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Assessing environmental justice through potential exposure to air pollution: A socio-spatial analysis in Madrid and Barcelona, Spain

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ABSTRACT

The concept of environmental justice (EJ) has recently gained currency, both as a factor for and a goal of sustainable development. Its implementation in practice implies establishing current environmental injustice patterns and analysing planning policies, with the aim to reduce socio-demographic inequalities in the negative environmental impact borne by different population groups. This paper proposes a method to assess differential exposure to excessive pollution levels by socio-demographic groups in intra-urban spaces.

The approach developed in this paper is based upon GIS and quantitative spatial analysis techniques. It incorporates the idea of an 'environmental justice weighting scale' for policy-making, using normative pollution thresholds to measure inequalities more objectively and consistently. Spain's two largest cities, Madrid and Barcelona, have been chosen as case-studies, taking nitrogen dioxide as the pollutant, and the geographic distribution of six vulnerable population groups (children, elderly people and international immigrants) in the year 2010. The results reveal that a large part of these groups suffer exposure to air pollution exceeding the maximum permitted levels disproportionately, which would imply a case of environmental injustice.

1. Introduction

The way we understand social and physical development has evolved over time. Today there is a consensus that it must satisfy a wide range of socially shared principles: quality of life and well-being, sustainability, social and territorial cohesion, competitiveness, spatial justice, social empowerment, participation and responsibility, etc. A further principle that is gaining international recognition within this framework is that of environmental justice (EJ) (see Agyeman and Evans, 2004; Blanchon et al., 2009; London et al., 2011; Martinez-Alier, 2002, Ch. 8 & 9). The richness and complexity of this concept is dealt with in numerous theoretical works on this subject (see for example Dobson, 1998; Kuehn, 2000; Walker, 2009; Wenz, 1988). EJ encompasses plural implications, as stated in the First National People of Color Environmental Leadership Summit document in 1991 and meanings, and is designated as a movement – indeed a right – to claim-making as distributive, procedural, corrective, social, geographical or political justice (see Bullard, 1994, 1996; Kuehn, 2000).

Although the scope of EJ has evolved and expanded (Walker, 2012, 2) one of its main components relates to 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" (Landrigan et al., 2010:178). This interpretation, named as distributive justice and adopted for our purposes here, implies that environmental 'burdens' (hazards, degradation, discomfort, unhealthy conditions, etc.) should be borne equally by a diversity of socio-demographic groups across space in a non-discriminatory manner. The disproportionate affection of the weakest or most vulnerable populations should be especially avoided (Moreno-Jiménez, 2010). Environmental inequalities can emerge in different ways (e.g. Walker, 2012) and are actually present in a wide range of situations, greatly affecting the wellbeing and health of certain population strata. For instance, studies conducted by Künzli et al. (2000), Peters et al. (2004), Schwela (2000), and Vimercati (2011) have demonstrated a clear correlation between a high prevalence of morbidity and mortality and high urban pollution, while the World Health Organization (2009, 2013) has established it as a major modern mortality risk.

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However, the effective implementation of the EJ principle is hindered by several challenges. It must firstly overcome political and governance challenges. Despite EJ being taken into account in some countries (particularly in the USA, for over two decades) when drafting policies, by and large, this aspiration is still awaiting public recognition by policy-makers elsewhere. The ideal goal would be for the EJ principle to permeate spatial and environmental decision-making processes, demanding the elimination or amelioration of this type of injustice by several means, for example, ex-ante assessment of socio-economic policies, urban planning or development projects (vid. Hervé Espejo, 2010), or through citizens' collective action (see Nweke and Lee, 2011; Schlosberg and Carruthers, 2010). Secondly, it must reach some sort of consensus amongst important theoretical debates on EJ set by various scholars over recent years (e.g. Abara et al., 2012; Blanchon et al., 2009; Boone, 2008; Brulle and Pellow, 2006; Elvers et al., 2008; Gottlieb, 2009; Schlosberg, 2004; Wakefield and Baxter, 2010; Walker and Bulkeley, 2006; Wilson, 2009). Thirdly, new methodological tools and empirical case studies are required, establishing procedures to evaluate environmental inequalities validated across a wide range of geographical locations and socio-political contexts. Finally, a fourth challenge is the dissemination of the implications of such analyses of EJ among decision-makers as well as public and private stakeholders, with a view to generating public awareness and promoting a more rigorous, better-informed and participative development decision-making processes.

Nonetheless, any rigorous assessment of such inequalities is yet to be concluded – Mitchell (2011) even argued that it was still only in its infancy. This is due to a host of problems around issues of data scarcity and limitations, as well as imperfect measurements and methods of analysis. Likewise, attention paid to assessment of environmental justice also differs greatly from country to country, as seen below.

The main objective of this contribution is twofold. It firstly aims to contribute with relevant case studies of environmental injustice in Spain, a country in which there is a lack of research-based evidence and public awareness on this subject. In particular, its two main cities are studied: Madrid (3,273,049 inhabitants in 2010) and Barcelona (1,619,337 inhabitants). As result of a quite similar urban history, their urban structures and social maps run parallel to each other in many ways. However, differences in their respective physical setting (Barcelona is on the coast and has a more diverse topography) have driven to some dissimilarities in the relative location of some human components and environmental characteristics inside both cities. Secondly, the paper proposes and evaluates a different procedure, based on well-known statistical techniques, for estimating cases of environmental injustice arising in intra-urban spaces. The case studies focus on the unequal spatial distribution of certain vulnerable population groups and on spatial differences in the quality of the atmospheric environment (expressed in terms of a major pollutant: nitrogen dioxide, NO_2).

The approach proposed in the paper features certain noteworthy characteristics. Firstly, it uses the concept of potential population exposure to air pollution estimated at different points throughout the city. Secondly, it not only aims to measure the presence of environmental inequality (by quantifying a pollution-to-population ratio), but it also attempts to establish a procedure for computing the magnitude of such inequality, in terms of how far a given situation diverges from theoretical equity, thus assessing its severity in order to prioritise possible public policy interventions. Finally, it should be also stressed that application of this approach is limited to issues concerning the social and spatial distribution of external environmental factors. It therefore does not address other important aspects such as the source of these emissions (external factors), who generates them (activities, population) and who benefits from their externalities.

The first section offers a review of the relevant bibliography on EJ assessment. The second section provides the rationale for the methodology proposed in the paper, as well as the data sources and analysis using Geographical Information Systems (GIS) and statistical tools. The third section offers an account and discussion of the results, showing that a large part of the studied population groups disproportionately suffer exposure to high pollution levels. The paper concludes with a section presenting the implications for future research and potential policy-making.

2. Literature review of EJ assessment

Research on EJ is clearly expanding all over the world, particularly in methodological developments and case studies contributions. Several literature reviews grounded on well-known bibliographic databases (Chakraborty et al., 2011; Holifield et al., 2009; Martuzzi et al., 2010; Mohai and Saha, 2006; Mohai et al., 2009; Reed and George, 2011) have synthesised the main contributions and research practices in this field.

The growing stream of academic publications on EJ predominantly originate from English-speaking countries (mainly the US and UK). In other European countries, research began later and is still in its infancy (see the reviews by Maier and Mielk, 2010; Moreno-Jiménez, 2010; Raddatz and Mennis, 2012), while in other parts of the world, such as Asia (Harding, 2007), Latin America (Carruthers, 2008), or Africa, attention to this topic is only just beginning.

Furthermore, the majority of the EJ literature remains focussed on the socio-spatial distribution of environmental hazards, primarily toxic waste, dangerous activities, air pollution, noise and physical risks. Jerrett (2009) pointed to a shift in emphasis from studying the unequal exposure of racial and social groups to specific sources of toxic pollution (e.g. Bowen et al., 1995; Chakraborty and Armstrong, 1997; Maranville et al., 2009; Mohai and Bryant, 1992; Wilson et al., 2012) to more recent efforts centred on the social inequalities in the exposure to noxious gases and noise from traffic (Bocquier et al., 2013; Buzzelli and Jerrett, 2007; Havard et al., 2009, 2011; Moreno-Jiménez, 2007; Moreno-Jiménez and Cañada-Torrecilla, 2007) and airports (e.g. Sobotta et al., 2007). Recently, some health-related multiple environmental deprivation indexes have been designed, integrating the pathogenic and 'salutogenic' characteristics of places (e.g. Pearce et al., 2010, 2011; Richardson et al., 2010).

An emphasis on social aspects, race/ethnicity and income has prevailed in US studies (e.g. Bullard, 1983; Buzzelli and Jerrett, 2004). A variety of socio-demographic data have also been considered to define groups by age, gender, nationality, education level, occupation, disability, vulnerability, religion, etc. (see for example Bosque-Sendra et al., 2001–2; Brainard et al., 2002, 2003; Liu, 2001, Ch. 5). Other researchers have developed synthetic measures that can be applied in the study of EJ, such as social deprivation or socioeconomic status indexes (e.g. Havard et al., 2009, 2011; Mitchell and Norman, 2012; Pearce et al., 2011; Wheeler, 2004). A key idea underlying most of these studies concerns the issue of developing empirical measurements of the potential exposure of populations to different levels of environmental quality (e.g. Isakov et al., 2009; Jerrett et al., 2005; McKone et al., 2009; Ozkaynak et al., 2008; Wheeler et al., 2008; Zou et al., 2009; Zou, 2010). The exception is perhaps studies in public health, in which morbidity or mortality indicators have been the preferred measurable outcomes as the effects derived from exposure to environmental risks (e.g. Bolte et al., 2011; Portnov et al., 2009).

Regarding their spatial extent, studies have prioritized the local scale (cities and rural areas in the vicinity of industrial zones or large facilities), although countrywide research has also been conducted. There are quite a few of these in the USA, dating from the past century (e.g. Hird, 1993; Zimmerman, 1993; Been, 1995; Hamilton, 1995, etc.) to recently (e.g. Clark et al., 2014; Zwickl et al., 2014). Some examples can be found elsewhere: in England (Mitchell and Norman, 2012; Wheeler, 2004), France (Lavaine, 2010), and New Zealand (Pearce and Kingham, 2008).

Methodologically, studies that measure environmental injustices have become increasingly complex over the last decade. These include spatial matching analysis, quantitative coefficients, regression models and other spatial analysis techniques (e.g. spatial autocorrelation) and statistical (Kolmogorov–Smirnov's D, χ^2) tests, indicating that there is still a need for standardised and widely-accepted methods to analyse EJ. A contribution towards bridging this gap is Maguire and Sheriff (2011) in their remarkable review of approaches to quantifying distributional equity and assessing some commonly-used techniques, specifying their advantages and shortcomings in urban planning and other policy applications. They conclude that the Kolm–Pollak inequality index is the most promising measure for consistently evaluating EJ, although to date it still lacks a sufficient range of applications and wide acceptance.

Research outcomes have mostly confirmed stark environmental inequalities for racial/ethnic minorities and disadvantaged people (see Martuzzi et al., 2010). In some cases, areas mainly populated by specific demographic groups (e.g. affluent groups, the elderly, children, immigrants, etc.) have been found to suffer from a lower environmental quality (e.g. Havard et al., 2011; Mitchell and Dorling, 2003; Moreno-Jiménez, 2007; Raddatz and Mennis, 2012). Occasionally, the environmental–sociospatial association has not been clearly established with some analysis finding various directions in such association depending on the population group, the type of risk or pollution or the method used (e.g. Buzzelli and Jerrett, 2007; Maroko, 2012; Romero-Lankao et al., 2013).

Although this disparity of findings may be partially due to spatial structures specific to each of the case studies, there is evidence of other types of causes, such as the difficulty in obtaining reliable data at the appropriate spatial scale and level of disaggregation (Chakraborty et al., 2011). Various problems can converge at this stage disturbing the accurate measurement of facts, thereby resulting in merely proxy data. Consequently, human–environment relationships or EJ hypotheses can only be approximated.

From a scientific point of view, it is crucial to make progress in data availability and methods of analysis as a prerequisite for establishing well-grounded evidence-based policymaking. Academics from several countries complain that EJ legal regulations are still insufficiently developed. In the US, for instance, the law is especially sensitive to racial/ethnic differences, but less so to social and income inequalities (Pastor, 2007). Pedersen (2011) has analysed the multiple responses taken by official and non-governmental organizations to EJ problems in the UK, and has concluded that the EJ principle is being applied quite ineffectively. Across the European Union (EU), public policy on EJ is being deployed much slower than in the US, although according to Laurent (2011) the key environmental issues facing current EU social policies have been adequately addressed with recommendations made to legislators, including Central and Eastern Europe (Steger and Filcak, 2008). In developing countries, such as India or China, citizens' lack of political power currently presents unsurmountable barriers for effective application of EJ (see Sen and Chakrabarti, 2010). Apart from other factors, Maguire and Sheriff (2011) have argued that a relevant obstacle for EJ regulation and its enforcement is the lack of a baseline criterion for assessing whether inequality exists and, if so, to what extent. This approach should involve answering three critical questions:

(a) What is the baseline distribution of the environmental outcome?
(b) What is the distribution of the environmental outcome for alternate policy scenarios?
(c) How do the policy options being considered improve or worsen the distribution of the environmental outcome among different subgroups?

This issue will be tackled in the next section, when choosing a straightforward tool for consistent environmental inequality measurement.

Finally, the last part of this literature review is a brief, chronological examination of previous studies in the application area developed in the rest of this paper: the study of environmental injustice related to air pollution, in particular atmospheric NO_2 concentration.

Brainard et al. (2002) studied the estimated CO and NO_2 emissions in Birmingham, England and the exposure of some disadvantaged populations to this pollutant based on their age, ethnicity and poverty indicators. Mitchell and Dorling (2003) presented a review of research in the UK focusing on some air pollutants and various socio-demographic groups and indexes. In particular, they estimated NO_x emission and the derived NO_2 air concentration from car ownership of the population in over ten thousand electoral wards across Britain (population average 6000 inhabitants), and they then examined its relationship with social variables, such as age and a poverty index. Chaix et al. (2006) tested whether children (aged 7 to 15 years) of low socioeconomic status residing and attending school in Malmö, Sweden, suffered greater exposure to outdoor nitrogen dioxide than more affluent ones, both at their home and at school. The study was based on a detailed spatial dataset of outdoor nitrogen dioxide obtained from an air pollution model and geo-coded children to their home address as well as their school. Pearce et al. (2006) modelled the dispersion of traffic emissions and its relation with the distribution of disadvantaged groups in Christchurch, New Zealand. In their Toronto case study, Buzzelli and Jerrett (2007) estimated atmospheric NO_2 based on sampling data for two weeks from a land use regression model (LUR) linking it to various socioeconomic data (income and immigrant, among others) in 606 neighbourhoods. Su et al. (2010) have examined the relation between NO_2 air concentration and socio-demographic indicators (income and immigration) by census tracts in a comparative study looking at Vancouver and Seattle. There too, land use regression (LUR) approach was applied to characterize atmospheric pollution. Fan et al. (2012) have developed a highly detailed analysis using an air dispersion model to estimate the exposure of the urban population to vehicular air pollution (concentrations of CO, NO_x, SO_2 and PM_{10}) in Hong Kong, analysing it against a number of socio-demographic indicators (age and income among others). Romero-Lankao et al. (2013) have explored whether human mortality is linked to air pollution and temperature in three big Latin American cities – Bogota (Colombia), Mexico City (Mexico) and Santiago (Chile), using raw atmospheric data from sensing stations. Finally, Clark et al. (2014) have addressed a USA nation-wide comparison between two high-resolution datasets (at Census Block Group spatial level): outdoor NO_2 concentrations, estimated by LUR, and Census demographic data. They looked for inequalities by race-ethnicity, household income, poverty status, education status, and age (young children and the elderly), and estimated some effects on Ischemic Heart Disease (IHD) mortality. In the discussion section these studies will be compared to the results found in this paper. In line with these efforts, our study attempts to provide additional knowledge in this field, presenting two relevant Spanish case studies and proposing new tools for measuring environmental inequalities.

3. Materials and methods

3.1. Area definition

Following the stated aims of this study, it was important to establish an appropriate geographical scope and unit of analysis for each of the case studies within the metropolitan areas of Madrid and Barcelona. Initially, we could have set these as the built-up spaces within the city's urban areas, but human presence, from the temporal perspective of the daily cycle, is very irregular in some areas. Therefore, we lack the necessary data to monitor daily population mobility in order to analyse the spatio-temporal exposure of the population to the atmospheric pollutants in the various parts of the city. Despite these limitations, we selected the most common alternative, which is to refer the population to their habitual place of residence. In doing so, we assume that the environmental conditions at the place of residence represent the potential exposure to the atmospheric pollutants faced by each population group.

The study territory for each city, named here as an urban populated area (UPA), has been defined as the urban space or built-up area in which there is a strong presence of long-term residents. Operationally, residential and commercial zones and parks and leisure areas were included, while other large zones primarily devoted to industrial, transportation (e.g. airports) or agricultural use and natural zones were excluded from the analysis. In the latter cases, population density is very low or negligible (Fig. 1). In order to delimit the boundary of UPA in each city, we interpreted recent aerial images (National Aerial Orthophotography Plan of the Spanish National Geographical Institute) and land-use maps (Corine Land Cover, 2006), supported by GIS. The task was straightforward, given the compact structure of both cities. The extension of the UPAs was 270.9 km^2 in Madrid and 70.6 km^2 in Barcelona.

3.2. Selection of socio-demographic groups

Another important decision was to determine the socio-demographic groups to include in the study, from the viewpoint of potential environmental inequalities. This choice was necessarily conditioned by the aim of the study and the geographical context of the two cities. As stated in the literature review, previous EJ studies analysing population-neighbourhood exposure to air quality have used several sources of demographic and socioeconomic data, as well as composite deprivation indexes. In this study, priority was given to the criterion of human vulnerability, followed by the criterion of deprivation. Because of this, only a small number of population groups were selected. The main source of data is the Municipal Population Register (Padrón Municipal de Habitantes), January 2010, for small spatial units of census enumeration districts (termed 'census sections'), each averaging between 1000 and 2000 inhabitants. The digital cartography for these census sections was provided by the Spanish National Institute of Statistics (INE) in 2010, edited to fit the boundaries of the UPA described above. Income data were not available for these spatial units and education and socioeconomic status data were obsolete. Ethnicity and race data is not available in Spain, but despite being a growing factor of segregation in many Spanish cities it is still not a major driver of uneven geographical distribution compared to first

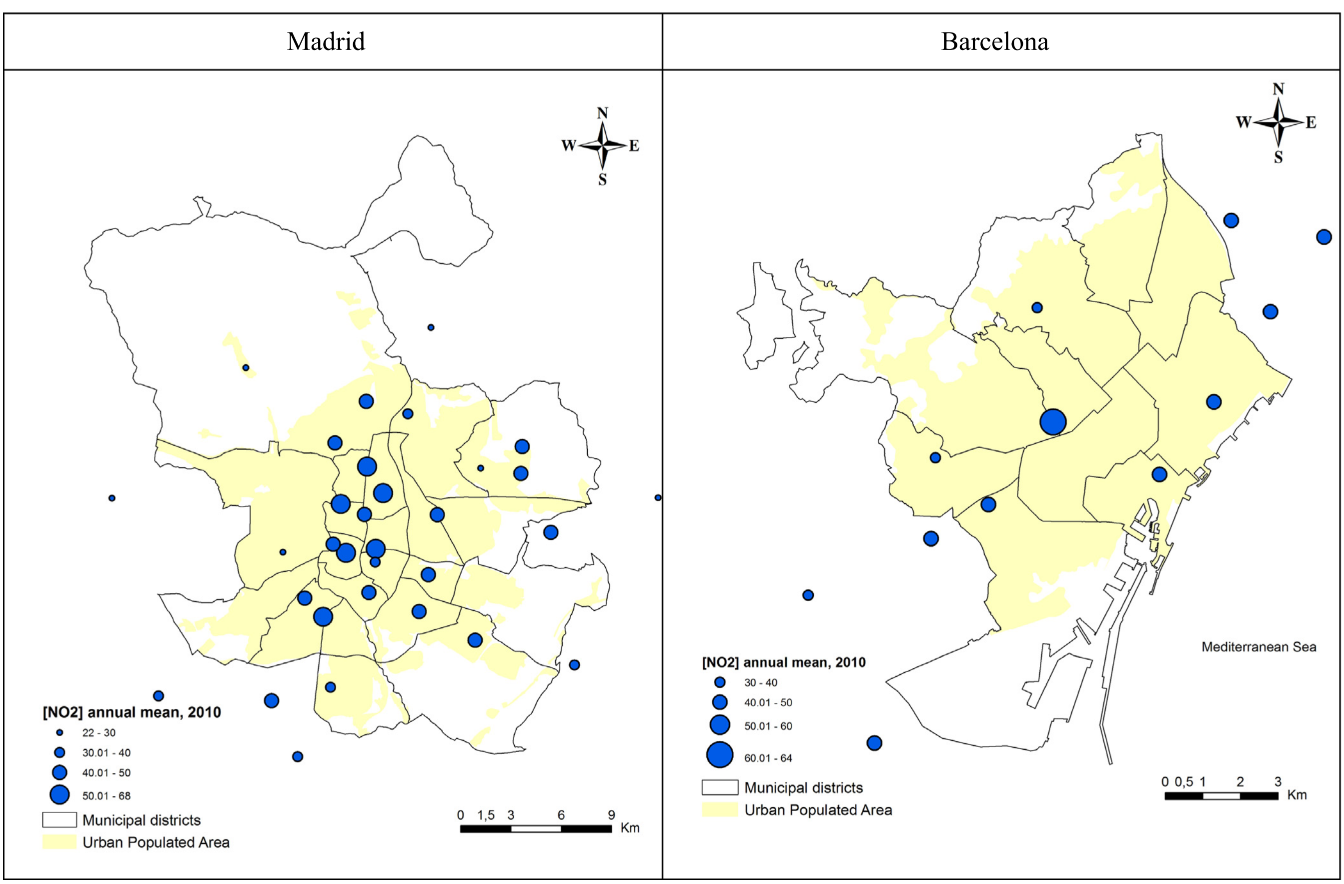

Fig. 1. Madrid and Barcelona: annual mean NO_2 (μg/m^3) concentration by air quality monitoring stations, urban populated areas and district boundaries, 2010.

generation migration, accounted for through country-of-birth data. As a result, the following population groups have been considered for study:

- Vulnerable age groups: children (0–4 years) and the elderly (80 years and over) since owing to biological characteristics these are more sensitive to environmental aggressions (see Landrigan et al., 2010).
- Immigrants from countries with a lower GDP per capita than the EU (European Union) average, the great majority of which are driven by economic reasons, entering the labour pyramid at the base. This is another group which, even showing great differences in individuals' geographical and social class origins, tends to suffer greater deprivation and more adverse social conditions.

Given the well-known segregation and clustering patterns exhibited by immigrant groups within cities, they may serve as the basis for elucidating socially meaningful EJ problems in our case studies. Therefore, in order to differentiate the possible variations among this heterogeneous collective, several sub-groups were established according to world region of origin: individuals originating from (a) Latin America, (b) Africa (in particular, from the Maghreb and Sub-Saharan Africa), (c) Asians (predominantly from China), and (d) Europeans from less-developed countries (mainly Romania, Bulgaria, Poland, Russia and Ukraine).

In total, the data comprised six socio-demographic groups: two age groups and four immigrant-origin groups. Full population figures by census sections were referenced exclusively within the space enclosed within the UPA limits and converted to raster layers (pixels at 50 m resolution – i.e. 0.25 ha). The population of each census section was divided up equally among the pixels it contained. This resulted in seven raster layers, consistent in scope and resolution, one containing the estimated value per pixel for the total population and six for each of the demographic groups. These data processing operations were performed using GIS.

3.3. Air pollution data

Air pollution data was provided by local and regional bodies (Madrid City Council and the Regional Governments of Madrid and Catalonia). Air quality monitoring stations located within the each of the municipalities were used, as well as others in neighbouring municipalities, to complete the spatial sampling coverage around the edges of the study areas. In Madrid, 24 out of 32 stations selected were inside the city (0.089 stations/km^2 in the UPA) while in Barcelona, 12 stations were considered, 6 of which were inside the municipality (0.085 stations/km^2 in the UPA). A dispersed spatial pattern emerged in Madrid (nearest neighbour ratio = 1.31, significant statistically at p-value = 0.0008) as well as in Barcelona (nearest neighbour ratio = 1.86 significant statistically at p-value = 0.0000).

The environmental variable selected for this study was a mean annual concentration of nitrogen dioxide, NO_2, in the year 2010 in μg/m^3 (Fig. 1). As we know, this gas is mainly formed through oxidation of NO, the main source of which is motor-vehicle emissions. NO_2 is therefore a good indicator of air pollution from road traffic. Inhaled NO_2 affects the respiratory system, inhibiting certain pulmonary functions and impairing resistance to infection. Children and asthmatics are those most affected by exposure to acute concentration levels of NO_2. Likewise, continued exposure to high concentrations have been associated with an increase in chronic respiratory diseases, premature aging of the lungs and with loss of pulmonary capacity. It should be noted that the mean annual level permitted by Spanish legislation (Ministerio de la Presidencia, 2011), the European Union (2008) and the World Health Organization (2006) is 40 μg/m^3.

To evaluate issues of environmental justice it is necessary to know the pollution levels in all locations in the city, but since air-quality monitoring station data makes up a spatial sample, an estimate from these points must be calculated for the rest of city (i.e. transforming discrete into continuous data). There is a wealth of material describing this task from various methodological approaches, the choice being mostly conditioned by data availability: emission dispersion models (e.g. Daly and Zannetti, 2007; Fan et al., 2012; Maroko, 2012; Wang et al., 2008), land use regression (e.g. Brauer et al., 2003; Jerrett et al., 2005; Su et al., 2010; Wang et al., 2012), or spatial interpolation techniques (e.g. Buzzelli and Jerrett, 2004; Cañada-Torrecilla et al., 2011; Jerrett et al., 2001; Li and Heap, 2011; Mesnard, 2013; Moreno-Jiménez and Cañada-Torrecilla, 2007; Wong et al., 2004). Due to data constraints for the cities studied, spatial interpolation methods were chosen.

In calculating these estimates, a step-wise procedure was designed, which is fully described in Cañada-Torrecilla et al. (2014). Briefly, the method works as follows: in the first stage, an exploratory analysis is made of the pollution data sample to obtain the properties of centrality, dispersion and its distribution pattern. In the second stage, a structural analysis is made of these properties based on the semivariogram. The aim here was to identify the directions of maximum and minimum continuity of the spatial trend. In the event of finding spatial anisotropy, an ellipse would be defined, establishing its major and minor axes. Should no anisotropy be found, the isotropic model would be chosen, in which only a distance decay function would be taken into account. In addition, in this stage, Trend Surface Analysis or TSA (also known as Global Polynomial Interpolation – GPI), with first-, second- and third-degree polynomials, were used as exploration instruments. In the third stage of this analysis, the application of two interpolation methods, Inverse Distance Weighting Mean (IDW), and ordinary Kriging are tested (Cañada-Torrecilla, 2007a, 2007b; Wong et al., 2004; Krivoruchko, 2011). The aim at this point was to compare results and to determine the acceptability of each method, adopting conventional statistical tests, such as goodness of fit, as well as others of a more qualitative nature such as coherence with the local topography, and urban structure.

These techniques were implemented using ArcGIS (Geostatistical Analyst). In both interpolation techniques, the analysis was begun with ArcGIS default parameters, which were then systematically changed for several further iterations to reach the lowest rate of prediction errors: mean error (ME) – mean errors approaching 0, root mean square error (RMSE) – lowest mean quadratic error, and root mean square standardized error (RMSSE) approaching 1. The solutions finally adopted and presented herein (Fig. 2) were obtained with the IDW method for the anisotropic mode, i.e. using, when selecting sampling points for interpolation at each location, an elliptical neighbourhood, with the most appropriate size, orientation, number of sectors, number of neighbours and exponent value (see Appendix A for details).

Once the estimated layer for mean annual nitrogen dioxide level was obtained, this was rasterized with a resolution of 50 m and fitted to the UPA. Finally, a binary layer was generated from this layer by means of reclassification, identifying pixels above and below the 40 μg/m^3 concentration level, the maximum level permitted by Spanish and European legislation.

Finally, absolute and relative population counts were computed (for the total and for the six demographic groups) within each of the two significant pollution intervals (above and below the critical level of 40 μg/m^3), obtaining the corresponding tables for distribution of frequencies. This was carried out using the Zonal Statistics function in ArcGIS.

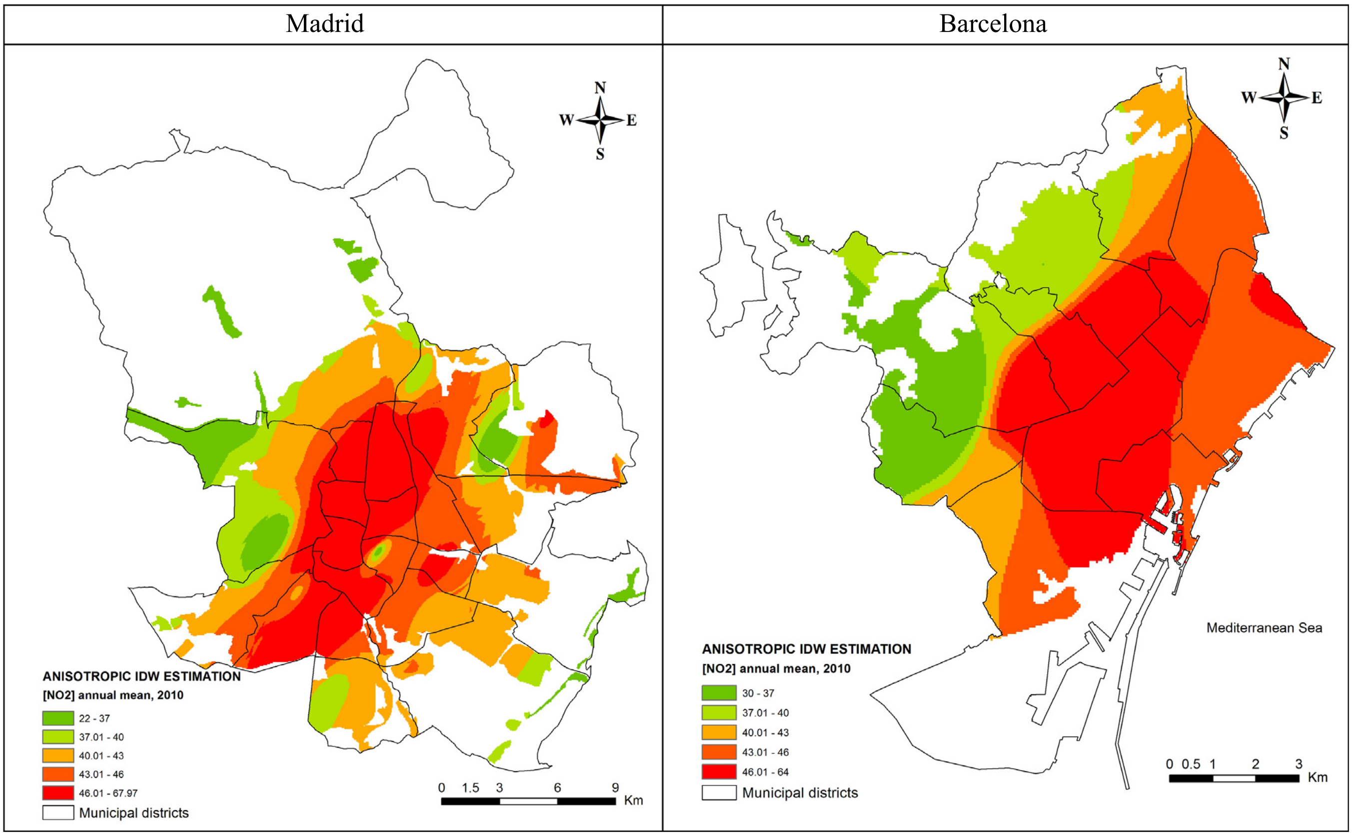

Fig. 2. Estimated NO_2 ($\mu g/m^3$) annual mean air concentration in 2010. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.4. Analysis of environmental justice

The inequity hypothesis was tested by two complementary techniques: the goodness-of-fit type one-sample χ^2 test (Siegel, 1972: 64–69; Ruiz-Maya et al., 1995: 75–77), and the environmental justice balance or scale diagram, described in Moreno-Jiménez (2010, 2012).

The first of these is a well-known independence test, which seeks to demonstrate the null hypothesis (H_o) that the exposure of a population group to different levels of atmospheric NO_2 is identical to that of the resident population as a whole, or, in other words, that both frequency distributions (of the group and of the total) regarding NO_2 levels are similar. The alternative hypothesis (H_1) assumes the reverse, in other words that they are different, which implies that the group is subject to smaller or greater exposure than the total population. In this case, interpretation of the results (differences in the observed and estimated frequencies and proportions, under the assumption of independence) would allow the existence of inequity to be determined. This approach is parallel to those used by Jacobson et al. (2005) and Brainard et al. (2003). It was solved with NCSS software.

The second of the techniques used, the environmental justice balance or scale diagram, was built (in MS Excel) from the proportional differences between the observed and the theoretical distribution. It visually displays to what degree (percentage) the frequency observed for the population group in each of the NO_2 intervals varies from the reference norm (the total population), thus allowing a clear and direct appreciation of the potential inequalities for each population group. The analogy of this graph of a balance or scale with the well-known icon of justice makes it easier to appraise environmental injustices.

In summary, with both techniques the method of EJ evaluation takes the total resident population as a reference, in such a manner that should the potential exposure of a given population group to elevated levels of NO_2 be proportionally higher than that of the city's total population, we would then be speaking of negative discrimination and environmental injustice. This would not occur in the case of similar levels of exposure. In the reverse case, that a group's exposure to high pollution levels was lower than for the total population, this would be classified as an environmentally-privileged group in that context.

4. Analysis of results

4.1. The pattern for air pollution by nitrogen dioxide in the cities of Madrid and Barcelona

The estimated maps for this pollutant in both cities show certain common features, revealing a similar basic pattern (Fig. 2): the inner-central area exhibits higher pollution, which diminishes generally toward the periphery (with some alterations). The coastal nature of Barcelona (Mediterranean Sea to the ESE) and the higher altitude of the coastal mountains (to the NW) give this city some unique characteristics. However, it is confirmed in both cities that the areas in which the critical level of 40 $\mu g/m^3$ is exceeded (orange-red[1] in Fig. 2) are very extensive, revealing a serious lack of environmental quality.

[1] For interpretation of color in Fig. 2, the reader is referred to the web version of this article.

4.2. Intra-urban distribution of vulnerable groups

Madrid and Barcelona, the two main metropolitan areas of Spain, are compact cities. Historic urban planning and growth, conditions for access to the housing market and the nature of such housing have been contextual determinants in the intra-urban distribution and segregation levels of the population groups analysed here, which expose them to highly variable environmental conditions. These patterns are described briefly below (a more detailed study can be found in Vidal-Domínguez and Palacios-García, 2012).

4.2.1. Madrid

With regard to age groups in Madrid, the intra-urban pattern for elderly people and children is consistent with the usual patterns observed within many cities and is related to spatio-temporal growth, with higher numbers of the former in the innermost zones (developed in 19th century), while the latter are more numerous in areas closer to the 20th century developed periphery (Fig. 3). The intra-urban distribution of immigrant groups shows certain spatial coincidences, as well as clear disparities (Fig. 3). While several such groups show preferences for the same neighbourhoods, there are also specific patterns that vary according to each group. For example, numerous groups of Latin Americans are present in many areas of Madrid, while Asians are present in fewer zones; Europeans prevail in the southern and eastern districts, while Africans are present in the southern and central-northern areas. The study by Palacios-García and Vidal-Domínguez (2014) reveals that Asians and Africans, in this order, are the most segregated within each city and display the greatest tendency toward centrality. Europeans and Latin Americans are less segregated and less centralised. These patterns are related to lower quality housing and socioeconomic level, as well as the characteristic clustering of chain migration flows.

4.2.2. Barcelona

In Barcelona (Fig. 4), again, the oldest residents seem to prefer inner-city locations (the districts of Eixample, Gracia and Horta), while children are more common in the periphery. The four groups of immigrants show similarities and differences regarding location. Asians, followed by Africans, appear more segregated and concentrated, as well as having a greater presence in the historical quarter of the city (Ciutat Vella). Latin Americans are the most widely spread throughout the city (less segregation and centrality). Europeans show distribution levels similar those of other groups, displaying a lesser degree of segregation and centrality than the first two groups. Urban development processes have been parallel in Barcelona and Madrid, therefore the main underlying factors of these sociodemographic patterns have operated alike.

To sum up, certain common features can be observed in the groups' spatial patterns in these two cities, but it must be pointed out at the same time that the groups' uneven intra-urban presence may lead to potential exposure to different air quality conditions, as seen below.

5. Potential exposure of vulnerable socio-demographic groups to air pollution: assessment of environmental inequalities

5.1. The situation in Madrid

On an overall scale, the estimated total resident population in areas with an excessive NO_2 concentration (>40 $\mu g/m^3$) in 2010 was very high: 3,116,950 people, or 95.2% of the total population. This figure is testimony of the seriousness of the problem and suggests that the various subgroups are also likely to suffer high exposure.

In fact, as shown in Table 1, children (0–4 years of age) and the elderly (80 or over) are highly exposed to this pollutant, with percentages in excess of 93%. However, in comparison with the total population, each of these demographic groups shows a quite different situation with regard to their relative environmental "burden". In Madrid, the geographic distribution of small children (more peripheral) as opposed to the elderly (more central) causes an uneven exposure between these two groups to this pollutant: children's exposure is lower than might be expected, which renders them slightly favoured, while on the contrary, the elderly suffer in proportion a slightly higher exposure to this pollutant. The scales in Fig. 5 demonstrate this. On examination of the figures for actual exposure compared to expected exposure (under the hypothesis of equity or proportionally similar exposure), it can be seen that they do not differ greatly, although the goodness-of-fit test χ^2 indicates that their degree of divergence is statistically significant.

For the four immigrant groups, the levels of exposure to NO_2 were very high (between 91% and 97%). Again, location patterns for each group led to proportionally better or worse situations in comparison with the total population. On the one hand, Africans and Europeans were found to be in slightly more favourable conditions, since they are over-represented in areas below the critical NO_2 threshold. On the other hand, Asians and Latin Americans are more concentrated in areas above the critical level, and are therefore penalized by higher environmental inequity. The environmental justice scales (Fig. 6) show that Latin Americans are a little closer to equity, whereas Africans appear as the most favoured, probably because they show a significant cluster in the less polluted southern area. In all cases, the χ^2 test gave a degree of probability (p-value) close to zero, indicating that the exposure levels in all groups differ significantly from those of the population as a whole.

5.2. The situation in Barcelona

This city has an estimated 1,412,640 inhabitants living in areas with mean annual levels exceeding 40 $\mu g/m^3$ of NO_2, which represents 87.2% of the total population. Although this is not as high as in Madrid, the relative figure for population potentially exposed is clearly dominant and unacceptable.

The percentages observed for exposure to excessive concentrations of this pollutant in the two most vulnerable age groups are also rather high, and similar to those for the city as a whole (Fig. 7 and Table 2). However, proportionately speaking, the situation in each of the groups differs. Whereas the young-children group, as in Madrid, exhibited relative sub-exposure (hardly reaching a percentage point), meaning that they are in a slightly advantaged position, exposure levels for the elderly were similar to the total population, so that in their case the scales are almost level. The χ^2 test corroborates this – while it confirms a statistically significant difference in the children group, the p-value (0.036) for the group of elderly citizens does not allow a rejection of the null hypothesis, i.e. similar exposure to that of the total population. This can be seen in the similar percentages of exposed members of the elderly group (87.4%) and of the total population (87.2%).

The estimated exposure for the four immigrant groups show one common feature: over-exposure in all cases to levels exceeding the permissible maximum values, higher than those found for the population as a whole (see Fig. 8). Comparatively, those suffering the greatest environmental harm are those of Asian and African origin; both are five percentage points over the city total, whereas the figure for Latin Americans and Europeans is a little lower. This distinct and more environmentally harmful situation is confirmed by means of the χ^2 test, which gives, in all four cases, a statistical

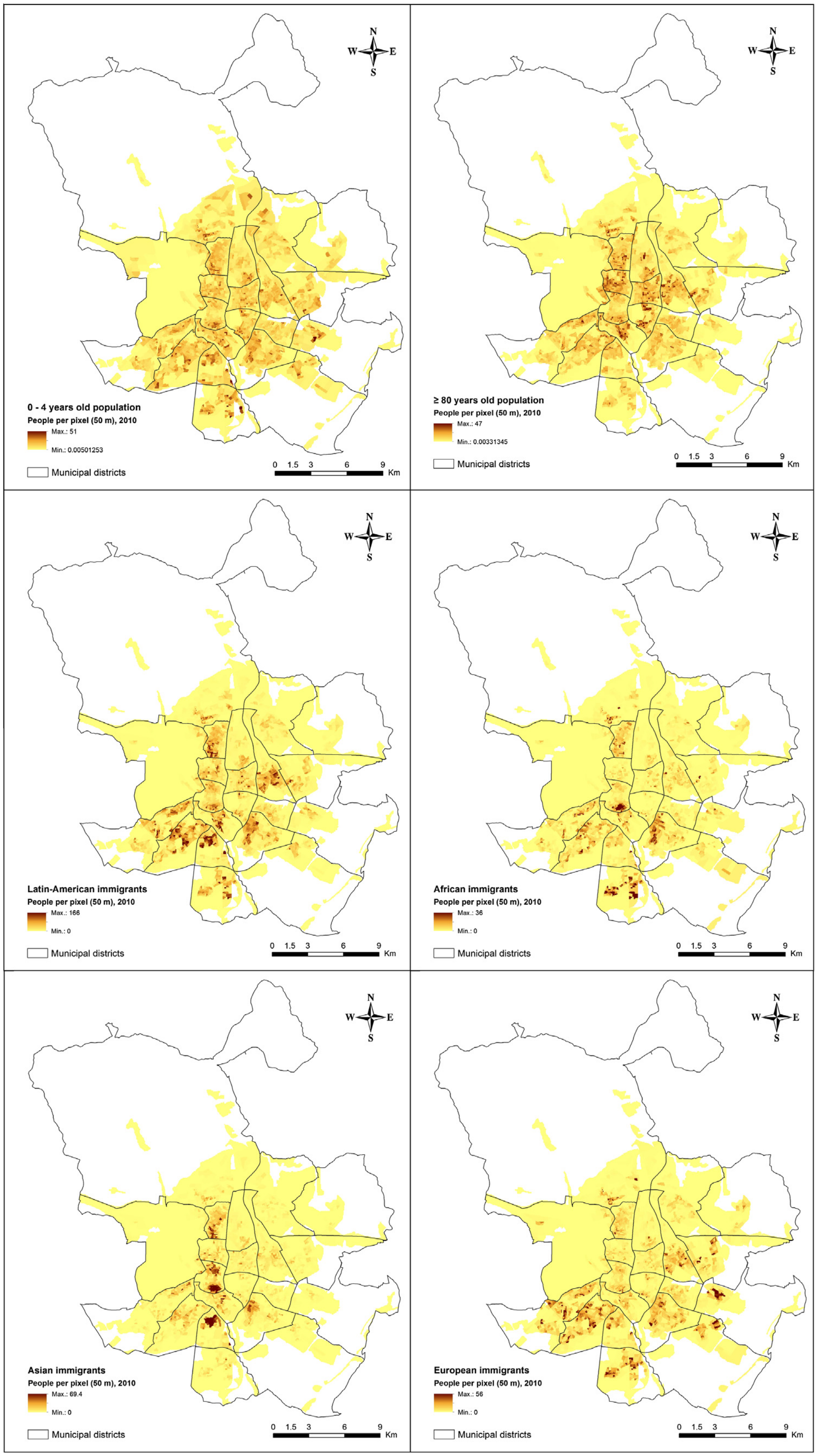

Fig. 3. Population density of vulnerable groups (inhabitants per 0.25 ha) in Madrid urban populated areas, 2010. Note: Ramp color symbols set with linear stretch, standard deviation option, and $n = 6$ trimming parameter. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

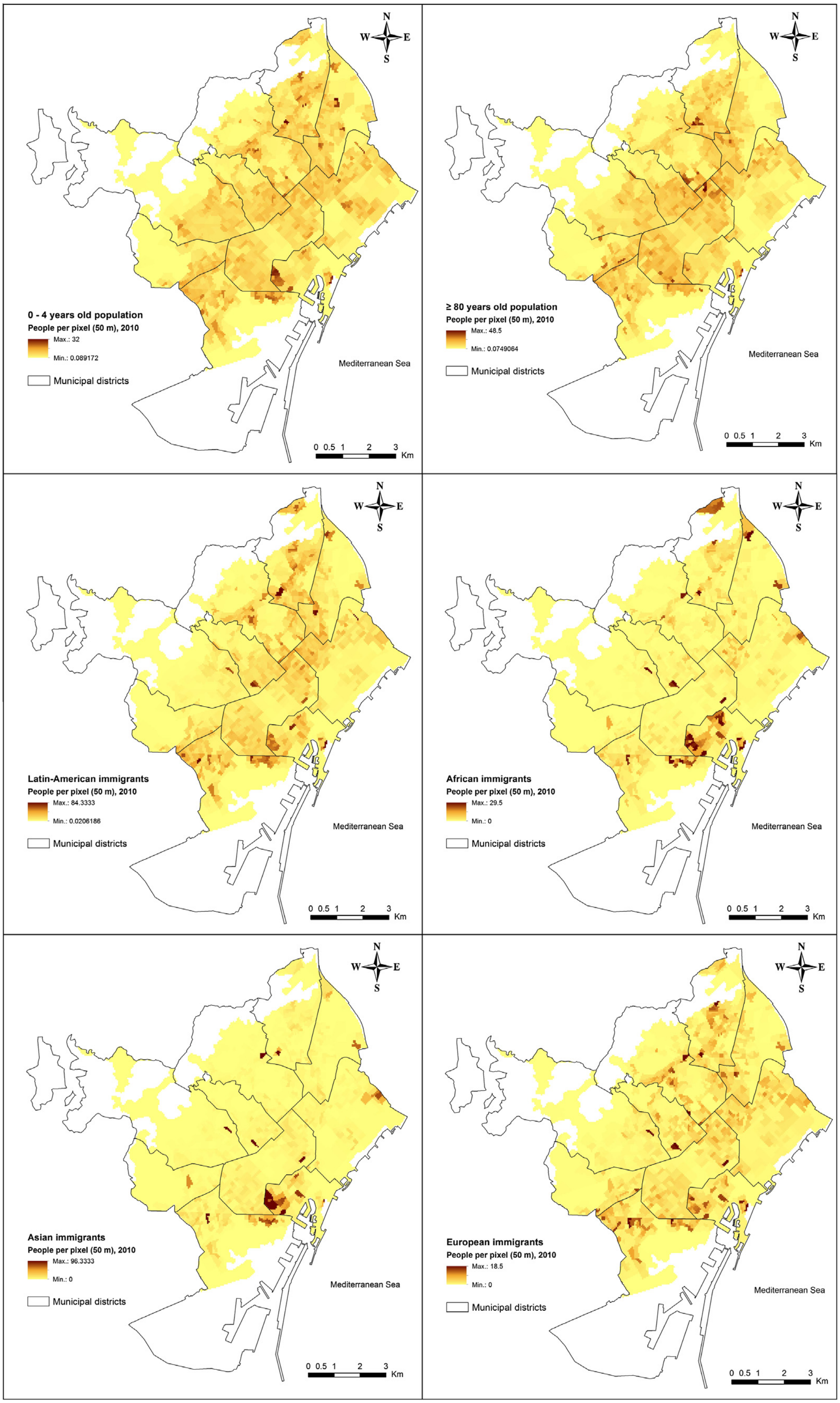

Fig. 4. Population density of vulnerable groups (inhabitants per 0.25 ha) in Barcelona urban populated area, 2010. Note: Ramp color symbols set with linear stretch, standard deviation option, and $n = 6$ trimming parameter. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Environmental equity (goodness of fit) statistical tests for vulnerable groups in Madrid regarding NO_2 air pollution exposure (>40 μg/m^3), 2010.

Variable	χ^2 with 1 degree of freedom	Probability level	Exposed population	Expected population
Population 0–4 years old	1168.7	0.00	151,871 (93.4%)	154,808 (95.2%)
Population ⩾80	689.88	0.00	182,647 (96.5%)	180,212 (95.2%)
Latin American immigrants	153.35	0.00	289,141 (95.71%)	287,690 (95.2%)
African immigrants	1416.55	0.00	38,899 (91.3%)	40,554 (95.2%)
Asian immigrants	374.10	0.00	50,401 (97.0%)	49,462 (95.2%)
European immigrants	1285.26	0.00	88,441 (92.8%)	90,800 (95.2%)

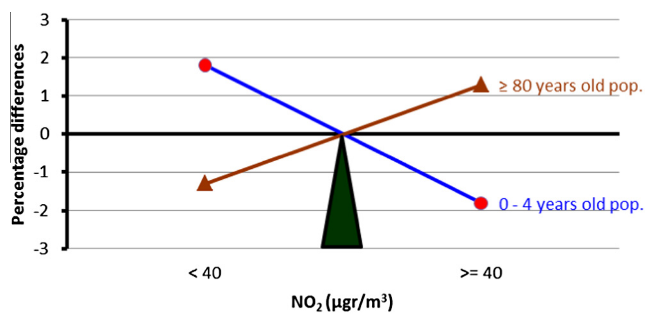

Fig. 5. Environmental equity scales for two vulnerable age groups in Madrid regarding NO_2 air pollution, 2010. Note: Vertical axis displays deviations (in percentage units) of group exposure regarding total population exposure.

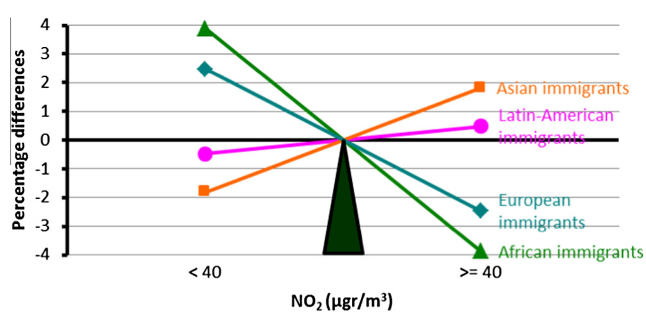

Fig. 6. Environmental equity scales for immigrants in Madrid regarding NO_2 air pollution, 2010. Note: Vertical axis displays deviations (in percentage units) of group exposure regarding total population exposure.

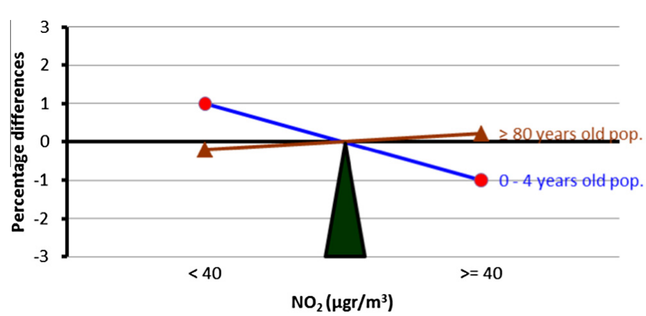

Fig. 7. Environmental equity scales for two vulnerable age groups in Barcelona regarding NO_2 air pollution, 2010. Note: Vertical axis displays deviations (in percentage units) of group exposure regarding total population exposure.

probability value (p-value) close to zero. In summary, in Barcelona, all these immigrants groups are found to be environmentally disadvantaged, which amounts to an injustice.

6. Discussion

Our study has conducted exploratory analysis of EJ as distributive justice in terms of urban potential exposure to a major air pollutant in Spain's two largest cities. As far as the environmental component of EJ analysis is concerned, how to estimate a continuous map of urban air quality at very fine spatial resolution is a major obstacle, derived from a small sample of non-random spatial distribution of air quality monitoring stations. The set of spatial interpolation methods applied here have been used by some of the previous literature cited in the methodological section, particularly those by Buzzelli and Jerrett (2004) or Jerrett et al. (2001). The selected set of tools and the steps taken to derive such a continuous map were all designed to obtain the best results in the most efficient manner, starting from a limited supply of information. Overall, the estimated intra-urban pollution levels seemed to be roughly coherent with the expected ones, taking into account our knowledge of spatial structure and traffic densities in both cities. We believe that the resulting map of NO_2 pollution provides a fairly general picture of the average NO_2 atmospheric concentration at across the city, although it is clearly not suitable for detailed spatial analysis at a neighbourhood level. Further improvements would therefore be required – to the availability of air monitoring data – for example through new, inexpensive sensing networks (see Knox et al., 2013) and to spatial estimation methods, such as those based on emission dispersion models (Baldasano et al., 2008; Fan et al., 2012; Pearce et al., 2006) or land use regression (Brauer et al., 2003; Briggs et al., 1997; Jerrett et al., 2005; Su et al., 2010).

The demographic groups analysed are relevant subsets which are subject to environmental vulnerability, either because of their age or their socioeconomic characteristics as immigrants from developing countries. Other criteria have been deemed relevant in previous studies, although because of lack of data availability at small area level in the Spanish census these were not feasible for this case study. Particularly, deprivation, income, education, or socioeconomic status are also notable determinants of intra-urban segregation in Spanish cities, and should be taken into account in wider EJ appraisals, as stated in the above mentioned literature. It should be stressed that although ethnicity and race feature prominently in previous studies of EJ, international immigration is a relatively recent phenomena in Spain, and therefore second-generation racial segregation is still at an early stage, furthermore, ethnicity is not recorded in the Spanish census.

The spatial allocation of the population has been subject to two decisions. Firstly, we discarded official municipal divisions, and delimited the extent of the UPA in order to retain residential spaces and those proximal land uses where people conduct their daily lives and to exclude the non-residential land uses with very low population densities. Secondly, the population reported at small area census units was allocated to a high-resolution grid (50 m), thus enabling a more flexible cross-comparison of pollution and population layers. This is a straightforward technique that could obviously be improved with the use other procedures (see Santos

Table 2
Environmental equity (goodness of fit) statistical tests for vulnerable groups in Barcelona regarding NO_2 air pollution exposure (>40 μg/m^3), 2010.

Variable	χ^2 with 1 degree of freedom	Probability level	Exposed population	Expected population
Population 0–4 year old	63.2	0.00	60,791 (86.2%)	61,495 (87.2%)
Population ⩾80	4.41	0.036	95,078 (87.4%)	94,847 (87.2%)
Latin American immigrants	778.7	0.00	94,616 (90.1%)	91,599 (87.2%)
African immigrants	544.6	0.00	19,245 (92.6%)	18,122 (87.2%)
Asian immigrants	2,501.4	0.00	50,614 (94.4%)	46,750.54 (87.2%)
European immigrants	51.0	0.00	15,197 (89.1%)	14,886 (87.2%)

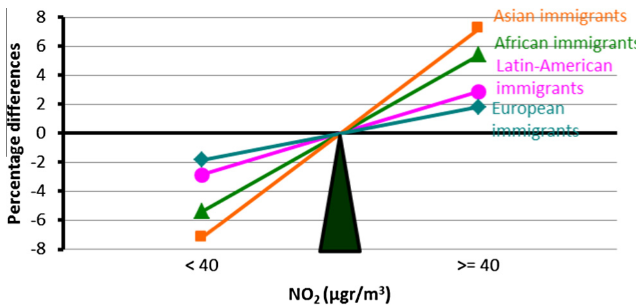

Fig. 8. Environmental equity scales for immigrants in Barcelona regarding NO_2 air pollution, 2010. Note: Vertical axis displays deviations (in percentage units) of group exposure regarding total population exposure.

Preciado et al., 2011), for example to estimate populations at the block of building level, although we did not follow this efforts because of data and resource availability. In any case, obtaining more representative location data about populations on the move across urban spaces (Martin et al., 2009) still remains a challenge in terms of environmental exposure, since most studies are reduced to home residential areas, valid mostly for night-time populations (Chakraborty et al., 2011). As Gaffron (2012) has underlined, due to human mobility, the daily and weekly spatio-temporal distribution of populations across urban areas is the foremost requirement to assess exposure more accurately.

The findings from Gaffron's study of home permanence time have disclosed other significant implications on the formerly discussed criteria to select socio-demographic groups in EJ studies. For instance, he particularly highlighted the fact that age and sex were variables as important as any other commonly considered in health impact studies. At this point we can recall the investigation conducted in the city of Haifa by Portnov et al. (2009) who showed that women's lung cancer was related to atmospheric NO_2 pollution (because of their long stay in residential areas close to highly polluted roads), but this relation was not established for the whole population. The analysis focusing on the 'activity places/people involved' subset should be an important alternative, as used by Chaix et al. (2006) for children and school/home areas, mainly for environmental health research, or as Gupta et al. (2011) showed in a study of lung function among non-smoking police officers exposed to daily traffic, compared to those not exposed.

The specific EJ evaluation method applied here has some peculiarities in comparison to earlier studies. A baseline has been proposed for measuring the potential over- or under-exposure to atmospheric hazards – the burden on the whole population in the relevant study area – while the focus is set on the relative distribution of risk among the zones. The amount of environmental burden share has been estimated by population groups, but other measures (e.g. by area) could also be envisaged. In spite of its simplicity, the method applied here features a threefold advantage:

(a) an estimate of the amount of environmental burden excess affecting each population group (in absolute and relative terms), facilitating comparison between groups. In our opinion, these kinds of figures could be considered as meaningful input for more consistent regulation or public action, as claimed by Laurent (2011), Maguire and Sheriff (2011) and Pedersen (2011).
(b) An effective visualization of environmental justice for each group by means of the environmental balance or scale graph. This is a useful tool for communicating EJ reports to stakeholders.
(c) A statistical evaluation of the significance of these relations based on the goodness-of-fit test, offering additional support to scientific and public discussion.

In order to compare results, we have selected some studies similar to this work. According to our study, zones with higher shares of children aged 0–4 appear relatively privileged in both cities compared to the whole population's NO_2 burden. This is, of course, derived from lower NO_2 pollution in peripheral areas where young population is more abundant. In Madrid, elderly people are significantly over-exposed to this pollutant, because they are over-represented in inner city neighbourhoods, according to a well-known demographic pattern. In Barcelona, the results point to the same trend, but the relation is not statistically significant. In a study of Hong Kong by Fan et al. (2012) elderly people, were also found to be exposed to relatively higher levels of traffic air pollution. Although at a different spatial scale, Mitchell and Dorling (2003) concluded that "pollution is most concentrated in areas where young children and their parents are more likely to live and least concentrated in areas to which the elderly tend to migrate". These singular results might be due to the spatial scale of this study, focusing in the whole Britain at coarser resolutions than the intra-urban study presented here. However, in the English city of Birmingham, Brainard et al. (2002) stated that neither children nor pensioners appear to differ from the general population in their likely exposure patterns of air pollution, so no relationship could be established on the basis of age. In a recent study of inequality for residential outdoor NO_2 concentrations in the contiguous United States, Clark et al. (2014) found similar levels for the elderly (>65 years) or the young (<5 years) as for other age groups (5 to 65 years). However, for below-poverty level non-white individuals, NO_2 concentrations were significantly higher for young children and elderly people. There are sufficient grounds to consider age structure across space as a meaningful dimension for EJ assessment.

Concerning immigrants, the results presented here show a prevalent trend. In Barcelona all groups suffer inequity regarding the NO_2 pollutant, whereas in Madrid the situation is more diverse: in relative terms Latin American and Asian people are penalised, while Africans and Europeans benefit. A focus on international immigrants is not frequent in EJ studies, which tend to examine differences by race/ethnic group, but it is here used as a proxy concept for comparison purposes with our Spanish case study since no other ethnicity data is available. It is worth highlighting that race and ethnicity has been largely linked to environmental inequities in published work in the English-speaking world, so a few relevant case studies will be cited here by way of illustration. McLeod et al. (2000) reported a positive relationship between minority ethnic groups and pollution in England and Wales. Brainard et al. (2002) found a striking relationship between modelled emissions and poverty indicators and ethnicity in the English city of Birmingham. In the case of Hamilton in Canada, Buzzelli and Jerrett (2004) highlighted varying results – the proportion of Latin Americans in a census tract was positively associated with pollution exposure, while Asian-Canadians were negatively associated with air pollution, and black Canadians showed no clear correlation at all. The same authors (Buzzelli and Jerrett, 2007) in the Toronto case study unexpectedly found that "visible minorities were sometimes negatively associated with exposure, though this variable was less robust". Su et al. (2010) observed that immigrant populations displayed different results: they did not correlate with high pollution levels in Vancouver as they did in Seattle. In the USA, the Black Hispanic urban residents suffered higher NO_2 concentrations too, according to Clark et al. (2014). In conclusion, the main findings in Madrid and Barcelona have parallels in other studies showing predominant negative discrimination of immigrant or ethnic minority groups, but in some cases this relationship cannot be proved.

7. Conclusions

The concept of environmental justice has emerged over the past few decades as a social movement, but it still attracts uneven attention around the world and has only been applied to policy-making in very few countries. Research on this subject is hampered by serious data availability issues and although a variety of techniques have been proposed for analysing inequalities, there is a lack of consensus as to how EJ should be measured in a manner that is consistent and appropriate for decision-making processes. In addition, as rightly stated by Mohai et al. (2009), "it is not immediately obvious what should be done after an injustice has been documented – addressing environmental injustice with public policy could involve complex and expensive local, national, or perhaps even global interventions."

This paper has presented two case studies from Spain, a country with very little previous research on this subject, representing a contribution for international comparisons. The focus in this case has been on the assessment of potentially unjust situations in intra-urban spaces, on the basis of the spatial distribution of certain socio-demographic groups that are considered vulnerable, and the dissimilar concentration levels of an air pollutant generated by human activities (especially traffic).

Despite the limitations on data availability, this problem has been tackled here with rigour. This implies certain particularities and innovations concerning the methodology applied for this purpose. Firstly, the extent of the study areas was delimited to only include the populated residential urban areas, omitting spaces and land uses where resident population is null or very scarce. Secondly, population was represented spatially on a grid with a pixel resolution of 50 m using the data provided by the census sections, which facilitated more flexible estimates for potential exposure to pollution. Thirdly, a set of analytical and spatial interpolation techniques were applied to estimate the mean annual concentration of nitrogen dioxide in the air from the monitoring stations to a continuous surface covering both cities at the same 50 m. resolution grid. Finally, a statistical goodness-of-fit test, the χ^2, and environmental equity scales were used to compare the proportion of people in each vulnerable group exposed to high levels of pollution against the city's total population. Using these evaluation measures, the hypothesis of whether there is significant divergence between each group and the total population was tested, and inequalities were visualized easily and intuitively through an environmental balance or scale diagram. Adopting the normative maximum NO_2 values to gauge whether pollution levels are acceptable or not has the added advantage of making a more objective and consistent assessment.

As a result, it was empirically demonstrated that there are worrying levels of over-exposure to high concentrations of NO_2 in both cities, a situation we deem to be totally unacceptable. In Madrid, the elderly, Latin Americans and Asians suffer from environmental injustice; while in Barcelona, it is all the groups of immigrants suffer disproportionate exposure. To conclude, we consider that the results presented here provide evidence of environmental inequalities (i.e. distributive injustice) in a way that is sufficiently accurate and visually clear to help in policy-making.

In pursuing future research, some directions could be outlined. As environmental hazards impacting unequally on different categories of people vary considerably, a comprehensive view is needed. The challenge is to select a sufficiently representative set of environmental threats and impacts to be systematically scrutinized in order to highlight important injustices and the factors that cause them. Similarly, contributions which discuss and propose socially-vulnerable groups and indicators to be considered in EJ assessments should be encouraged. Data allowing a better measurement and representation of spatial patterns of environmental dangers and actual people exposure are also needed to achieve more accurate results. Some recent technological advances might greatly help in this direction in the near future. Finally, comparison of international case studies and analytical methods, moving towards a more widely-accepted assessment approach for policy purposes should be welcomed.

Spatial EJ appraisals could be proposed for a whole city at a given date, for temporal comparisons, or for policy outcome estimations. Furthermore, potential exposure analyses for meaningful areas (e.g. administrative divisions such as neighbourhoods or urban districts) could be appropriate as part of long-term policy-making tasks (e.g. urban or strategic planning). For studies targeting environmental health, much more detailed spatio-temporal data is required in both environmental and socio-demographic dimensions, in order to properly test the relationships.

From a wider perspective, it should be pointed out that the evidence collected in this and other similar studies calls for society to organize and establish land uses that comply with a set of shared principles or values. The conceptual definition of the latter and their operational expression from a spatial viewpoint, would greatly contribute to the establishment of a more desirable framework for public policy and urban planning, where private development projects are subject to strict scrutiny. Only then, can its degree of convenience or goodness for society be determined, based on appropriate criteria and objective indicators. The time seems to have come for the principle of environmental justice to form part of that set of fundamental criteria that is routinely regulated and implemented systematically in any assessment of development proposal, urban planning and public spatial policies anywhere in the world. Contributions on this subject, by researchers in various countries, such as this study conducted in Spain, will undoubtedly prove very valuable in achieving this high aim.

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Appendix A

Model parameters and goodness of fit for NO_2 spatial interpolation, 2010

City/Method	Model parameters					Cross validation statistics ($\mu g/m^3$)	
	Power value	Maximum/minimum neighbour points	Shape/sectors/axis sizes (m)	Angle (°)	Anisotropy factor	Error mean	RMSE
Madrid/Anisotropic IDW	1.85	7/4	Ellipse/4 sectors 45° offset/9000/4000	34	2.25	2.19	9.25
Barcelona/Anisotropic IDW	2.25	7/4	Ellipse/4 sectors 45° offset/9000/4000	31	2.25	0.48	8.48

Statistical comparison of NO_2 ($\mu g/m^3$) measured and predicted data

Statistical summary	Madrid		Barcelona	
	Measured sample values	Anisotropic IDW predicted data	Measured sample values	Anisotropic IDW predicted data
Mean	41.8	43.06	42.9	44.4
Standard deviation	10.18	5.29	8	7.5
Maximum	68	67.97	64	64
Minimum	22	22	30	30
Range	46	45.97	34	34
Sample *n*	32		12	

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