Land Use Policy 59 (2016) 375–385

Contents lists available at ScienceDirect

Land Use Policy

journal homepage: www.elsevier.com/locate/landusepol

Mapping alternatives for public policy decision making related to human exposures from air pollution sources in the Federal District, Brazil

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ARTICLE INFO

Article history:
Received 4 February 2016
Received in revised form
14 September 2016
Accepted 19 September 2016
Available online 22 September 2016

Keywords:
Mapping
Human exposures
Air pollution sources
Public policy
Decision-making

ABSTRACT

Several studies have assessed air pollution risks to guide environmental and public health policies. However, most studies have proposed risk management actions that address a specific situation. To our knowledge, no studies have investigated the spatial distribution of risks to evaluate alternatives for environmental public policies. Therefore, this study had two specific aims. The first was to map human exposures to emissions from air pollution sources in the Federal District, Brazil. The second was to create and map the alternatives for public policies related to human exposures. For this study, we used the following approaches: techniques in Geographic Information System (GIS); multicriteria model – Analytic Hierarchy Process (AHP); and, Fuzzy logic. Our findings suggest that vehicle traffic control and public transportation development are the most effective alternatives with weights equal to 0.318 and 0.332, respectively. The estimated weights for land use management and new green areas are equal to 0.179 and 0.171, respectively. Vehicle traffic, population density, illegal urban settlements, economic activities and daily flux of people (origin and destination) were the main factors determining the spatial distribution of each alternative. This proposed analytical framework may be of interest to policy makers seeking to minimize costs for designing and evaluating effective public policies.

1. Introduction

Air pollution is a serious public health problem worldwide. In 2010, it was responsible for 3.3 million premature deaths globally (Lelieveld et al., 2015). Specifically exposure to Particulate Matter ($PM_{2.5}$) contributes to approximately 2 million premature deaths per year, ranking it as the 13th leading cause of worldwide mortality (Lozano et al., 2012).

Several studies have assessed air pollution related risks to guide environmental and public health policies (Bind et al., 2015; Lee et al., 2012; Lin et al., 2013; Pereira et al., 2014; Réquia Júnior et al., 2015a; Valdés et al., 2012). Risk-based decision-making can generate more efficient and consistent public policies (Tran et al., 2002; Vlachokostas et al., 2009; Yerramilli et al., 2011). However, studies have only suggested types of risk management actions necessary to address a given exposure problem situation. To our knowledge, there are no studies that have shown the spatial distribution of the specific alternatives for public policy decision making related to risk assessment.

According to Berry (1993) and Mitchell (1999), geographical mapping of proposed element (e.g., alternatives for public policy) is a potential tool to identify priority areas, to monitor conditions on the ground, to calculate temporal changes and to compare populations. The conceptual mapping of alternatives for public policy makes it much easier to communicate to potentially affected people and governmental agencies (Bateman et al., 2013).

Our study had two aims. The first was to map human exposure from air pollution sources in the Federal District. The second was to create and map alternatives for public policy decision making related to human exposures.

This study arose from the exchange of ideas with the Environmental Agency in the Federal District. The Environmental Agency is developing the Ecological-economic zoning (EEZ) based on several

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http://dx.doi.org/10.1016/j.landusepol.2016.09.017
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pieces of information, one of them are the findings from previous researches (Réquia Júnior et al., 2015a,b,c). However, the Environmental Agency in the Federal District does not has a guide for public policy decision making related to spatial variation of the human exposure.

2. Materials and methods

2.1. Study area

The study area was the state of Federal District (FD), Brazil, which has 2.8 million inhabitants in 5802 km^2. The FD is located in the center west of Brazil, between the parallels of 15° 30′ and 16° 03′ South Latitude and the meridians of 47° 25′ and 48° 12′ West Longitude. The area of FD is divided into 31 administrative regions of which one of them is Brasilia, Brazil's capital (IBGE, 2013). Fig. 1 presents the FD and its 31 administrative regions.

The FD faces several challenges. Two of them are urban growth and air pollution. Effective public policy addressing these challenges would improve quality of life among the FD population and reduce economic cost to government. Several studies have shown the relationship between urban growth and air quality (Cervero 2013; Réquia Júnior et al., 2015b,c; Torres et al., 2007), and the economic value of deaths and diseases due to air pollution (Davis, 2012; Shah et al., 2013). In short, the economic values corresponds to the amount societies are willing to pay to avoid these deaths and diseases with necessary interventions.

The FD is the fourth most populous state in Brazil. Over the last 15 years, the FD urban area became30% bigger. By 2030, FD population is expected to surpass 3.7 million inhabitants (IBGE, 2013). The FD has approximately 1.6 million vehicles, a rate of 0.6 vehicles per inhabitant, ranking it as the 5th Brazilian state with the higher rate (IBGE, 2013). Over the last 5 years, 15,000 people died due to cardiorespiratory diseases in the FD (Datasus, 2015). Studies have shown that in the FD air pollution is associated with an increase in cardiorespiratory diseases (Réquia Júnior and Abreu, 2011; Réquia Júnioret al., 2015b) and vehicle traffic is a significant source of air pollution (Réquia Júnior et al., 2015a,c).

2.2. Study design and data

This study was performed in nine stages. Stages 1 through 4 refer to the first aim (to map human exposure from air pollution sources) and stages 5 through 9 refer to the second aim (to create and map alternatives for public policy decision-making related air pollutant emissions). These stages were as follows: i) define the hierarchical network; ii) develop a spatial multicriteria model to generate weights for risk maps; iii) perform sensitivity analysis for the estimated weights; iv) apply GIS techniques for risk maps consolidation; v) definition of the alternatives; vi) include the alternatives in the hierarchical network, which was established on the stage 1; vii) use a spatial multicriteria model to generate the weights only for the alternatives; viii) perform sensitivity analysis for the weights, considering the alternatives, and; ix) apply GIS techniques for public policy maps consolidation (Fig. 2).

We used one input data to represent human exposures (Fig. 2). This data results from previous study in the Federal District (Requia et al., 2016).

The human exposure data refer to 9 risk maps of cardiorespiratory disease prevalence in the FD. Each map represents one predictor variable, which was identified by Requia et al. (2016) as significantly associated with an increase in cardiorespiratory disease. The variables were: highways, streets/avenues, wildfires, light vehicles, motorcycles, heavy vehicles, commercial areas, industry areas and exposed soil. Appendix B presents the description of all 9 variables and Appendix C presents the risk maps.

2.3. Hierarchical network (Stage 1)

The hierarchical network characterizes the conceptual model, which is needed for most multi-criteria models. The goal of our conceptual model was to create a map that depicts air pollutant exposures in the FD. We established the hierarchical network using nine-predictor variables, which were associated with an increase in cardiorespiratory morbidity (as shown in Appendix C).

We defined two primary criteria: transport; land use and other sources. Fig. 3 shows the complete hierarchical network.

2.4. Spatial multi-criteria model (Stage 2)

We used a multi-criteria decision-making (MCDM) approach to generate weights for risk maps. According to Gwo-Hshiung and Huang (2011), a MCDM is represented by various methods such as Elimination et Choix Traduisant la Réalité (ELECTRE), Preference Ranking Organization Method for Enrichment Evaluations (PROMETEE), Simple Additive Weighting, and Analytic Hierarchy Process (AHP). Among these possibilities, we choose the AHP.

The AHP method was developed by Saaty (1980) and has been frequently used in environmental studies (Fontana et al., 2013; Greening and Bernow, 2004; Tran et al., 2002). It is considered one of the best approaches of MCDM, because it is flexible because and it enables us to make decisions by combining judgment and personal values in a pairwise comparison. In addition, it can be used to decompose a complex decision-making problem into numerous simple sub problems (hierarchy network). It is a process for identifying, understanding, and assessing the interactions of a system as a whole. In summary, the advantages of AHP are as follows: it is a flexible model for a wide range of unstructured problems; it does not rely on consensus but synthesizes a representative outcome from different judgments, and; it provides a scale for measuring intangibles and a method for establishing priorities (Saaty, 1980).

Therefore, after defining the hierarchy network in Stage 1, we used AHP to assign the weights in a stratified fashion by obeying each level of the hierarchy that was established. The agents of FD Environmental Agency established the weights. One of the agents was the Assistant Administrator of the Agency. This local agency is one of the main stakeholders in the decision-making to reduce air pollution risks.

According to Saaty (1980) the weight scale varies from 1 to 9, with 1 = equal importance; 3 = weak importance; 5 = strong importance; 7 = very strong importance; 9 = maximal importance; and 2, 4, 6 and 8 representing intermediate importance. After assignment, we modeled the importance values using matrix (A) shown in Eq. (1).

$$A = \begin{bmatrix} a_{11} & \cdots & a_{1j} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ a_{i1} & \cdots & a_{ij} & \cdots & a_{in} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nj} & \cdots & a_{nn} \end{bmatrix} \quad (1)$$

Where $a_{ij} = \alpha$; $a_{ji} = \frac{1}{\alpha}$; a is a joint comparison; and α is the assigned importance value. We calculated the matrix (A) by the auto valueV_i, as shown in Eq. (2).

$$V_i = \left(\prod_{j=1}^{n} a_{ij} \right)^{1/n} \quad (2)$$

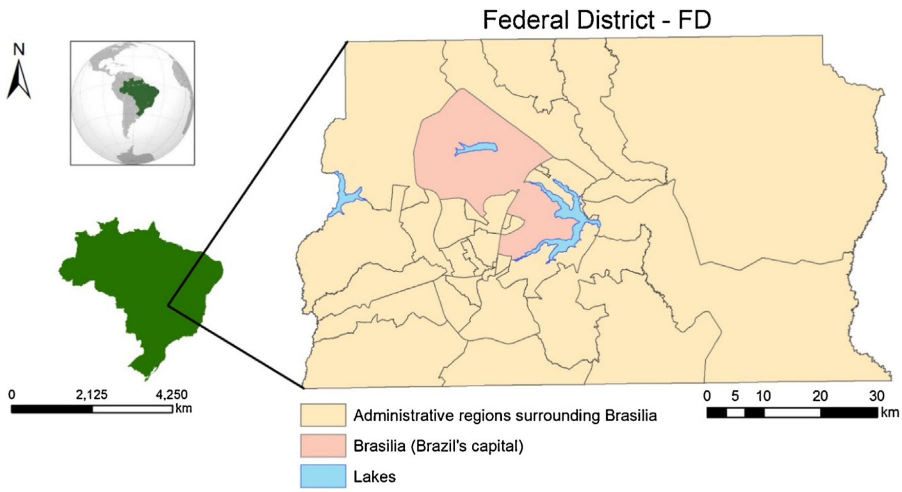

Fig. 1. Study area.

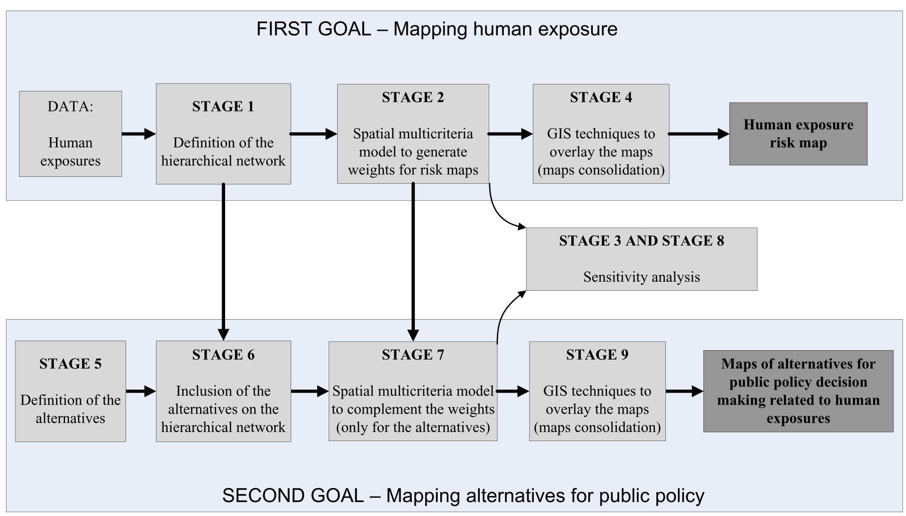

Fig. 2. Stages of the research.

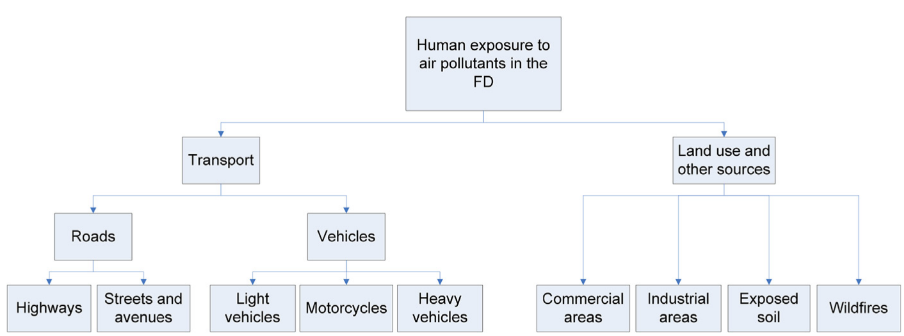

Fig. 3. Hierarchical network.

Normalization of Eq. (2) generates the vector W, which is the priorities vector (it represents the relative importance attributed for each criteria). We calculated W using Eq. (3):

$$W_{nx1} = \begin{bmatrix} W_1 = V_1 / \sum_{i=1}^{n} V_i \\ W_2 = V_2 / \sum_{i=1}^{n} V_i \\ W_3 = V_3 / \sum_{i=1}^{n} V_i \\ W_n = V_n / \sum_{i=1}^{n} V_i \end{bmatrix} \quad (3)$$

The multiplication of the matrix (A) by the value for each weighing $W = (W_1, W_2, \ldots, W_n)$ generates the value Aw, which is represented by Eq. (4).

$$A=\begin{bmatrix} W_1/W_1 & \ldots & W_1/W_j & \ldots & W_1/W_n \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ W_i/W_1 & \cdots & W_i/W_j & \cdots & W_i/W_n \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ W_n/W_1 & \cdots & W_n/W_j & \cdots & W_n/W_n \end{bmatrix}\begin{bmatrix} W_1 \\ \vdots \\ W_j \\ \vdots \\ W_n \end{bmatrix}=n\begin{bmatrix} W_1 \\ \vdots \\ W_j \\ \vdots \\ W_n \end{bmatrix}=nW \tag{4}$$

The relation $Aw=nW$ cannot be calculated directly. Instead, Saaty (1980) suggests the use of Eq. (5):

$$\lambda_{max}=\frac{1}{n}\left(\frac{W_1}{W_1}+\frac{W_2}{W_2}+\ldots+\frac{W_n}{W_n}\right) \tag{5}$$

Based on Eq. (5), we calculated the vector of priorities as shown in Eq. (6).

$$\mathrm{Aw}=\lambda_{max}w \tag{6}$$

The individual judgments from the agents of FD Environmental Agency were aggregated by calculating the geometric mean of all vectors of priorities (*Aw*).

Saaty (1980) proposed a validation method for assigning weights using Inconsistency Rate (IR) values, which is calculated based on properties of reciprocal matrices. According to the author, IR should not exceed 0.10. Values lower than 0.10 indicate rational logic in the judgment process.

Finally, to perform the process of judgment and attribute weight values, we used the Software Expert Choice version 3.01.

2.5. Sensitivity analysis (Stages 3 and 8)

According to Saaty (1980), sensitivity analysis in AHP is a step to test the responsiveness or sensitivity of the outcome of a decision to changes in the priorities of the major criteria of the problem. It is a test to check whether a small change in weights will affect the results. If so, it would have little effectiveness for the formation of an effective policy.

In this study, we performed sensitivity analysis for the primary criteria (transport and land use/other sources) and we used Numerical Incremental Analysis (NIA). This approach works by incrementally changing one parameter at a time, calculating a new solution, and presenting how the global ranking of criteria changes. Eq. (7) shows the function used to perform the sensitivity analysis.

$$P_i=\frac{P_i''-P_i'}{w_i''-w_i'}\left(w_i-w_i'\right)+P_i' \tag{7}$$

Where P_i'' and P_i' are the priority values for w_i'' and w_i', respectively. Finally, only one weight w_i was changed at a time.

2.6. GIS techniques for human exposure risk maps consolidation (Stage 4)

We used GIS techniques to consolidate human exposure maps, including reclassify, map algebra and filter.

Initially, we applied the reclassify tool for all maps presented in Appendix C. We defined for all maps 10 classes using the quantile method. Then we applied the map algebra tool in order to overlay the maps. This tool was performed obeying the groups of criteria and the hierarchical level, which we generated the final human exposure map considering the last level (transport and land use/other source). We used the weights generated by the AHP method (Stage 2) as coefficients to perform the map algebra. Eq. (8) was used to create the final human exposure map.

$$FMHE=w_tHEMt+w_lHEMl \tag{8}$$

Table 1
Description of the alternatives for public policy.

Alternatives	Description
LUM	Public policy related to managing and controlling the use and development of land, including built environment and natural resources.
NGAIU	Public policy related to creating of new green spaces intra urban.
VTC	Public policy related to managing and controlling the number of vehicles, including congestion charge and toll.
PTD	Public policy related to investment in public transportation, including subways and buses

Land use management (LUM), New green areas intra urban (NGAIU), Vehicle traffic control (VFC), and Public transport development (PTD).

Where *FMHE* is the final map for human exposure; w_t and w_l are the weights for the criteria transport and land use/other sources, respectively; *HEMt* is the human exposure map only for the criteria transport; and *HEMl* is the human exposure map only for the criterion land use/other sources. We used the same logical process (GIS techniques for the groups of criteria and observing the hierarchical level the maps) to process the maps for *HEMt* and *HEMl*.

Finally, we applied the filter tool for the final human exposure map in order to eliminate spurious data or enhance the depiction of the data.

We performed all GIS techniques in the software ArcGIS version 10.2 and we defined the raster grid with 10×10 m.

2.7. Alternatives for public policy (Stage 5) and its inclusion in the hierarchical network (Stage 6)

The agents of the FD Environmental Agency defined the alternatives. We asked them to define alternatives for public policy decision making for reducing source emissions, considering the current and future FD challenges. Four alternatives were defined: i) land use management; ii) new green areas intra urban; iii) vehicle traffic control, and; iv) public transportation development. Table 1 shows the description of each alternative.

Fig. 4 presents the alternatives included in the hierarchical network. Note that the alternatives are related to all criteria defined previously in the Stage 1.

2.8. Spatial multi-criteria model – complement the weights for the alternatives (Stage 7)

We estimated weights for the alternatives using the same approach described for Stage 2. However, here the agents assigned the values considering the alternatives for each criteria. For example, the agents performed the judgment in order to answer the following question: considering only the presence of highways as air pollution source, what are the weights for each one of the four alternatives for public policy, in order to minimize the human exposure to air pollutants in the FD?

Finally, in order to establish a global value of each alternative and for each criterion, we used Eq. (9), which is the next math procedure following from Eq. (8):

$$\mathrm{V(a)}=\sum_{\mathrm{j=1}}^{\mathrm{n}}\mathrm{W_jv_j(a)} \tag{9}$$

Where *V(a)* is the global value; W_j is the importance relative to the criteria *j*; V_j is the level of preference of the alternative for criterion *j*, which $\sum_{j=1}^{n}W_j=1v_j(a)$, and $0<\mathrm{W_j}<1$ ($j=1,\ldots,$n).

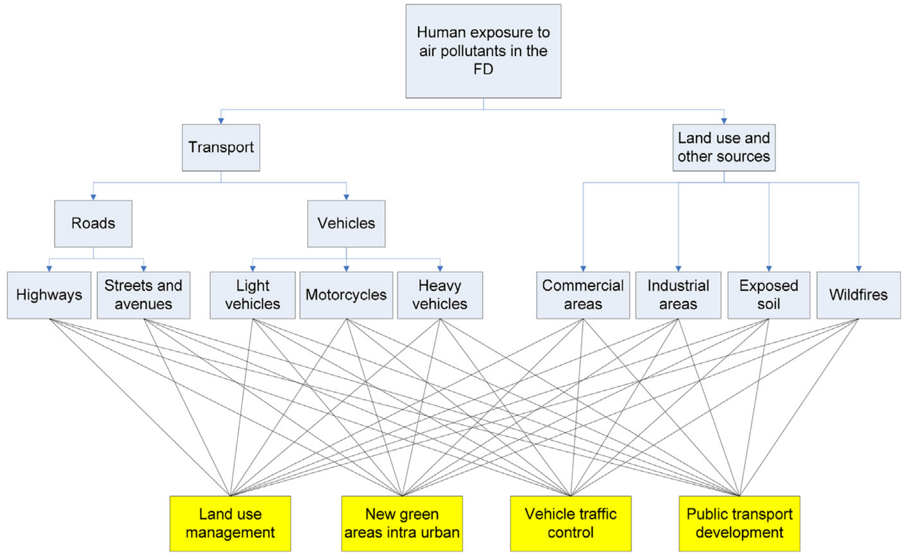

Fig. 4. Hierarchical network with alternatives. *Note*: yellow boxes – alternatives.

2.9. GIS techniques for public policy maps consolidation (Stage 9)

We used here the same technique as in Stage 4, GIS methods and logical process, to perform the map algebra. The difference is that here we considered only the alternatives for public policy (created in Stage 5 and judged in Stage 7). Therefore, we created a final map for each of the four alternatives, as shown by Eq. (10):

$$FMPP_y = w_{t,y}HEMt_y + w_{l,y}HEMl_y \tag{10}$$

Where *FMPP* is the final map for public policy; *y* is the alternative; w_t and w_l are the weights for the alternative *y* modeled for the criteria transport and land use/other sources, respectively; *HEMt* is the public policy map for the alternative *y*, considering only the criterion transport, and; *HEMl* is the public policy map for the alternative *y*, considering only the criterion land use/other sources.

To conclude the process to consolidate the public policy maps, we used fuzzy logic (fuzzification algorithm) to transform the result into a 0 to 1 scale, where 0 is considered low priority to implement public policy *y*, and 1 is considered high priority. Specifically, we applied fuzzy membership with large spread parameter, where large values of the input map have high membership in the fuzzy set. Eq. (11) shows the large fuzzification. Appendix D shows a hypothetical example of fuzzy large membership function.

$$\mu(x) = \frac{1}{1 + \left(\frac{x}{f_2}\right)^{-f_1}} \tag{11}$$

Where *x* is the input variable, f_1 is the spread of the transition from a membership value of 1 to 0 and f_2 is the midpoint where the membership value is 0.5.

3. Results and discussion

3.1. Weights of criteria and alternatives

The FD Environmental Agency prioritizes transport as the most important primary criteria (weight = 0.75). Considering only the subcriteria, land use and other sources, commercial area is assigned with the higher importance (weight = 0.405). In addition, considering the subcriteria, vehicles and roads, light vehicles (weight = 0.618), and highways (weight = 0.750) were defined with the highest weights, respectively (Table 2).

Table 2
Weights attributed to each criteria and alternatives.

TARGET / CRITERIA / SUBCRITERIA	WEIGHTS FOR CRITERIA (FROM STAGE 2)	ALTERNATIVES	WEIGHTS FOR ALTERNATIVES (FROM STAGE 7)
TARGET: HUMAN EXPOSURE TO AIR POLLUTANTS IN THE FD	-	Land use management	0.179
		New green areas intra urban	0.171
		Vehicle traffic control	0.318
		Public transport development	0.332
Transport	0.750	Land use management	0.121
		New green areas intra urban	0.180
		Vehicle traffic control	0.332
		Public transport development	0.367
Roads	0.750	Land use management	0.121
		New green areas intra urban	0.181
		Vehicle traffic control	0.342
		Public transport development	0.356
Highways	0.750	Land use management	0.120
		New green areas intra urban	0.168
		Vehicle traffic control	0.328
		Public transport development	0.383
Streets and avenues	0.250	Land use management	0.125
		New green areas intra urban	0.219
		Vehicle traffic control	0.383
		Public transport development	0.273
Vehicles	0.250	Land use management	0.122
		New green areas intra urban	0.180
		Vehicle traffic control	0.300
		Public transport development	0.399
Light vehicles	.618	Land use management	0.094
		New green areas intra urban	0.198
		Vehicle traffic control	0.257
		Public transport development	0.451
Motorcycles	0.086	Land use management	0.084
		New green areas intra urban	0.252
		Vehicle traffic control	0.194
		Public transport development	0.469
Heavy vehicles	0.297	Land use management	0.191
		New green areas intra urban	0.120
		Vehicle traffic control	0.418
		Public transport development	0.271
Land use and other sources	0.250	Land use management	0.354
		New green areas intra urban	0.144
		Vehicle traffic control	0.275
		Public transport development	0.226
Commercial areas	0.405	Land use management	0.195
		New green areas intra urban	0.138
		Vehicle traffic control	0.391
		Public transport development	0.276
Industry areas	0.377	Land use management	0.480
		New green areas intra urban	0.102
		Vehicle traffic control	0.219
		Public transport development	0.199
Exposed soil	0.080	Land use management	0.264
		New green areas intra urban	0.492
		Vehicle traffic control	0.176
		Public transport development	0.068
Wildfires	0.138	Land use management	0.526
		New green areas intra urban	0.079
		Vehicle traffic control	0.149
		Public transport development	0.246

Regarding the public policy alternatives for minimizing human exposure to air pollutants in the FD, vehicle traffic control and public transportation development are the most important alternatives with, weights equal to 0.318 and 0.332, respectively. The estimated weights for land use management and new green areas intra urban 0.179 and 0.171, respectively (Table 2).

The alternative weights considered in our study represent the main challenges in the FD, which faces significant air pollution problems due to emissions from vehicle traffic and public trans-

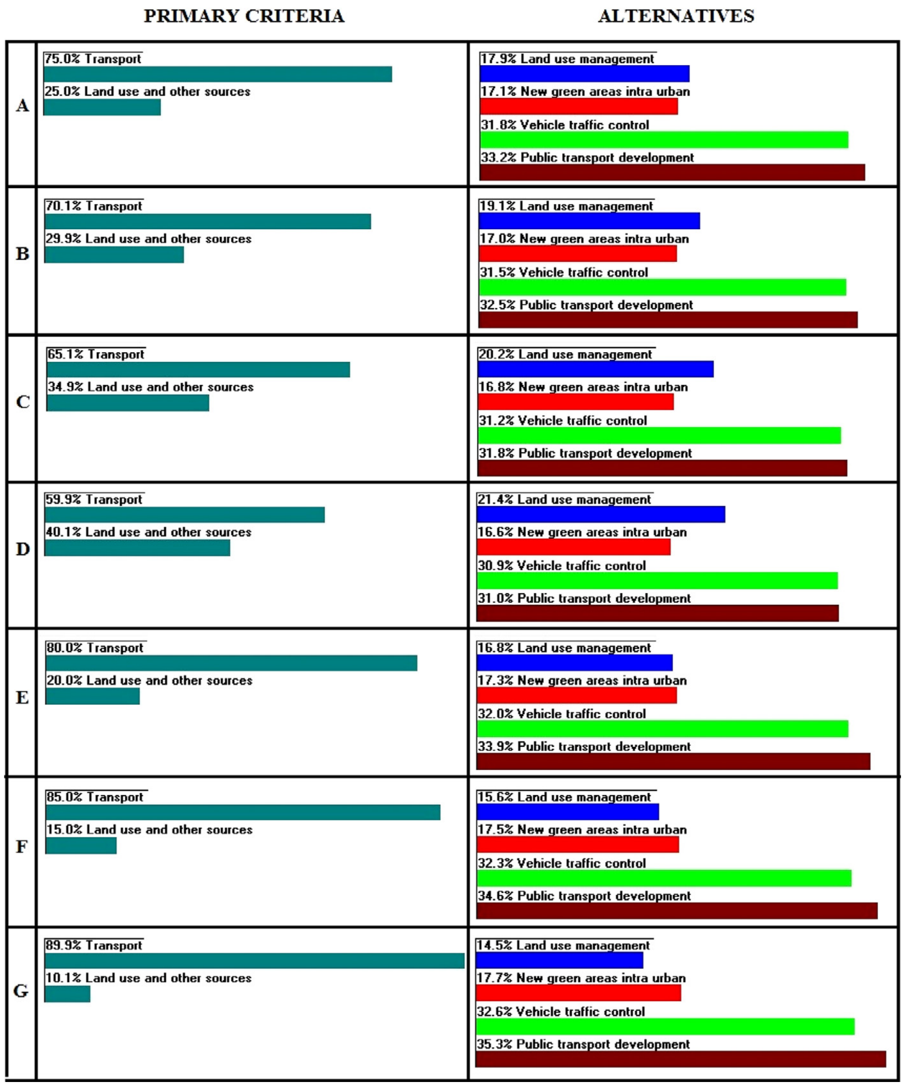

Fig. 5. Sensitivity analysis results.
Note: weights defined by FD Environmental Agency: (A) hypothetical variation: −5% for transport criteria and +5% for land use and other sources criteria; (B) hypothetical variation: −10% for transport criteria and +10% for land use and other sources criteria, (C) hypothetical variation: −15% for transport criteria and +15% for land use and other sources criteria, (D) hypothetical variation: +5% for transport criteria and −5% for land use and other sources criteria, (E) hypothetical variation: +10% for transport criteria and −10% for land use and other sources criteria, and; (F) hypothetical variation: +15% for transport criteria and −15% for land use and other sources criteria (G).

portation. As we mentioned in Section 2.1 – study area, the FD has approximately 1.6 million vehicles, which corresponds to 0.6 vehicles per inhabitant. This ranks it as the 5th Brazilian state with the higher rate (IBGE, 2013). Almost 5500 tons of particulate matter; 155,000 tons of nitrogen oxides; 120,000 tons of carbon monoxide; and 180,000 of non-methane hydrocarbon are emitted per year from the main routes in the FD (Réquia Júnior et al., 2015a). As the public transportation (buses and subway) in the FD, it is still very inefficient, in terms of the cover (39 km of subway lines; and three buses per line – one of the lower rates among the Brazilians cities), quality and security. For example, 60% of passengers claim that do not feel safe using public transportation. Most of the trips in FD are made by the modal of private transport (50.98%), while modal of public transport represents 41.05% of the travel; and the other modals (biking, walking etc.) represent 7.97%. Most of the people who use public transport in the FD have low income (GDF, 2008, page 45).

Many studies have suggested that controlling traffic emissions and improving public transportation are very effective policies for areas with similar challenges. For example, Zhang et al. (2013) showed that controlling vehicular emissions in Guangzhou, China, during 2005 and 2009, was very effective in reducing human exposures to air pollution. The authors reported that during this period CO and PM_{10} emissions decreased by 12 and 20%, respectively. Silva et al. (2012) showed that public transportation in São Paulo, Brazil, especially subway, is critical to efforts reducing traffic and its environmental and health impacts. The authors estimated the public health costs of a one-year strike by subway employees would be approximately 18 billion dollars.

3.2. Sensitivity analysis

Overall, our results were insensitive to any hypothetical variation in the weights of primary criteria. We performed six hypothetical variation scenarios. First, we decreased the preference for transport criteria by 5, 10 and 15%, and consequently, we increased the preference for land use and other sources criteria 5, 10 and 15% (totaling three simulations, altering 5% at time). Furthermore, we increased by 5, 10 and 15% the preference for transport criteria, and consequently, we decreased by 5, 10 and 15% the preference for land use and other sources criteria (totaling

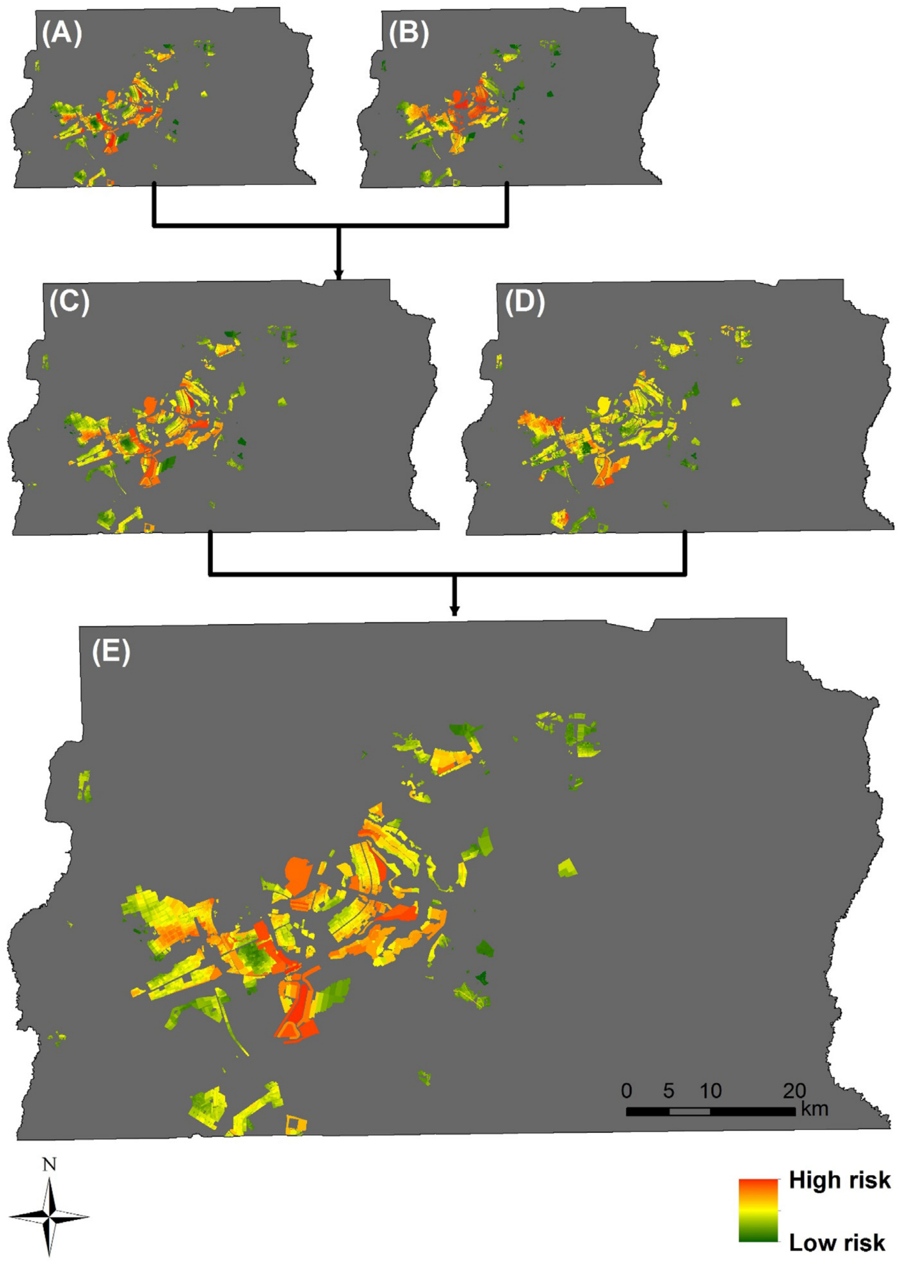

Fig. 6. Human exposure map.
Note: roads subcriteria (A); vehicles subcriteria (B); transport criteria (C); land use and other sources criteria (D); final human exposure map (E).

three simulations, altering 5% per time). The maximum change in these alternatives was 3% (Fig. 5).

According to Xu et al. (2014), our findings are robust and can be used to formulate sound policies, and regulators should feel confident that altering the preferences of the primary criteria would not change the effectiveness of the proposed policies.

3.3. *Mapping human exposure risk and alternatives for public policy*

Fig. 6 presents the structure used to generate the final human exposure map. First, we processed the maps that represent roads subcriteria (Fig. 6, map A) and vehicles subcriteria (Fig. 6, map B) to generate the transport criteria (Fig. 6, map C). Then we processed the transport and land use/other sources criteria maps (Fig. 6, map D) to create the final map indicating human exposure to air pollutants in the FD (Fig. 6, map E).

The regions at intermediate to high risk have some similarities such as high population density and vehicular traffic. Appendices 4 and 5 show the spatial distribution of traffic and population, respectively.

Numerous studies in urban areas have found associations between vehicular traffic and health (Brugge et al., 2013; Slezakova et al., 2013; Williams et al., 2009). Specifically in the FD area, Réquia Júnior et al. (2015a) have reported that the population density is an important element to estimate health problems. For example, the authors showed that in some FD regions with high population density, the risk increased more than 200%. Most of the regions which Réquia Júnior et al. (2015a) have presented as a 200% increase in risk (due to high population density) are the same areas with high risk estimated in this present study.

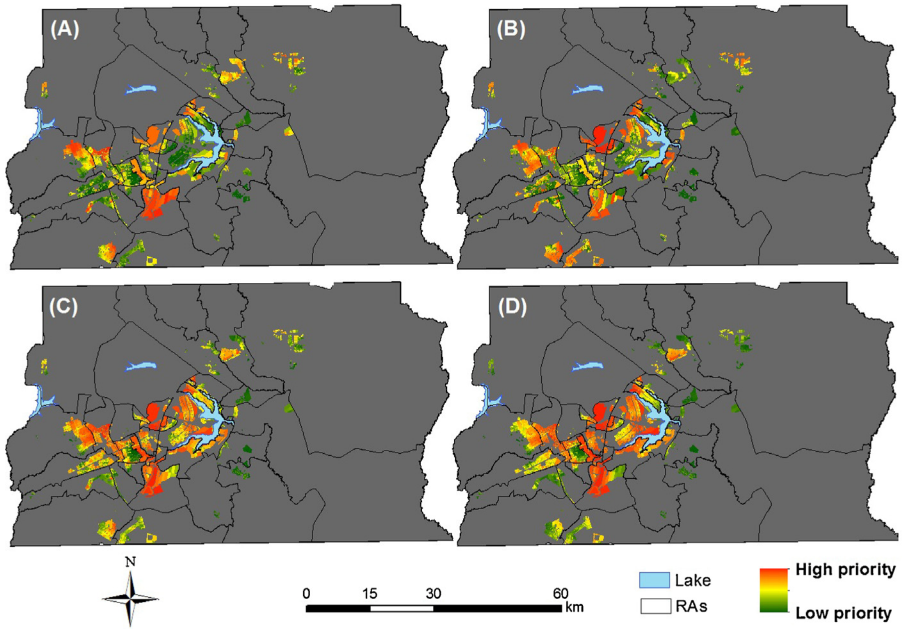

Fig. 7. Public policy maps.
Note: Alternative – Land use management (A); Alternative – New green areas intra urban (B); Alternative – Vehicle traffic control (C); Alternative – Public transport development (D); Administrative regions of the FD (RAs).

Fig. 7 presents four public policy maps – one for each alternative determined by the FD Environmental Agency. Each map shows the priority level (low to high) to implement the alternative in analysis.

The areas identified as high priority in the map for the land use management alternative (Fig. 7, map A) are almost identical to those with problems related to illegal urban settlements. According to the Urban Development Agency (SEDUH, 2006), the FD has 317 areas with illegal urban settlements. SEDUH (2006) reports that 23% of the population in the FD live in illegal settlements. This is a disorderly urbanization process with no land use management, which can cause environmental, social, and especially health impacts. Problems related to illegal urban settlements have been reported for other urban centers, including São Paulo – Brazil (Torres et al., 2007), Mexico City – Mexico (Aguilar, 2008) and Lucknow – India (Dutta, 2013).

Fig. 7 map B, shows the new green areas intra urban alternative. Most of the green areas intra urban are located in the administrative region of Brasília and surrounding areas (Fig. 1 shows the location of Brasília). Our findings suggest low priority to develop new green spaces intra urban in the Brasília area. In contrast, we found high priority levels in areas that overlap the high priority areas for the land use management alternative (Fig. 7, map A). This is expected, considering that illegal urban settlements represent areas losing green space.

Many studies have demonstrated the benefits of green areas to public health. In a previous study, we estimated that a 1 km^2 increase in green areas intra urban is associated with a decrease of two hospital admissions for cardiorespiratory diseases (Requia et al., 2016). Nowak and Heisler (2010) showed that green spaces in US neighborhoods reduce air pollution and save approximately $500 million per year in public health costs.

We found similarity between the maps for the vehicle traffic control alternative (Fig. 7, map C) and for the public transport development alternative (Fig. 7, map D). This suggests that increasing public transportation use is an effective way to control the vehicle traffic in the FD. Previous studies have proposed this alternative for controlling vehicle traffic and consequently improving the quality of life (Bhouri and Lotito, 2005; Djurhuus et al., 2014; Geng et al., 2013; Hamre and Buehler, 2014). Specifically for the FD, effective investment to improve the access to transportation modal is an option in order to reduce vehicle traffic.

Our findings suggest that most of the high priority levels for vehicle traffic control (Fig. 7, map C) and public transport development (Fig. 7, map D) are located in areas with high daily flux of people (origin and destination). The Brasília region (Fig. 1 shows this region) is an important travel destination and is the region with most employment opportunities in the FD. It is responsible for 39.70% of all economic activity in the FD, and serves as headquarters for most of the Brazil's government agencies. Part of the public policy strategies to minimize vehicular emissions is related to the improvement of job offer in other areas of the FD, which would reduce the daily travel (GDF, 2008).

4. Conclusions

To our knowledge, this is a first attempt to map alternatives for public policy decision making related to human exposures from air pollution sources. Our results are innovative because it open several opportunities to public management for many government sectors. The method is straightforward and transparent, and can be used for other priorities and study areas.

National, state, and local agencies that are responsible for planning and managing environmental resources, urban system, and public health can design efficient public policies in a cost effective way.

Acknowledgement

This publication was made possible by USEPA grant RD-83479801. Its contents are solely the responsibility of the grantee and do not necessarily represent the official views of the USEPA. Further, USEPA does not endorse the purchase of any commercial products or services mentioned in the publication.

Appendix A.

Table A.1

Table A.1
Summary of all 9 variables.

Variables	Unit	Variable definition
Highways	m	Major roads which were mostly interstate
Streets and avenues	m	Roads in an urban context
Light vehicles	Vehicles	Passenger vehicles
Heavy vehicles	Vehicles	Bus and trucks
Motorcycles	Numbers	Vehicles with two in-line wheels
Industry areas	m^2	Area of land designated for industrial use
Commercial areas	m^2	Area of land designated for commercial use
Exposed soil	m^2	Degraded areas (no vegetation, no urban structures)
Wildfire	Coordinates	Location points of wildfire

Source: Réquia et al. (2016).

Appendix C.

Fig. C.2

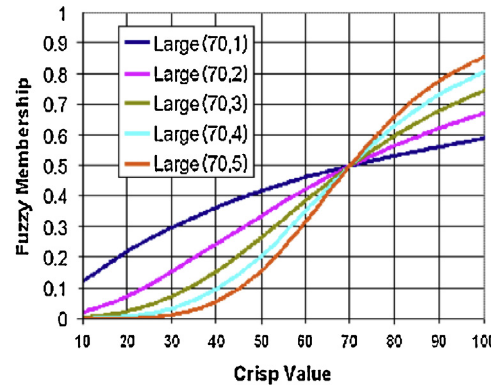

Fig. C.2. Hypothetical example of the fuzzy lard membership function.
Note: in this hypothetical example, 70 was assigned as midpoint. In addition, the chart presents an example of five spread parameter (1, 2, 3, 4 and 5). In our study, we defined 5 as spread parameter.

Source: Esri (https://desktop.arcgis.com/en/desktop/latest/tools/spatial-analyst-toolbox/how-fuzzy-membership-works.htm).

Appendix B.

Fig. B.1

Appendix D.

Fig. D.3

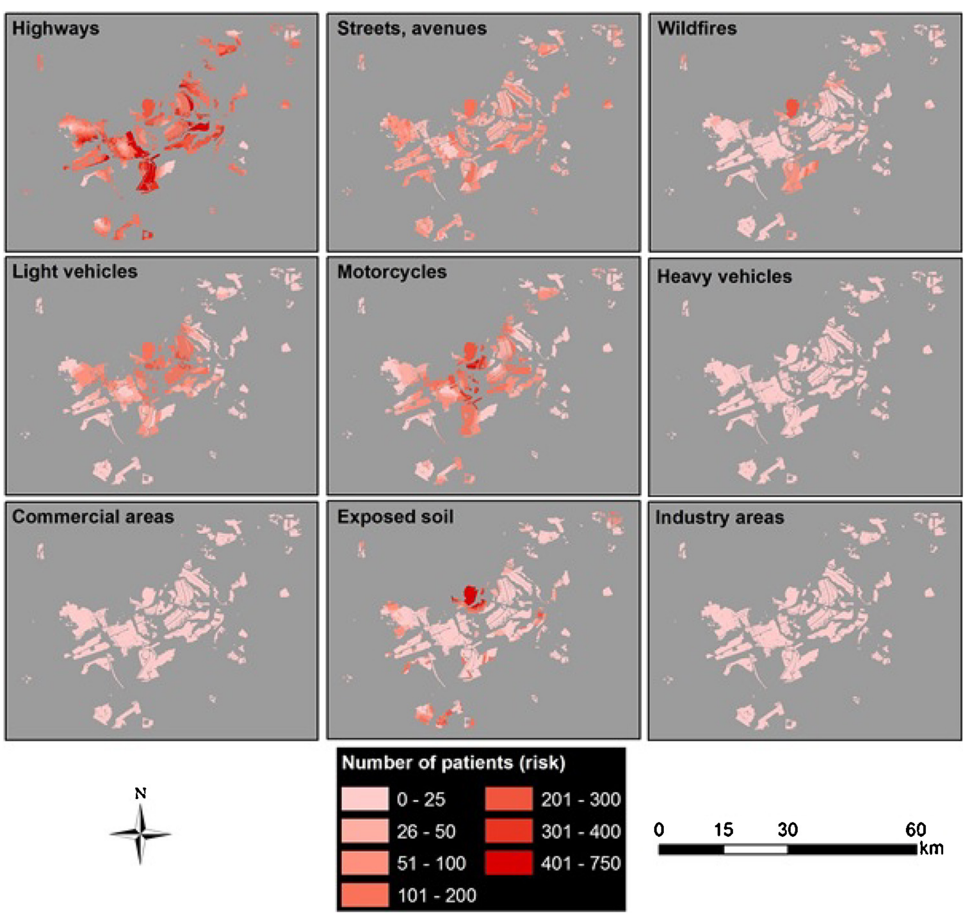

Fig. B.1. Risk maps of all 9 variables.

Source: Réquia et al. (2016).

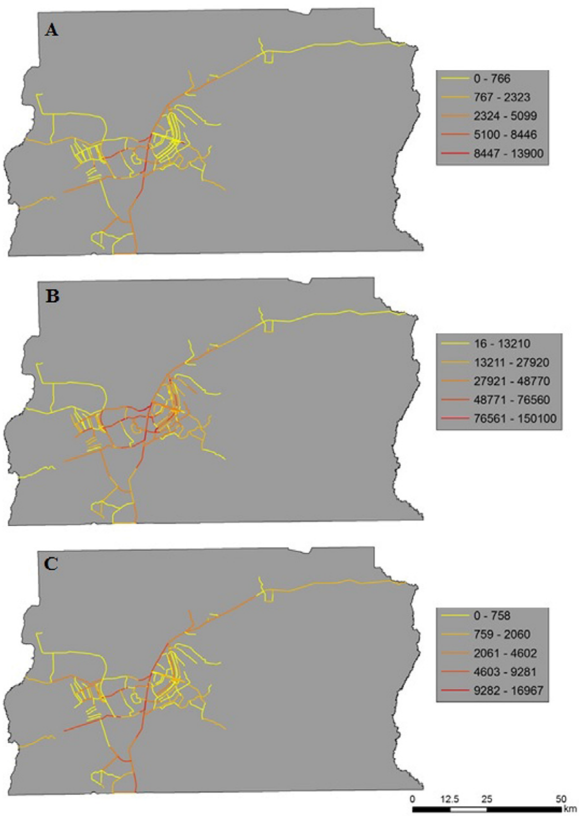

Fig. D.3. Spatial distribution of traffic in the main roads of the FD.
Note: motorcycle (A); light vehicles (B); heavy vehicles (C).

Appendix E.

Fig. E.4

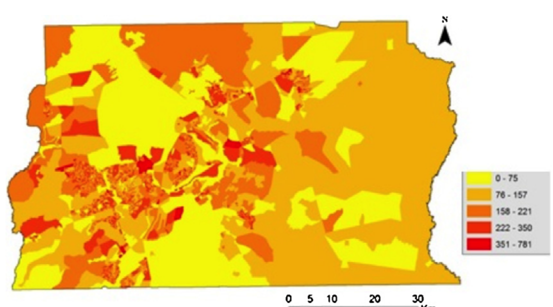

Fig. E.4. Spatial distribution of population in the FD.

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