelona, this area with the highest relationship between income level and greater exposure to pollution is located in the Eixample area and adjacent neighbourhoods. This area of the city is characterised by a high level of traffic, high building density and is also one of the areas with the highest residential demand in the city. In this case, it seems clear that the profitability of housing in the area acts as a deterrent to increased exposure to pollutants, especially NO2, which is related to car traffic. This Barcelona model, like that of other European cities where the historic centre has undergone significant gentrification processes, is contrary to the North American model where pollutants tend to concentrate in the most degraded metropolitan peripheries due to increased car use (Chi et al., 2016; O' Lenick et al., 2017).

The models that our results reveal for Barcelona has shown a clear relationship between building and population density, higher income levels, road traffic and the presence of isolated trees at street level with exposure to a greater number of the pollutants normally analysed. At the same time, it has been shown that the presence of large green areas or urban parks reduces the presence of pollutants. Given these results and the obvious impossibility of building large parks and reducing building density in the areas of the city where it would be most necessary (the Eixample and surrounding areas), it is clear that local politicians should opt for measures to reduce the main source of pollution, i.e. motorised traffic. In this sense, the implementation of plans for the restriction of private traffic, the promotion of public transport and pedestrianisation, such as those developed by Barcelona City Council with the Climate Plan 2018-2030, have marked a line that has shown results in only two years of application. However, its partial paralysis due to the decision of the High Court of Justice of Catalonia opens important unknowns for the future of the city.

Finally, the variety of results offered by the OLS and GWR and MS-GWR models, the contrast between them and the possibility of qualifying the conclusions with the data offered by the spatial and non-espatial statistical approach, open a very important way to a more rigorous study of the distribution of pollutants in the city and their relationship with different socio-ecological variables. For the future, this study should be contrasted with the results pending publication on pollutants in the city of Barcelona in order to analyse the effects of the lockdown during the start of the COVID 19 crisis, as well as the implementation of the Climate Plan in the city.

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