How much inequality in exposure to high PM$_{10}$ pollution is too much to be considered environmentally unfair? An assessment for vulnerable groups in two major Spanish cities

¿Cuánta desigualdad en exposición a alta polución por PM$_{10}$
es demasiada para considerarla ambientalmente injusta? Una evaluación
para grupos vulnerables en dos grandes ciudades españolas

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Abstract

Inequality in the environmental conditions or burden (negative externalities, hazards, discomfort, etc.) between places and people is an issue of growing interest. Many of works, using a variety of approaches, conclude that there is often discrimination and injustice. However, from the public decision-making and governance perspective, one question needs a clear answer: how much inequality is there? Is this too much, and therefore unfair, and does it justify public action? This paper looks at this question in a case study on the threat posed by air pollution in Madrid and Barcelona (Spain), by examining the spatial distribution of several vulnerable population groups and their potential exposure to high concentrations of PM_{10} in the atmosphere, and using an affordable method involving GIS and statistical techniques. Adopting an explicitly impartial operating criterion makes it possible to measure the amount of inequality for each population group and determine more objectively if it significantly exceeds the baseline criterion. This would make it more accurate for citizens and decision-makers alike to better assess the possible inequities.

Key words: environmental justice; air pollution; vulnerable population groups; geographical information systems.

Resumen

Las desigualdades en la afección o carga ambiental (externalidades negativas, peligros, malestar, etc.) entre lugares y personas son un tema de creciente interés. Se han publicado abundantes estudios, utilizando métodos diversos, en los que se concluye que, a menudo, existe discriminación e inequidad. Ahora bien, desde el punto el punto de vista de la formación de decisiones públicas y de la gobernanza una pregunta sigue siendo necesario responder con claridad: cuánta desigualdad existe y si ésta es demasiada para ser calificada de injusta y justificar, por tanto, la acción pública. En este artículo se aborda esa cuestión a partir de un estudio de caso relativo al peligro por polución del aire en Madrid y Barcelona (España). A tal fin se examina la distribución espacial de varios grupos de población vulnerables y su exposición potencial a alta concentración de PM_{10} en la atmósfera, usando un método razonable que implica el uso de SIG y técnicas estadísticas. La adopción de un criterio operativo y explícito de imparcialidad posibilita medir la cantidad de desigualdad para cada grupo de población y determinar si ésta excede significativamente al criterio de referencia. Ello facilita una valoración más certera de la situación por los ciudadanos y los decisores públicos.

1   Introduction

It seems quite justified to argue that territorial development involves bringing together a set of principles or values, and one that should be deemed a priority challenge is environmental justice (EJ), as various authors often claim (Sandler & Pezzullo, 2007; Colsa Pérez et al., 2015). Certainly, it would be hardly tenable to imagine future scenarios of our civilisation in which such injustices still existed or were even larger. This concept has been addressed in well-founded theoretical analysis, although for our purposes here it suffices to recall Landrigan's et al. (2010, p. 178) brief statement: "Environmental injustice is the inequitable and disproportionately heavy exposure of poor, minority, and disenfranchised populations to toxic chemicals, contaminated air and water, unsafe workplaces, and other environmental hazards". A more general statement might be: there is injustice wherever the (real or potential) negative environmental situation experienced by a population (or socio-demographic group) exceeds the amount corresponding to them. In other words, an environmentally just situation would mean, inter alia, that several socio-spatial groups bear environmental "burdens" (hazards, degradation, discomfort, poor health, etc.) on a non-discriminatory basis, and such burdens are shared out equally among everyone, avoiding any disproportionate burden on the weakest, the most disadvantaged or vulnerable (Moreno Jiménez, 2010). This would show the need to find out and clarify what exactly these environmental "evils" are and how they are distributed socially and spatially. In the complex people-environment interaction, the challenge of measuring these positive and negative aspects calls for some kind of accounting system, which is being tackled from different approaches, with the vision of the EJ being one of the most suggestive in this respect.

As Walker (2012) has shown, environmental inequality may stem from a wide range of sources. Studies have revealed that it exists in many situations and could have a serious impact on human health (e.g. Laurent et al., 2007; Hornberg & Pauli, 2007; Bolte et al., 2011; Collins et al., 2015) and well-being. According to the knowledge gained to date, one could argue that several public policies and plans, as well as private sector organisations, should bear this principle in mind. Likewise, environmentally discriminatory (real or foreseeable) situations and dynamics and the notorious socio-environmental conflicts seen in many places should be examined from this perspective in order to help do away with or reduce the unfair environmental "burdens" borne by different socio-demographic groups.

Studies have shown that much remains to be done, not only in terms of regulations and public policies, which are significantly lacking in many countries, but also in terms of assessment methods, because of the difficulties in accurately gauging environmental injustice. From a public governance perspective, better decision-making should answer a key question, namely: how much inequality in terms of the environmental burden in a place and by a population (or group) can be considered being too much, and therefore unfair? This is a general matter that requires: (a) a consensus regarding the criteria that define fairness (based on quantitative and qualitative aspects and criteria); and (b) an analysis that assesses the level of inequality in each case, adapted to very different problems, sometimes dealing either with static situations, or with dynamic processes, and demanding a spatial and temporal comparison in order to better monitor equity.

Under these premises, this paper seeks to make both a methodological and an empirical contribution to determining to what extent certain sub-populations are over- or underexposed within a city to high PM_{10} pollution levels, and therefore unjust, as this would bear people's health. The two largest Spanish cities were chosen as case studies, along with various population groups that were considered to be vulnerable. Using a method that combines statistical techniques, spatial interpolation and geographical information systems (GIS), the study attains: (a) an estimate of the spatial pattern of the average annual concentration of PM_{10} in the two cities; (b) a spatially-disaggregated estimate of the distribution of the total population and certain vulnerable groups; (c) a determination of the unequal potential exposure of these vulnerable groups to high level of PM_{10}; and (d) having established a plausible criterion of environmental justice, an assessment of to what extent potential exposure to high levels of pollution by each population group might be considered excessive and therefore unjust.

The aim is to implement a practical approach to quantifying environmental injustice in urban areas, facilitating a periodic application and providing helpful, intelligible information for local people and decision makers on the extent of the environmental inequality in their living places. These results could contribute to social empowerment and provide a better basis for political and citizen action.

The following section presents the most significant research and background on the subject, before outlining the data and methods proposed. We then analyse and discuss the results, before drawing the conclusions and giving some further perspectives.

2 Literature review

The published material on EJ continues to grow apace, a sign that, as Stephens (2007) pointed out, the scientific community is committed to facing the challenge of soundly managing these kinds of problems of which, despite having been present throughout history, we only started becoming aware in the late 20th century. Schlosberg (2013) highlighted the increased attention being paid to environmental justice in a wide range of scientific disciplines over the past two decades. The EJ concept has been discussed in well-known works (e.g. Wenz, 1988; Dobson, 1998; Walker, 2012, ch. 1; Ramírez et al., 2015), and its various interpretations have been established (e.g. Kuehn, 2000; Ikeme, 2003; and Schlosberg, 2007).

Chakraborty (2017, p. 3) has argued that EJ is becoming more significant in today's societies due to "the refusal of governments and corporations across the world to address the causes and consequences of environmental degradation, as well as their disproportionate affects on socially disadvantaged groups". There has been increasing recognition of EJ as both a principle and a right (e.g. Hill, 2009; Pedersen, 2010), but its practical implementation around the world has posed many difficulties, with unequal effectiveness, according to research by Arnold (1998–1999, 2007), or Bell (2015). These studies seem to show that applying EJ in public governance would entail adopting the decision-making and policy analysis paradigm, and its associated methodology (see Patton et al., 2012). Here, a geographical perspective may be useful.

Several literature reviews (e.g. Holifield et al., 2018; Chakraborty et al., 2011; Martuzzi et al., 2010; Mohai & Saha, 2006; Mohai et al., 2009; Reed & George, 2011) have synthesised the main contributions and practices in EJ research. An important part of these empirical studies have focused on the question of clarifying whether, in a particular place and situation, there is discrimination against certain social groups, as a result of having to put up with an excessive environmental burden. A vision of EJ as fair distribution, as described by Kuehn (2000) or Ikeme (2003), is assumed. The importance of this line of work lies in the contribution it can make to ensuring rigour in the decision-making process, determining discrimination in terms of who, when, where, how and how much.

Considering the role of the research activity, two key components should be mentioned when making EJ principle-based decisions. Firstly, the quantity and quality of and access to environmental information and knowledge. Inequality awareness and assessment of policy options by stakeholders hinges on clearly understanding these environmental problems. International law and many countries have increasingly sought to enshrine the right to this information as essential

in the path towards environmentally equitable situations (see Bermúdez, 2010). This question is of direct concern to researchers and experts, as the people who have to analyse the complex interactions between society and the environment in order to highlight existing inequalities. Secondly, the question of the methodology used to assess such environmental discriminations. Studies that evaluate environmental injustices are quite diverse. Maguire and Sheriff (2011) reviewed the approaches to quantifying distributional equity and stated that a major difficulty for EJ regulation and its enforcement is the lack of a baseline criterion for appraising whether inequality exists and, if so, to what extent. These are key concerns considered in this paper.

It is worth restating here that geotechnologies are playing a key role in this research field, as has been stated by Esnard et al. (2001), Maantay (2002) or Mohai & Saha (2015). The outstanding capability of geotechnologies has been proved: (a) when measuring the spatial intensity and extension of environmental hazards and risk, for example, concerning air pollution, for which a several approaches have been adopted: models to measure the emission and diffusion of pollutants (e.g. Fan et al., 2012), spatial interpolation (e.g. Cañada et al., 2014), land-use regression models (e.g. Clark et al., 2014; Cooper et al., 2019, remote sensing of aerosols (e.g. Nordio et al., 2013), biomonitoring parameters of element deposition over time (Lanier et al., 2019), etc.; (b) in the size's determination and spatial location of the population exposed to environmental problems; and (c) in evaluating the inequality emerging from this interaction between society and the environment. As shown by Mohai & Saha (2006), the results are dependent on some GIS-based methodological decisions and spatial analysis. Our research echoes this concern to test methods based on geotechnologies, producing results that can be better understood and gauged by stakeholders.

With specific regard to unequal exposure to air pollution, Walker (2012, ch. 5) has highlighted the main difficulties and choices in the distributional analysis, and various publications have reviewed the findings from these studies in the USA (e.g. Shrader-Frechette, 2002; Stretesky & McKie, 2016), Europe (Glatter-Götz et al., 2019; Steger, 2007), Latin America (Carruthers, 2008), Canada (Vaz et al., 2017), etc. Research outcomes have often established environmental inequalities harming racial/ethnic minorities, deprived and disadvantaged people. Sometimes, areas mainly populated by specific demographic groups (e.g. higher income groups, the elderly, children, immigrants, etc.) have been found to suffer from a lower environmental quality too (e.g. Bakhtsiyarava & Nawrotzki, 2017; Cooper et al., 2019; Havard et al., 2011; Mitchell & Dorling, 2003; Moreno Jiménez, 2007; Raddatz & Mennis, 2012; Hernández et al., 2015). Occasionally, the environmental—sociospatial association has not been clearly proved,

depending on the population group, the type of risk or pollution or the analytical techniques used (e.g. Buzzelli & Jerrett, 2007; Maroko, 2012; Romero-Lankao et al., 2013). Deguen and Zmirou-Navier (2010, p. 27), in their review focused on Europe, concluded that "some studies found that poorer people were more exposed to air pollution whereas the reverse was observed in other papers". The more recent work by Bulten (2016, pp. 49-50) found "a significant U-shaped association ..between air pollution levels and income on zip code level in Rotterdam and surrounding municipalities, meaning that air pollution levels are worse in lower- and higher-income areas". In their study for the whole of Europe, Richardson et al. (2013) reported that "no association for particulate matter and income was found taking Western Europe and Eastern Europe separately. However, when combining these data and looking for an association for particulate matter and income in Western and Eastern Europe combined, particulate matter was higher in more low-income areas". Moreno Jiménez et al. (2016) showed that exposure to high concentrations of nitrogen dioxide caused intra-urban imbalances, often at significant levels, among differing socio-demographic groups in Madrid and Barcelona (Spain).

Bearing in mind the different approaches taken in the aforesaid research, and given that population-environment interaction varies considerably, it is reasonably sound to approach environmental inequality problems using disaggregated diagnostics, i.e. considering different types of environmental hazards and different kinds of people. This is a prime assumption of our research, which focuses on the well-known empirical problem of PM_{10} concentration in the city air and the potential exposure of specific population groups considered to be vulnerable in previous work. Yet most notably, our approach involves a rationale and some relevant methodological decisions envisaging: 1) enhancing the diagnosis of possible environmental injustice, using a high spatial data disaggregation; and 2) addressing certain critical questions in EJ appraisal: What is a convenient baseline distribution of the environmental outcome? How much deviation of this baseline (i.e. inequality in environmental burden) is too much to be considered unfair and, therefore, to entail political action (regulation or action)? The ultimate goal is to support experts in better justifying their analytical decisions and help in a more consistent social and political judgement of environmental inequities.

3   Data and methods

In line with many other studies (e.g. Pesaresi et al., 2017), the concept of potential exposure (vs. actual exposure) to high concentrations of PM_{10} has been adopted as an expression of man-environment interaction. This involves some elements that introduce uncertainty when measuring.

The pollution indicator used here is a yearly average, which hides the usually important time variability. The amount of this pollutant recorded by a number of ground observatories has been used to estimate spatially disaggregated concentration levels. The current residence has been chosen to set the pollution level to which the population is exposed, so each individual's spatial-temporal mobility is disregarded. The main data sources and the pre-processing operations undertaken are now described in greater detail.

Firstly, a very important step in this research is accurately defining the relevant study area. Madrid and Barcelona are the two biggest cities in Spain (3.27 and 1.62 millions inhabitants respectively in 2011), and both show a quite compact urban structure. At first glance, the so-called urban space might be deemed appropriate, although some parts have had very unequal human presence over time. Therefore, our approach here has been to define the "urban populated area" (UPA) as one which, along with its surrounding area, has a significant amount of people every day. Residential, commercial and leisure, etc. land uses are included. At the same time, the extensive industrial, transport (e.g. seaports, airports), agricultural, and nature areas, with a very low or null population density are excluded. Operationally, the UPA limits have been based on a GIS-based interpretation of aerial photographs (The Spanish National Geographic Institute's National Plan for Aerial Orthophotography) and land use cartography (Corine Land Cover, 2006). Figure 1 shows the municipalities of Madrid and Barcelona and the UPA in the two cities, whose extension was 270.9 km^2 and 70.6 km^2 respectively.

Secondly, PM_{10} air pollution data have been provided by local and regional authorities (Madrid City Council and Regional Government, and Catalonia Regional Government). The ground stations used are located in the cities studied, Madrid and Barcelona, as well as in some neighbouring municipalities to improve spatial sample data coverage. All stations with available data in the study area and surroundings have been included. The environmental indicator selected was the average annual particulate matter of less than 10 μm, PM_{10} (μg/m^3) in 2010. Figure 1 displays this indicator in both cities, using graduated symbols and equal intervals techniques. As is well known, the main source of particulate matter in many cities is vehicle traffic, which is responsible for both direct emissions from combustion and those stemming from the re-suspension of material from the road surface, as a consequence of the mechanical abrasion of vehicles, brake pads, tyres, etc. A further significant part stems from emissions derived from building work, demolition etc. The concentration depends on atmospheric dynamics, which influences the dispersion, stagnation and transport, as shown in Barcelona and the Western Mediterranean (Viana et al., 2005; Querol et al., 2003; Rodríguez et al., 2002).

Figure 1. The cities of Madrid (left) and Barcelona (right) showing the municipal and district boundaries, the study area (UPA) and the average air PM$_{10}$ levels (2010) recorded by the ground stations used in the study
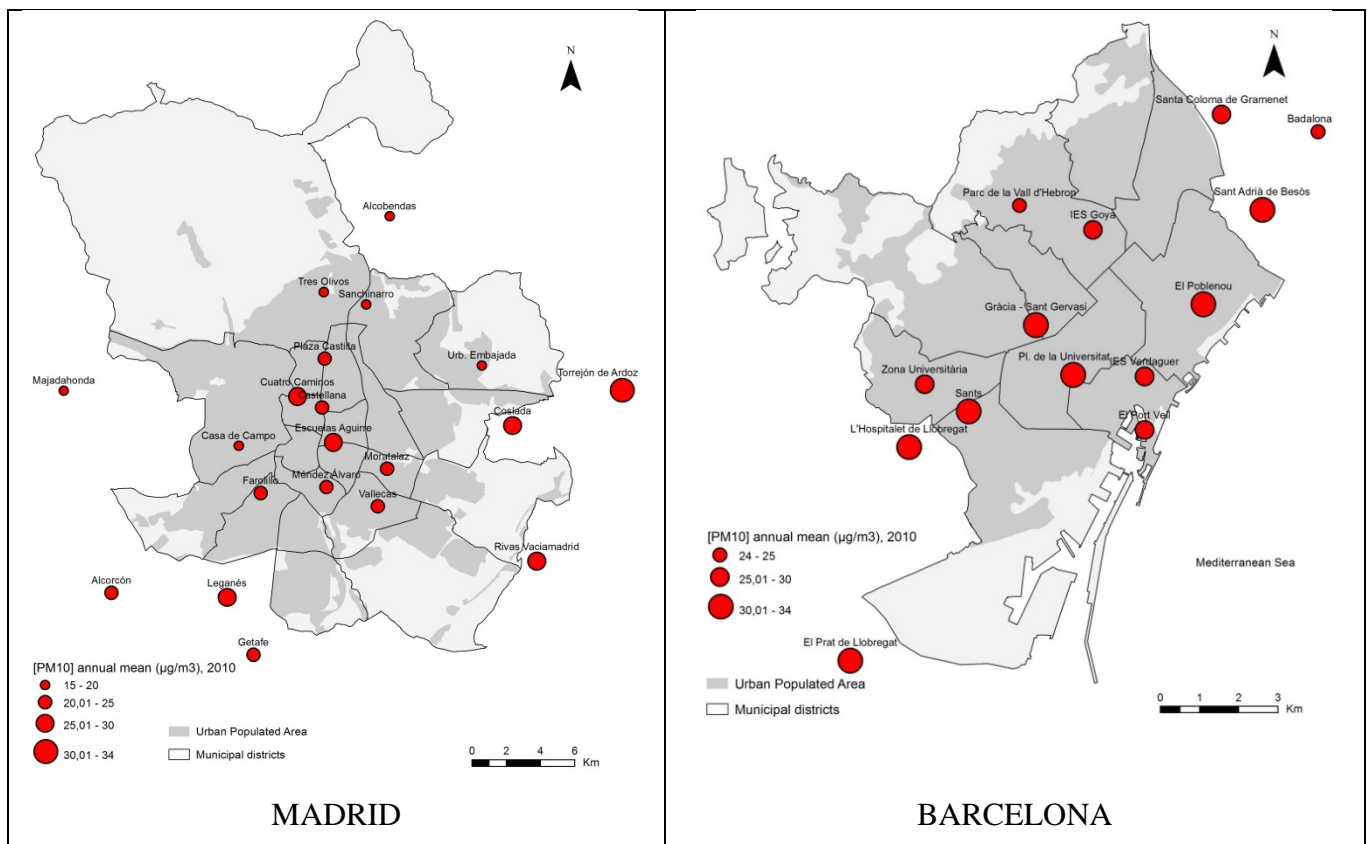
Warning note: maps at different scales.

Source: own elaboration

Given that available data are a quite limited spatial sample, assessing intraurban environmental inequalities involves estimating detailed pollution levels throughout the city (UPA), and this was achieved by using spatial interpolation (Cañada Torrecilla et al., 2014). Anisotropic Kriging provided the best results in the predicted values, both in Madrid and Barcelona, with predicted value mean errors (ME) near 0, low root mean square errors (RMSE) and a root mean square standardised errors (RMSSE) of near 1. Table 1 shows the model goodness-of-fit and the parameters used in each city. This involved selecting PM$_{10}$ estimation sampling points at each site, adopting an elliptical neighbourhood with the best size, orientation and number of sectors, and nearby points that also show the lowest differences between the observed values and those predicted by the model. Table 2 displays a statistical comparison of the original and the estimated values by spatial interpolation. In general, there is an acceptable similarity between the two cities, except for the estimate of the maximum value and range in Madrid. This seems to obey the logical-mathematical structure of Kriging that results in some smoothing of estimates.

Table 1. Parameters used in the interpolation of PM_{10} and models goodness-of-fit

MODEL	PARAMETERS / MEASURES	CITIES	
		MADRID	BARCELONA
Anisotropic Kriging	Number of neighbouring points (max/min)	7/3	5/2
	Search vicinity: form, sectors, rotation, axes length	Ellipse, 4 sectors, 45°, 9000/5000	Ellipse, 4 sectors, 45°, 9000/3000
	Angle of ellipse rotation	35°	61°
Goodness-of-fit	Mean error (ME)	-0.04	0.35
	Root mean square error (RMSE)	3.58	2.86
	Root mean square standardised error (RMSSE)	0.98	0.91

Source: own elaboration

Table 2. Descriptive statistics of the PM_{10} observed values and predicted by Kriging

DESCRIPTIVE STATISTICS	MADRID		BARCELONA	
	OBSERVED DATA	ESTIMATED DATA	OBSERVED DATA	ESTIMATED DATA
Mean	22.85	22.13	29.7	29.3
Standard desviation	4.36	2.26	3.1	2.11
Maximum	34	26.96	34	32.7
Minimum	15	16.86	24	25.5
Range	19	10.10	10	7.2
n	20		14	

Source: own elaboration

It should be underscored here that 40 µg/m^3 is the PM_{10} average annual limit acceptable by Spanish law and by the European Union (hereinafter referred to as EU). Nevertheless, the World Health Organisation is stricter, setting a level of 20 µg/m^3. It should be recalled that prolonged exposure to such pollution contributes to a number of cardiovascular and respiratory illnesses, as well as lung cancer (WHO, 2013; Querol et al. 2006). EU studies show too that life expectancy can be reduced by 8.6 months (Gurjar et al., 2010).

One crucial point of our fairness analysis lies in the fact that a limit has to be set to assess whether or not the concentration of the pollutant in the air is acceptable. Adopting the WHO or the EU/Spain criteria for this purpose brings different and partially contradictory situations: observed PM_{10} data show that neither Madrid nor Barcelona exceeded the 40 μg/m^3 limit, so if this maximum is used there would be no environmental problem. However, adopting the far stricter WHO threshold of 20 μg/m^3 brings differing scenarios. Some areas in Madrid would be over the limit, while the whole city of Barcelona would exceed that value. For this reason, a methodologically flexible approach has been adopted, assuming that air pollution is a problem that has to be reduced over time to acceptable levels. Consequently, the strictest threshold of 20 μg/m^3 (WHO limit) was adopted for Madrid, while in the case of Barcelona, a 30 μg/m^3 limit was established, halfway between 40 μg/m^3 (EU) and 20 μg/m^3 (WHO), as a short-term sustainability target.

The choice of socio-demographic groups or indicators to be considered in the environmental inequality assessments is an essential social and political issue. In this study, criteria of human vulnerability, and indirectly deprivation, have been prioritised. To this end, a small but relevant set of six population groups have been selected, taking into account the data available in the Municipal Register of Inhabitants, for small spatial units (Spain "census sections", commonly ranging from 1,000 to 2,000 people):

- Age criterion: children (0 to 4 years) and the elderly (over 80) are, due to their biological characteristics, quite sensitive to environmental hazards (see Cutter et al., 2003; Landrigan et al., 2010; Sánchez-González & Egea, 2011).

- Economic migration criterion: foreign immigrants from less developed countries than the EU and who usually occupy the lower levels of the employment pyramid, form another group that, while differing due to their country or region of origin, tend to suffer greater deprivation, experiencing poorer social and economic conditions (Bustamante, 2002). Published material consistently recognises these people as heavily vulnerable (e.g. Bakhtsiyarava & Nawrotzki, 2017, p. 60), equating their situation to that defined for criteria of race and ethnicity (e.g. Cutter et al., 2003). In order to differentiate the possible variations within this heterogeneous group, they were divided into four sub-groups, based on the region of origin, given its known tendency to spatial coalescence and segregation inside the city. Consequently, immigrants were differentiated depending on whether they came to Spain from Latin America, from Africa (mainly from the Maghreb and sub-Saharan Africa), Asians (mainly from China) and those from

less-developed Eastern European countries (mainly from Rumania, Bulgaria, Poland, Russia and the Ukraine).

The source of these population data sets and the vector digital cartography used in the analysis was Spain's National Institute of Statistics (2010). The census section polygons covering the whole municipal area were edited to include just the UPA extent and the population data was later converted to raster layers (50 m-resolution pixels, i.e. 0.25 ha), to ensure a higher spatial disaggregation of inhabitants. The result was a set of six, extent and resolution-consistent raster layers, each with an estimated per-pixel figure for the total population and for each of the six vulnerable demographic groups. These pre-processing operations were performed by using ArcGIS software.

Measuring EJ involved computing the amount of population (total and for each of the six demographic groups) in the two pollution intervals (above and below the critical levels of 20 or 30 $\mu g/m^3$, depending on the city), which provided the frequency distribution tables. This was performed using the Zonal Statistics tool in ArcGIS.

As anticipated earlier, a critical point of our analysis was to establish an acceptable distributive EJ criterion, that is, to determine the fair environmental burden to be borne by each socio-demographic group. This point is controversial, and there is a potential variety of responses. Much of the literature contains an explicit or implicit premise that the environmental burden should be proportional. In short, if the burden borne by the total population is considered to be equivalent, for example, to the number (or proportion) of people affected by or exposed to an environmental hazard, then an equitable distribution would entail the same proportion of the burden being borne by each population sub-group. This is the baseline criterion assumed here as an operational rule of fairness. Obviously, other measures can also be envisaged, such as the proportion of the least-affected group, or eventually to pose some positive discrimination assuming that the most socially- or economically disadvantaged groups should bear a burden proportionally lower than the one borne by the population as a whole.

Various inferential statistical techniques were used to test the inequity hypothesis for a population group, according to the strict proportionality criterion, provided a convenient rule for EJ diagnostics and were applied with the NCSS statistical system.

A) The first technique was the goodness-of-fit χ^2 test for a sample (see Siegel, 1972, p. 64-69 and Ruiz-Maya et al., 1995, p. 75-77). This well-known independence test checks, as null hypothesis, H_0, that a population group's exposure to high PM_{10} air pollution level is equal to

that experienced by the whole population of the city, i.e. the group and the total frequency distributions (per PM_{10} level) are similar. The alternative hypothesis, H_1, would imply that the two distributions are different, that this, the group's exposure is either higher or lower than the total population's exposure. In this case, the differences between the observed and expected (supposing independence) frequencies and proportions will reveal whether or not there is any discrimination.

B) In the second, an environmental justice balance (Moreno Jiménez, 2010, 2012) was obtained for each group. This is based on the difference between the observed and the theoretically fair exposure distribution. The diagram shows, in percentage terms, by how much the observed frequency of the population group for each of the two PM_{10} intervals matches or deviates from the reference standard (the exposure of the total population). The analogy with the justice symbol permits a clear comparison and appreciation of situations among groups.

C) The third technique was the well-known One Proportion test. The Exact test version, based on the binomial distribution, compares the proportion of group's population exposed to high PM_{10} level and that observed in Madrid (≥ 20 µg/m^3) and Barcelona (≥ 30). The hypotheses are set as follows: H_0: $\pi = p$ versus H_1: $\pi \neq p$; this is usually called the two-tailed test, where π = the proportion of total population exposed to high pollution, and p = the proportion of a group's population exposed to high pollution. The decision criterion is set to $\alpha = 0.05$ and also for computing lower and upper confidence limits of a $100(1-\alpha)$ % confidence interval. It should be pointed out that $\pi = 0.9148$ in Madrid and $\pi = 0.5816$ in Barcelona.

It is worth adding some brief remarks on how these tests are used for this spatial data, in order to properly interpret the results. Tests usually assume that the sample (any population group) is randomly taken from the population, but in our case, although we are dealing with population samples, it is clear that they are not spatially random, but the result of the various factors driving the residential urban dynamics and structure. In this context, the hypothesis to be examined can be restated as follows: given the proportion of people exposed to high pollution in the total population (due to spatial patterns of the population and the pollution), to what extent is the proportion of those exposed in a specific population group (having a particular spatial pattern) similar to the overall population? Infinite intra-urban patterns of that group can be imagined, many resulting in accepting H_0, and some others resulting in rejecting it (and accepting H_1). Yet, in the last case it could be asserted that the particular spatial distribution of the population group

would be significantly different than the one observed in the whole population (otherwise it would be compatible with H_0).

The aforementioned techniques provide non-subjective rules, are complementary and can compare their respective sensitivity to elucidate the EJ measurement problem posed here. They are also consistent, because they adopt the same assessment criterion: the relative exposure in the city population is set as the benchmark. If the potential exposure of a particular population group to high levels of PM_{10} is significantly higher than that of the total population, then it would be negatively discriminated (environmental inequity). This would not be the case in the event of a similar level of exposure. One group might also have a significantly lower exposure to high pollution levels than the whole population; this would indicate an environmentally privileged or favourable situation, in the study context.

Finally, as the analysis involves multiple statistical tests, the Benjamini-Hochberg procedure has been applied to adjust the p-values, taking into account the false discover rate (FDR) (McDonald, 2014, p. 254-260). As is known, this rate focuses on type I error, that is, on the estimated proportion of significant tests that are actually not significant. A 5% chance of getting a false positive has been established.

4 Analysis of results

4.1 The pattern of PM_{10} air pollution in Madrid and Barcelona in 2010

The highest pollution levels in Madrid were found in the city centre and in the South and South-East periphery (see Figure 2). These findings can be related to the higher inner-city traffic emissions in the former zone, and possibly to the particles from the abundant dry and bare land of the adjacent outskirts in the latter. The lower polluted areas form a discontinuous peripheral fringe shape stretching from the North towards the West and the South-West.

Figure 2. A) Estimated average annual PM$_{10}$ pollution levels (equal intervals) in the Madrid atmosphere in 2010; B) pink lines depict the area that exceeded 20 μg/m^3
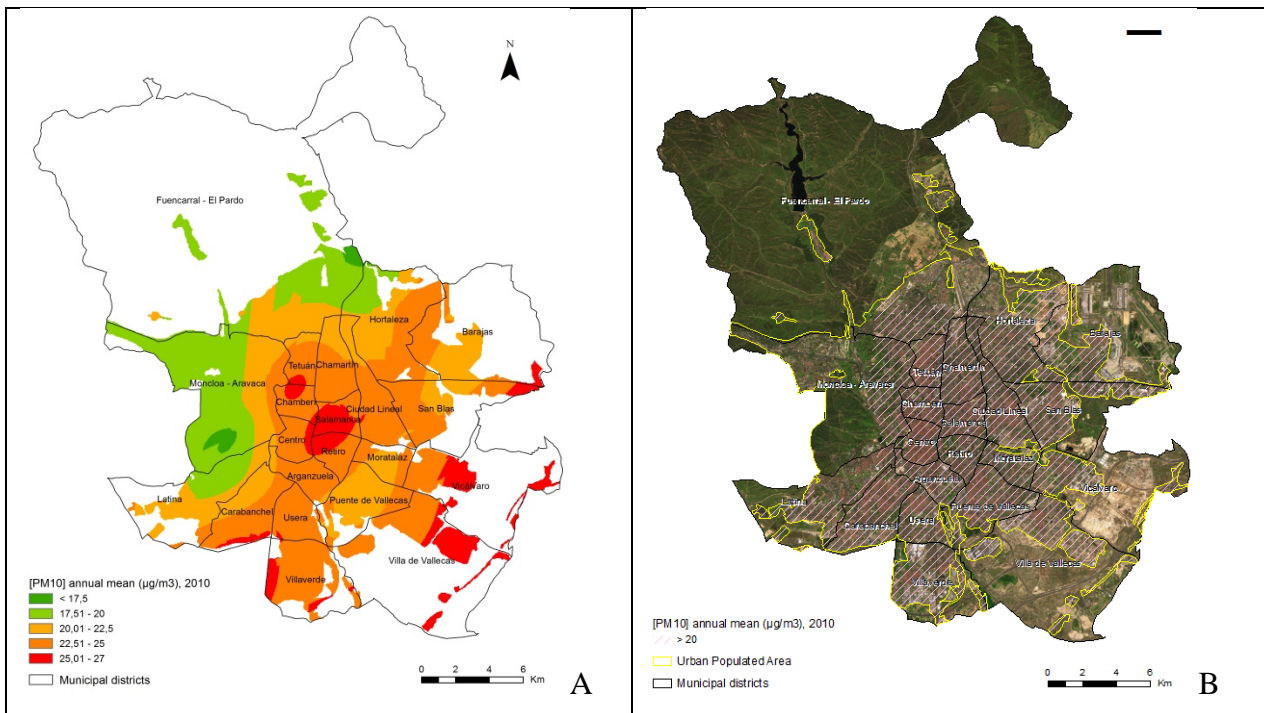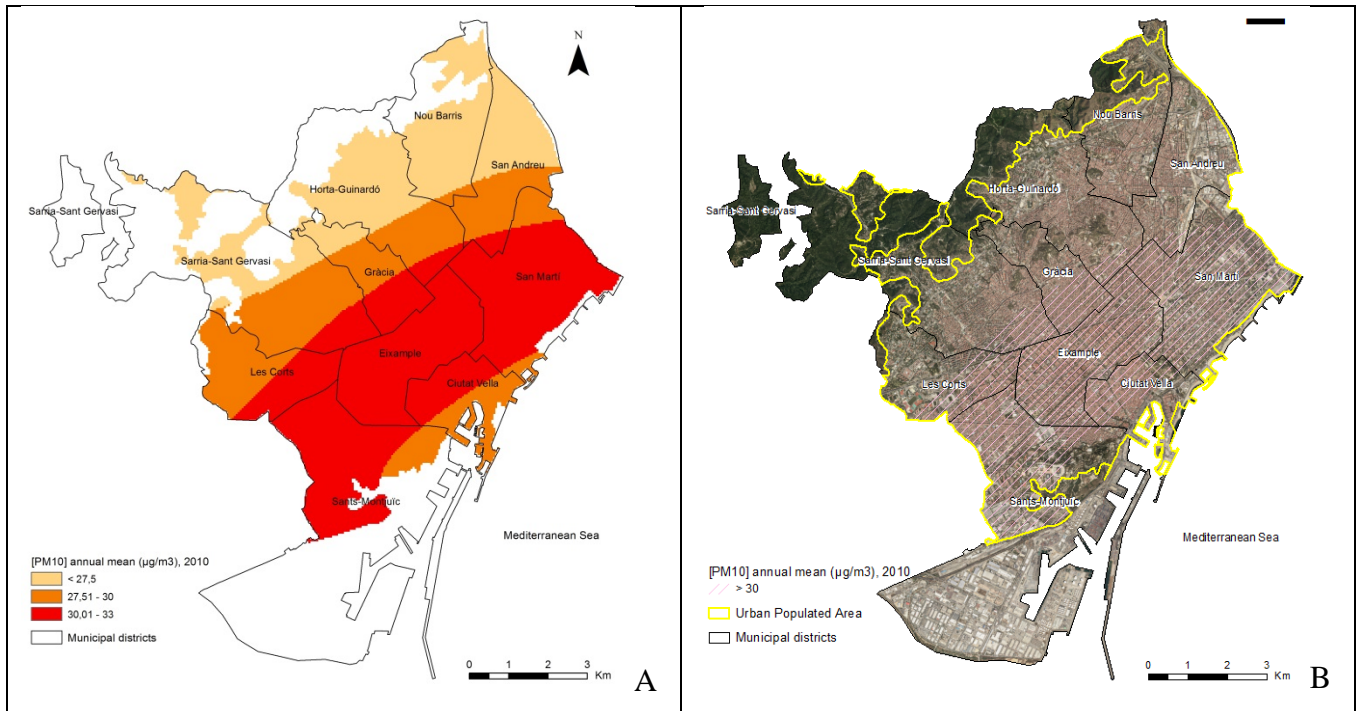

Source: own elaboration and Spanish National Geographic Institute (background aerial image)

In Barcelona, the estimated average annual PM$_{10}$ concentration formed a well-defined pattern (Figure 3), as a series of zones that ran almost parallel to the coastline. The pollution levels, except in the coastal-urban belt, fell as the altitude rose towards the northwestern hills. The lower and flat part of the city, next to the coast and dense traffic, suffered the worst air quality due to this source of pollution.

In short, the two cities did not show signs of serious risk of pollution per PM$_{10}$, according to the 40 μg/m^3 threshold set by the European regulation. However, given that the research cited by the WHO (2013) highlights the benefits of lower levels of PM$_{10}$ concentration in the atmosphere (and below the EU maximum), the thresholds applied here showed that there was inequality in terms of air quality. For example, using the 20 μg/m^3 threshold, Madrid would have 77.3% of the UPA classified as an at-risk zone, while 100% of Barcelona would be at risk of high PM$_{10}$ levels. Using an intermediate threshold of 30 μg/m^3, the percentage of the at-risk area in Barcelona drops to 45.6%.

Figure 3. A) Estimated average annual PM$_{10}$ pollution levels (nearly equal intervals) in the Barcelona atmosphere in 2010; B) pink lines depict the area that exceeded 30 μg/m^3

Source: own elaboration and Spanish National Geographic Institute (background aerial image)

4.2 The inequalities of potential exposure to high PM$_{10}$ in Madrid 2010

a) The contrasting situation of young children and the elderly

The analysis performed shows that the total estimated population exposed to levels of PM$_{10}$ in 2010 above the WHO threshold (>20 μg/m^3) was very high: 2,994,250 people, in other words, 91.48% of the inhabitants faced a major problem.

This figure anticipates a high level of exposure as far as population sub-groups are concerned, notwithstanding their differences. Table 3 shows the comparative results. The exposure to high PM$_{10}$ levels suffered by children aged 0-4, while still the lowest, was at around 88%, while in the case of the elderly (aged 80 and over) exposure figures were among the highest (93%). Different situations were also found for both groups when compared to the total population, as expressed by the environmental justice balance (Figure 4). These diagrams show that children were proportionally less exposed to pollution than expected, and therefore they enjoyed a slight environmental advantage. The elderly, however, a little more exposed than expected, were slightly disadvantaged. The findings highlight the fact that there was a higher number of elderly people in the central areas of the city (Figure 5A), where there was a higher pollution level per PM$_{10}$, due to heavier car traffic. Children, who were more abundant in the outlying suburbs,

were subject there (mainly in the West and North areas) with a lower air particle concentration, which gave them a statistical comparative advantage (over 3%).

Figure 4. Environmental equity scales for two vulnerable age groups in Madrid regarding PM$_{10}$ air pollution, 2010
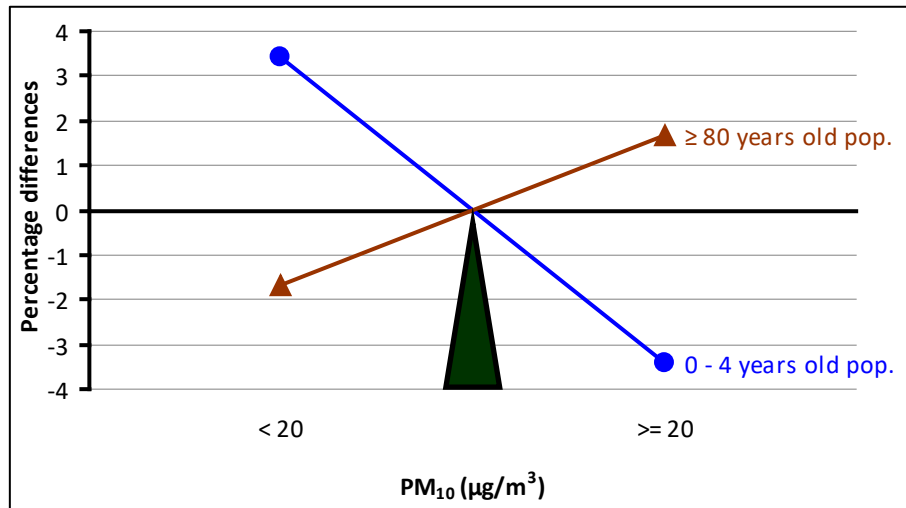
Note: Vertical axis displays group exposure deviations (in percentage units) from total population exposure.

Source: own elaboration

Figure 5. Maps showing the grey area with high concentration of PM$_{10}$ in the air (annual average > 20 μg/m^3) in 2010 and the population densities of people aged 80 (A), Asian immigrants (B) and African immigrants (C) in Madrid (2011)
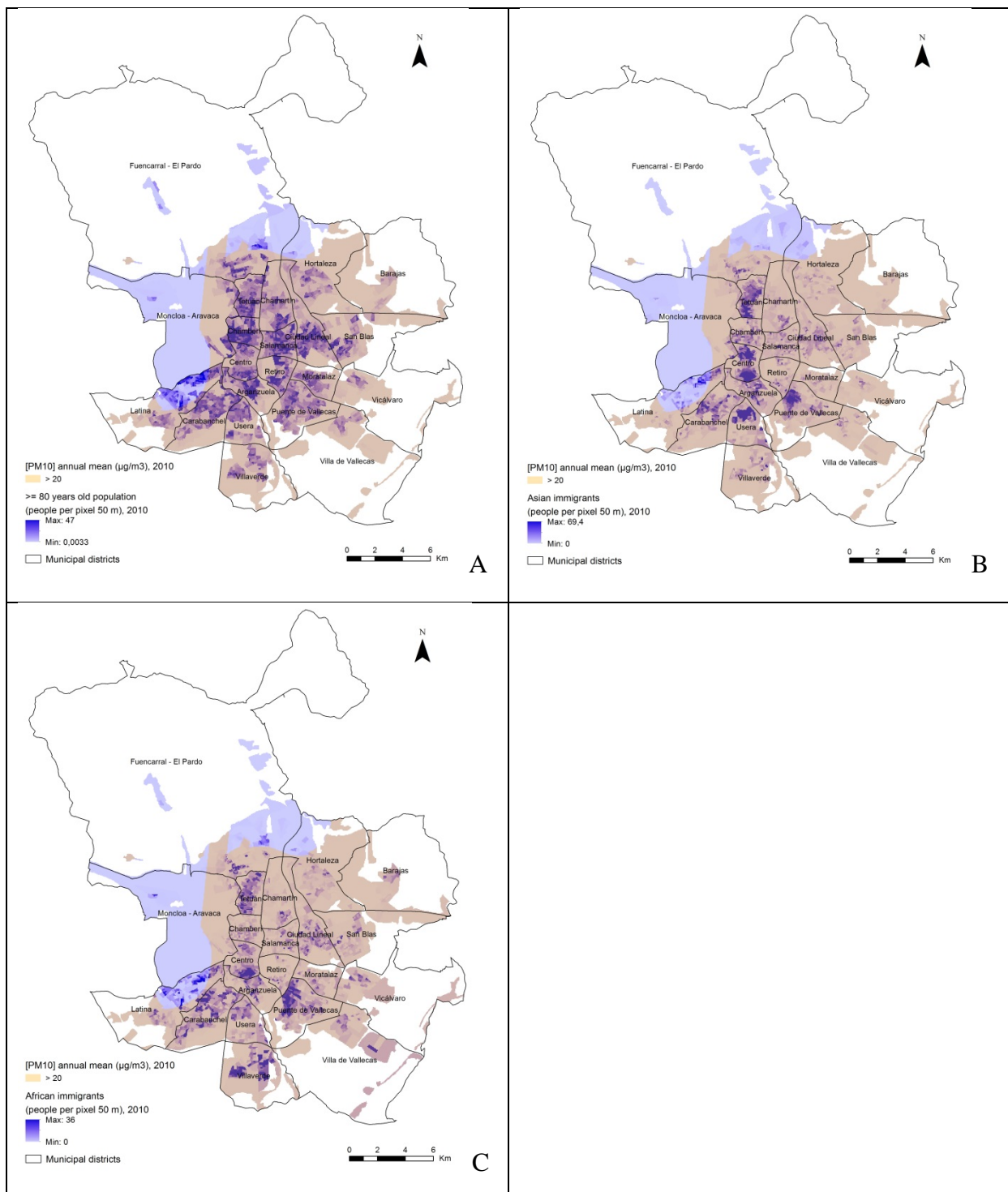
Source: own elaboration

According to Table 3 (rightmost column), there are important differences between the absolute exposed population figures and the expected figures (given the hypothesis of equity, i.e. a similar proportional exposure level). Accordingly, the goodness-of-fit test χ^2 indicates that all

divergences are statistically significant (not explainable by chance), with a p-value near 0 (Table 3). It could be therefore asserted that the pollution exposure of these two groups was noticeably different to that of the total population, with a clear disadvantage for the elderly.

Table 3. Environmental equity (goodness-of-fit) statistical tests for vulnerable groups in Madrid regarding PM_{10} air pollution exposure (2010)

VARIABLE	x^2 WITH 1 DEGREE OF FREEDOM	p-VALUE	ESTIMATED EXPOSED POPULATION TO PM_{10} >20 µg/m^3 (A)	EXPECTED EXPOSED POPULATION ACCORDING TO EQUITY SITUATION (B)	ESTIMATED UNDER- OR OVEREXPOSURE (A) - (B)
Population 0–4 year old	2466.23	0.000000	143125 (88.04 %)	148714 (91.48 %)	-5589
Population ≥ 80 year old	696.87	0.000000	176324 (93.18 %)	173118 (91.48 %)	3206
Latin American immigrants	57.97	0.000000	277534 (91.87 %)	276366 (91.48 %)	1168
African immigrants	236.69	0.000000	39844 (93.56 %)	38958 (91.48 %)	886
Asian immigrants	457.01	0.000000	48875 (94.10 %)	47515 (91.48 %)	1360
European immigrants	269.06	0.000000	85812 (90.00 %)	87225 (91.48 %)	-1413

Key: Pink: unfairly overexposed groups / Green: underexposed groups.

Source: own elaboration

The One Proportion test for these two age groups (Table 4) confirms the rejection of H_0, and the acceptation of the H_1 alternative hypothesis (α = 0.05); therefore, due to their spatial distribution, they suffered a significantly different exposure (environmental burden) to that of the total population of the city.

Table 4. Results of the Exact One Proportion test (environmental justice) for vulnerable groups in Madrid regarding PM_{10} air pollution exposure (>20 µg/m³) (2010)

POPULATION GROUP	SAMPLE PROPORTION (p)	PROB. LEVEL	REJECT H₀ AT α = 0.05?	95% CONF. INTERVAL OF p	
				LOWER LIMIT	UPPER LIMIT
Population 0–4 year old	0.8804	0.0000	Yes	0.8788	0.8820
Population ≥ 80 year old	0.9318	0.0000	Yes	0.9306	0.9329
Latin American immigrants	0.9187	0.0000	Yes	0.9177	0.9197
African immigrants	0.9356	0.0000	Yes	0.9332	0.9379
Asian immigrants	0.9410	0.0000	Yes	0.9389	0.9430
European immigrants	0.9000	0.0000	Yes	0.8981	0.9019

Note: H_0: π (0.9148) = p; H_1: π≠ p

Pink: unfairly overexposed groups / Green: underexposed groups.
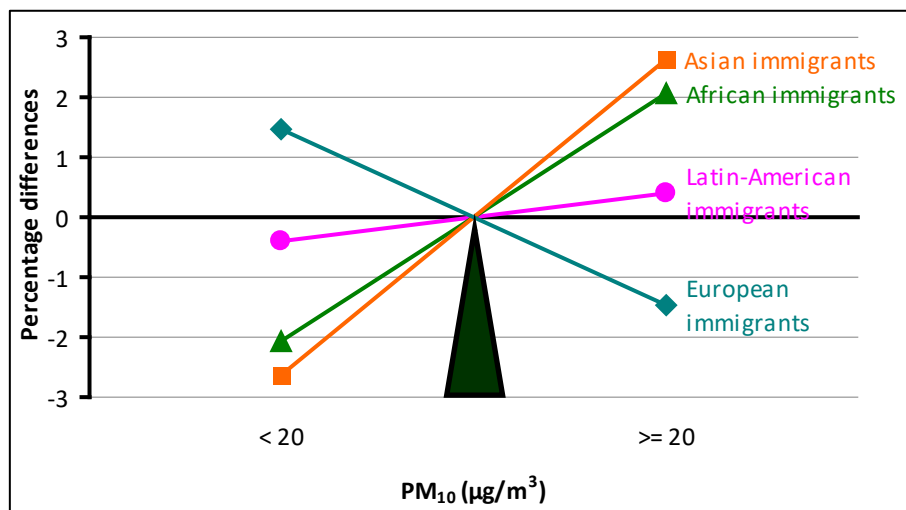
Source: own elaboration

b) The disparate situation of foreign immigrants from less-developed countries

The four groups of immigrants (Table 3) also suffered an important and mostly equally exposure to high concentrations of airborne particles, varying from 90% to 94%. Compared to the total population, the scales in Figure 6 show that three of the four immigrant groups were proportionally more exposed than expected in the baseline equity situation, and therefore more disadvantaged, especially those from Asia and Africa (over 2%). Figures 5B and C show that the uppermost densities of Asians and Africans were found in the most polluted areas. The exposure experienced by Latin Americans was quite similar to that of the total population, so they were close to the equity situation (only slightly disadvantaged). The same was not true for European origin immigrants, who were the only "advantaged" group, because of being less exposed than expected. That is why the right arm of the scale is the only one that falls beneath the horizontal line (i.e. the equity criterion), as shown in Figure 6, and the reason for this seems to be the larger number of European immigrants living in the South West of the city, an area where the average annual concentration of PM_{10} was estimated to be below 20 µg/m³. Anyway, the level of probability (p) resulting from the χ^2 test is close to zero for each of the four groups, showing that

these moderate differences in the potential exposure of all of them regarding the total population are statistically significant.

Figure 6. Environmental equity scales for four vulnerable immigrant groups in Madrid regarding PM$_{10}$ air pollution (2010)

Note: Vertical axis displays group exposure deviations (in percentage units) from total population exposure.

Source: own elaboration

The One Proportion test for these four groups of immigrants (Table 4) confirms the alternative hypothesis ($\alpha = 0.05$); this means that, due to their spatial distribution, their exposure to high pollution (i.e. an environmental burden) was significantly different to that of the city's total population.

A final highlight is that both statistical tests show consistent results, and both are quite sensitive to even seemingly moderate differences in exposure ratios. The adjusted p-values (Benjamini-Hochberg procedure) support all tests are significant, as shown in appendix table 3A; the same conclusion is got for table 4.

4.3 Inequalities of potential exposure to high PM$_{10}$ in Barcelona 2010

It is worth remembering that, as mentioned in the methods section, the adoption of the regulatory WHO or Spain/EU limits in Barcelona, regarding the average annual concentration of this pollutant, may lead to the conclusion that either there is no problem (as the critical level is not exceeded), or else there is full exposure for residents. The 30 µg/m^3 threshold adopted for this study represents an intermediate step toward an improved situation, useful for analysis, although a comparison with Madrid results is not possible.

a) The contrasting situation of young children and the elderly

In Barcelona, the estimated population living in areas with PM_{10} above the 30 µg/m^3 level was 941,880 people in 2010, that is, more than half (58.16%) of the total population was potentially exposed to this hazard.

The results of the potential exposure experienced by population sub-groups in Barcelona are set out in Table 5. The two age groups (children aged 0-4 and elderly over-80s), showed a relatively near and moderate level of exposure: 56% and 60%. However, clear differences appear when compared to the total population, as can be seen in the environmental justice scales in Figure 7: children were proportionally less exposed than expected (less than -2%), whereas in contrast, the elderly were slightly more exposed than expected (over +1%). Children were therefore more advantaged, while the elderly were somewhat disadvantaged. Figure 8A shows both the most polluted area and the density of elderly people, who are notably present in the city's worst air quality zone.

Figure 7. Environmental equity scales for two vulnerable age groups
in Barcelona regarding PM_{10} air pollution (2010)
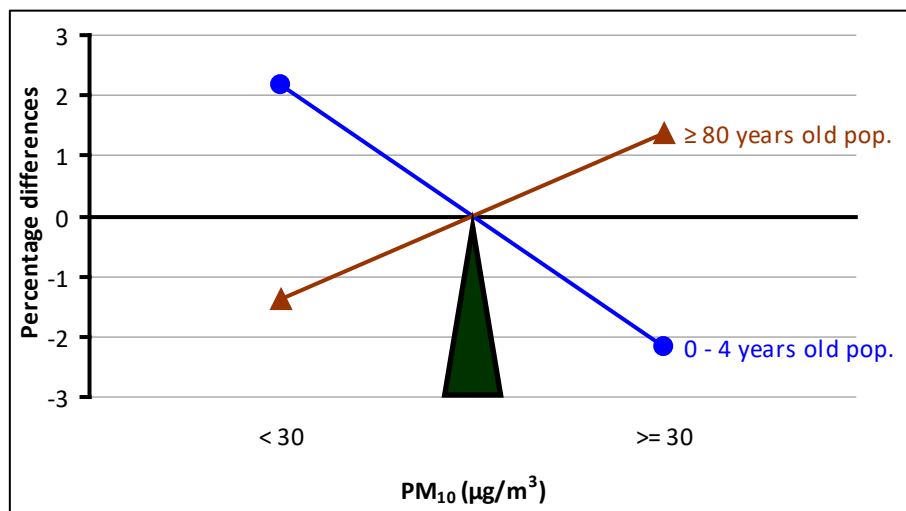
Note: Vertical axis displays group exposure deviations (in percentage units) from the total population exposure.

Source: own elaboration

Figure 8. Maps showing the grey area with high concentration of PM_{10} in the air (annual average > 30 μg/m^3) in 2010 and the population densities of people aged $\geqslant 80$ (A) and Asian immigrants (B) in Barcelona (2011)
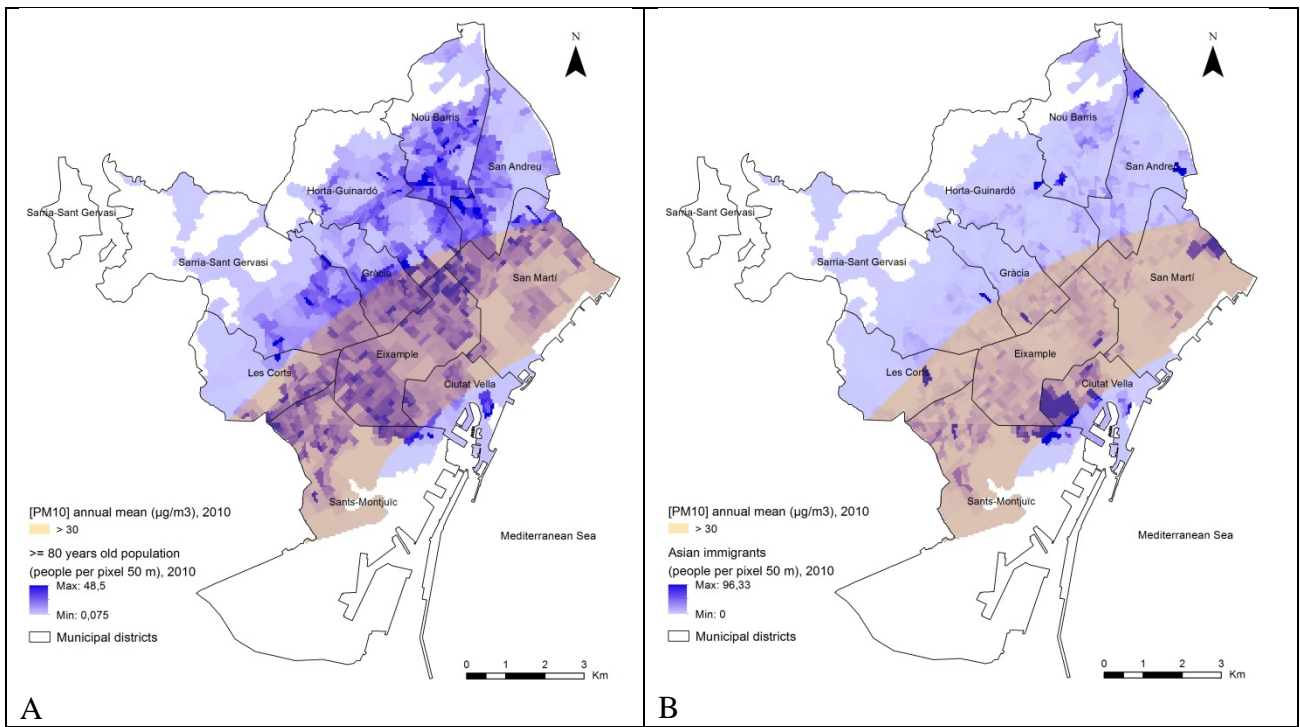
Source: own elaboration

Although both sub-groups showed moderate differences between the absolute exposed and the expected population figures, the quantitative testing of the environmental equity hypothesis (i.e. a similar proportional level of exposure), with the goodness-of-fit test χ^2 (Table 5), confirms that the potential exposure of both groups significantly diverges from that of the total population (p-value close to zero). The One Proportion tests for these two age groups (Table 6) reject H_0 and endorse the alternative hypothesis (H_1) in Barcelona as well ($\alpha = 0.05$). Given these findings, it can be interpreted that both groups deviated from the proportional equity, and that the elderly were somewhat negatively discriminated.

Table 5. Environmental equity (goodness-of-fit) statistical tests for vulnerable groups in Barcelona regarding PM_{10} air pollution exposure (2010)

VARIABLE	x^2 WITH 1 DEGREE OF FREEDOM	p-VALUE	ESTIMATED EXPOSED POPULATION TO $PM_{10} > 30$ $\mu g/m^3$ (A)	EXPECTED EXPOSED POPULATION ACCORDING TO EQUITY SITUATION (B)	ESTIMATED UNDER- OR OVEREXPOSURE (A-B)
Population 0–4 year old	137.30	0.000000	39467 (55.99 %)	41002 (58.16 %)	-1535
Population ≥ 80 year old	86.00	0.000000	64748 (59.55 %)	63239 (58.16 %)	1509
Latin American immigrants	1.21	0.271537	60898 (58.00 %)	61073 (58.16 %)	-175
African immigrants	21.77	0.000003	11751 (56.57 %)	12083 (58.16 %)	-332
Asian immigrants	3675.78	0.000000	38094 (71.08 %)	31171 (58.16 %)	6923
European immigrants	0.16	0.693150	9951 (58.31 %)	9925 (58.16 %)	26

Pink: unfairly overexposed groups / Green: underexposed groups / White: fairly exposed groups.

Source: own elaboration

Table 6. Results of the Exact One Proportion test (environmental justice) for vulnerable groups in Barcelona regarding PM_{10} air pollution exposure (>30 $\mu g/m^3$) (2010)

POPULATION GROUP	SAMPLE PROPORTION (p)	PROB. LEVEL	REJECT H_0 AT α = 0.05?	95% CONF. INTERVAL OF p	
				LOWER LIMIT	UPPER LIMIT
Population 0–4 year old	0.5599	0.0000	Yes	0.5562	0.5635
Population ≥ 80 year old	0.5955	0.0000	Yes	0.5926	0.5984
Latin American immigrants	0.5800	0.2833	No	0.5770	0.5830
African immigrants	0.5657	0.0000	Yes	0.5589	0.5724
Asian immigrants	0.7108	0.0000	Yes	0.7070	0.7147
European immigrants	0.5831	0.6923	No	0.5757	0.5905

**Note:** H_0: π (0.5816) = p; H_1: π ≠ p

Pink: unfairly overexposed groups / Green: underexposed groups / White: fairly exposed groups.

Source: own elaboration

b) The situation of foreign immigrants from less-developed countries

Table 5 shows that the potential exposure of the four immigrant groups selected in this study was also moderate, ranging from 56% to 58%, except for Asian origin immigrants, whose level rose dramatically to 71%. The environmental justice scales (Figure 9) show that the exposure to high PM_{10} experienced by Latin Americans and Europeans was proportionally similar to that of the total population (its lines almost match the horizontal) and were therefore relatively close to the equity baseline. Africans were somewhat advantaged (by more than 1%), due to their greater presence in the North of the city, an area which did not exceed the critical PM_{10} threshold set here. Conversely, Asian immigrants were environmentally strongly disadvantaged, as shown in the right arm of their balance, almost 13% above the critical PM_{10} threshold. This seems to be because this most of this group lives in just a few areas of the city, especially in the old centre, whose annual average PM_{10} concentration was over 30 $\mu g/m^3$, as shown in Figure 8b.

Figure 9. Environmental equity scales for immigrant vulnerable groups in Barcelona regarding PM_{10} air pollution (2010)
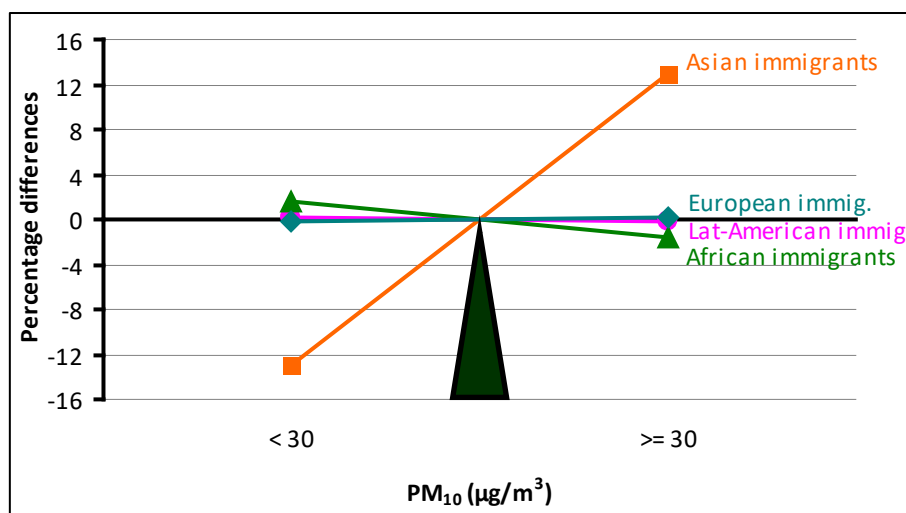
Note: Vertical axis displays group exposure deviations (in percentage units) from total population exposure.

Source: own elaboration

Table 5 shows that the p-value resulting from the χ^2 test is close to zero for Africans and Asians, showing a statistically significant difference in the potential exposure of both groups concerning the population as a whole. However, this is not true of Latin American and European immigrants, whose p-value is greater than 0.05, suggesting that their potential exposure to high PM_{10} was very similar to the total population of Barcelona (i.e. H_0 is accepted). Based on the

methodological rule-set here, it could be said that they did not suffer negative environmental discrimination vis-à-vis this pollutant.

The One Proportion test for African and Asian immigrants (Table 6) confirms the alternative hypothesis H_1 ($\alpha = 0.05$), meaning that due to their spatial distribution, their pollution exposure (environmental burden) differed significantly to that of the total population of the city. However, Latin Americans and European immigrants from less-developed countries showed a percentage of exposure similar to that of the city as a whole. In short, these results agree with the former findings from the χ^2 test.

Again, the two statistical tests show consistent results, both when rejecting or accepting H_0, so they help to discriminate between low and moderate differences in exposure. The adjusted p-values (Benjamini-Hochberg procedure) support that tests are significant, except for Latin-American and European immigrants, as shown in the appendix for table 5a (the same conclusion is got for Table 6).

5 Discussion

The possible environmental injustices in certain places or situations have fostered many studies that use quantitative techniques to test whether or not some population groups are negatively discriminated. The variety of environmental problems, the complexity involved in measuring environmental and human aspects and the multiplicity of analysis techniques have resulted in a wide range of approaches. Our comments here will focus, first, on the method used to assess EJ based on exposure to air pollution and, second, on the findings of this work.

Methodologically speaking, a common approach has been to use relative indicators for small spatial units, e.g. percentages of disadvantaged or vulnerable groups (ethnic and racial minorities, those with low incomes, low educational level, etc.), to verify whether the highest values appear in the areas exposed to hazards or are affected by negative environmental impacts. Different statistical techniques have been employed to this end, for example, correlation and association coefficients, ordinary and spatial regression models, etc. (see Buzzelli & Jerrett, 2004; Jerrett et al., 2001). Such analysis has enabled researchers to confirm this relationship in many cases. However, as Jacobson et al. (2005) point out, the use of such techniques has certain limitations and can only research EJ hypothesis to a certain extent. In part, because with these relative data, conditioned by a specific spatial partition and the consequent data aggregation, it cannot be clearly determined if these population groups are discriminated against, that is,

whether and how much the total amount and percentage of affected / exposed members of a group are greater or disproportionate in comparison to other groups or to the total population in the studied area. In other words, many of these techniques are unsuitable for accurately ascertaining if the exposure of a certain group to an environmental burden (expressed, for instance, as the number of people exposed or affected by a hazard) is too much vis-à-vis a baseline equity criterion, and consequently if it denotes an environmental injustice.

Some researchers have used different approaches and methods. Ogneva-Himmelberger & Huang (2015), for example, applied the two-sample Welch's t-test (an adaption of Student's t-test to compare means from two samples). The aim was to ascertain if tracts potentially exposed to an environmental hazard had a significantly higher percentage of some deprived or vulnerable groups than non-exposed tracts. Interestingly, the analysis was based on a comparison of the relative indicators for small spatial units, but it could not calculate the extent to which a population group experiences an unfair environmental burden (and how much) within the study area.

A number of studies, for example Chakraborty & Armstrong (1997) and Bosque et al. (2001–2002), albeit in a relatively descriptive manner, have compared proportions of population groups who are exposed to an environmental hazard. Brainard et al. (2003) assessed the EJ hypothesis more appropriately in their research on exposure to urban noise in Birmingham. They used Kolmogorov-Smirnov statistics for two-sample tests, comparing cumulative probability distributions for specific population groups and the total population. This let them determine which group was overexposed and whether or not this difference was statistically significant.

Our research method went further along this line and sought to prove environmental injustice by estimating the absolute and relative number of people from vulnerable groups who are potentially exposed to an environmental hazard within a specific place. This involved operationally defining a critical pollution threshold and a standard of fairness. Our baseline criterion was the total population exposed / not exposed to the hazard. However, other benchmarks, such as the exposure observed in the most advantaged or disadvantaged group in the study area, could be considered. Obviously, decision-makers would have to pre-define or pre-agree on this issue.

Having established that, the EJ hypothesis can be accepted / rejected through straightforward statistical testing. The method used here replicates that of Moreno Jiménez et al. (2016), but it adds the One Proportion test, as an alternative tool, and controls the false discovery rate. These techniques provide a more objective rule, enabling researchers to accurately discern if the difference between a group's and the total population's (as baseline) exposure to hazard is too

much, i.e. if it is statistically significant and can therefore be classified as disproportionate and unfair. Certain additional operations can be used to calculate the extent of the over- or under-exposure for each population group, and build an intuitive graphic representation, the EJ scale, as a way of supporting comprehension by and dissemination among the public at large. Results of this kind offer well-defined gains for their eventual inclusion in the analysis to support public decision-making processes on environmental hazards.

As far as the empirical findings are concerned, it should be remembered that, due to the diverse levels of pollution in the two cities, different PM_{10} thresholds were adopted for each: 20 $\mu g/m^3$, the threshold set by the World Health Organization in the case of Madrid, and 30 $\mu g/m^3$ for Barcelona, making it impossible to compare the two cities' results.

The findings have pointed to certain inequalities that deserve comparative comments. Children appear to be advantaged in both cities (by over 2%), as compared to the over 80's, who suffer over-exposure to higher PM_{10} levels. In a former study on Hong Kong, Fan et al. (2012) found elderly people to be exposed to relatively higher levels of traffic air pollution, and Ouyang et al. (2018) also found that older people (age≥60) were the most disproportionately exposed to $PM_{2.5}$ in Beijing, although exposures were too disproportionately high for children (age ≤ 4) in some seasons. Our results here coincide with other research into exposure to NO_2 in big Spanish cities, and are linked to the larger numbers of young people in the city outskirts and of elderly people in the city centre (Moreno Jiménez et al., 2016). However, other authors (e.g. Brainard et al., 2002; Clark et al., 2014) did not find any significant relationship between other air pollutants (CO, NO_2) and these age groups.

As far as immigrants from less-developed countries are concerned, there were some similarities in both cities: Asians were the most exposed, especially in Barcelona, while in Madrid, Africans were overexposed as well. In terms of better comparative situations, this only slightly concerned European immigrants in Madrid. Other groups showed a potential exposure burden that deviated relatively little from the estimate for the total population. Moreno Jiménez et al. (2016) found that Asian immigrants also suffered over-exposure to high NO_2 levels, although not all other immigrant groups did. Studies in USA, Canada or UK cities on ethnic group over-exposure to air pollution have reported diverse results (Moreno Jiménez et al., 2016, p. 128), although some of them confirm the inequalities (e.g. Hernández et al., 2015, for Hispanics in Houston, Texas). Despite only focusing on exposure to industrial facility emissions, Bakhtsiyarava & Nawrotzki (2017) paper on the USA showed that immigrants tend to be less exposed to toxins, while in

wealthy regions Mexican immigrants were disproportionately exposed to these environmental hazards.

6 Conclusions

Human exposure to severely polluted environments is an enduring issue in many human settlements. It has not been until recent decades, however, that it has been highlighted as an environmental injustice (manifested as discomfort, illness, etc.) affecting specific socio-spatial groups or territories. The scientific community has faced the challenge of determining these inequalities, and there is a growing body of work published on the subject. These have often highlighted different types and extents of discrimination, although the analytical tools and the information gathered are somewhat diverse, according to the specific approaches, objectives, available data and spatial context. This poses the challenge of improved diagnosis better suited to public decision-making.

As we have argued here, even though a range of different techniques can be used to detect inequality, as shown in the published works, they seldom explicitly establish a baseline criterion of distributive environmental justice for accurately assessing and comparing the extent of inequalities that affect several socio-demographic groups. This was one of our main interests here, and to this end, the following basic assumptions were made: a) the overall environmental human burden can be measured as the amount of population exposed to high levels of air pollution; b) the suitable threshold for categorising pollution (hazard) as high or low can be defined operationally, either by international/national standards, technical criteria or by collective consensus, according to the study area context; and c) the total population affected/exposed can be proposed as a reasonable and comparative baseline criterion for socio-environmental justice.

Methodologically, after pre-processing the data using GIS, we used a set of effective statistical tools to ascertain which groups were discriminated against and to what extent. The χ^2 goodness-of-fit and the One Proportion test showed consistent results when applied to determine, in a more objective and replicable way, whether differences in exposure to poor air quality by some demographic groups vis-à-vis the total population of the city, should be categorised as disproportionate, and therefore unfair.

These techniques, together with the intuitive understanding underpinned by the EJ balance, can improve comprehension and appraisal of socio-environmental inequalities by experts and stakeholders.

From an empirical point of view, our study has shown that, alongside the significant general level of exposure in the two cities, certain demographic groups were proportionally overexposed to an annual average concentration of PM_{10} above the limits adopted in 2010. In short, and according to the results of χ^2 and proportion tests, all vulnerable groups in Madrid had significantly different levels of exposure to the total population. Children and European immigrants appeared to be comparatively advantaged, while all other groups were disadvantaged. In Barcelona, Latin American and European immigrants were subject to a similar level of exposure to that of the total population, although all other groups significantly deviated from observed percentages in the total population. Of these groups, only Africans, and especially young children, appeared to be underexposed, and therefore comparatively advantaged. To sum up, the various socio-spatial patterns entailed correlative environmental inequities, albeit of different type and magnitude.

As a final consideration, and regarding their application, this type of analysis and the results can be said to provide a clear and sound appraisal of environmental unfairness, quite appropriate for supporting public consciousness and decision-making processes that promote the well-known "right to the city". As for future improvements, intra-urban analysis should be broadened by using spatial units suitable for governance, for example, districts or neighbourhoods, to focus priority actions on the areas with high vulnerable group densities overexposed to air pollution hazards above tolerable limits. Estimating air quality remains another area of further enhancement, particularly with more detailed and reliable spatial data; recent advances, both in the ground (Pons et al., 2018) and remote sensors (Kloog et al., 2011; Moreno Jiménez et al., 2020; Prunet et al., 2020), are opening up promising paths that should be explored. In short, future analytical developments should consider the changing spatial location of people over time, and also the temporal variability of weather and pollution, as ways to get finer measurement of exposure inequalities.

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Domínguez: data and methods, analysis of results, and conclusions. Antonio Palacios García: data and methods, analysis of results, and formatting.

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Appendix I. Correction for false discovery rate (fdr) in multiple testing

Table 3a. Madrid: sorted original p-values of χ2 tests, significance and adjusted p-values according to the Benjamini-Hochberg's procedure

↓ POPULATION ↓ GROUP	↓ P-values ↓	Benjamini-Hochberg significance	Benjamini-Hochberg adjusted P-value
Population 0—4 year old	0.000000	significant	0.00
Population ≥ 80 year old	0.000000	significant	0.00
Asian immigrants	0.000000	significant	0.00
European immigrants	0.000000	significant	0.00
African immigrants	0.000000	significant	0.00
Latin American immigrants	0.000000	significant	0.00

False discovery rate = 0.05

Source: author's own elaboration

Table 5a. Barcelona: sorted original p-values of χ2 tests, significance and adjusted p-values according to the Benjamini-Hochberg's procedure

↓ POPULATION ↓ GROUP	↓ P-values ↓	Benjamini-Hochberg significance	Benjamini-Hochberg adjusted P-value
Asian immigrants	0.000000	significant	0.00
Population 0—4 year old	0.000000	significant	0.00
Population ≥ 80 year old	0.000000	significant	0.00
African immigrants	0.000003	significant	0.0000045
Latin American immigrants	0.271537	not significant	0.3258444
European immigrants	0.69315	not significant	0.69315

False discovery rate = 0.05

Note: The p-values close to 0 are ordered according to the statistics χ2

Source: author's own elaboration