A GIS-BASED COMPARISON OF METHODOLOGIES FOR THE DEFINITION OF METROPOLITAN AREAS IN A DEVELOPING COUNTRY

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Abstract

This paper presents a comparison of two methodologies for the definition of metropolitan regions, both based on population density values analyzed in a GIS, when applied in a case study in the state of São Paulo, Brazil. The first one considers an index I resulting from density values normalized twice between zero and one, at the local and national levels. The second method is based on Exploratory Spatial Data Analyses (ESDA) techniques, which allow an analysis of the spatial distribution of densities through the four quadrants of a Moran's scatterplot. While the first method produces flexible outputs for analyses, the ESDA approach allows a clear identification of clusters of high density municipalities. However, as the two methods are not able to explore the changes of metropolitan areas through time, a CA-based approach is also discussed. It contains the temporal dimension, which is interesting for the formulation of urban planning policies.

Keywords: metropolitan areas, homogeneous urban areas, ESDA, spatial analysis

1. INTRODUCTION

Brazil is currently one of the five most populated nations in the world and it is still growing. From a planning perspective, however, even more important than the growth rate of 1.6 % per year of the total population is the intense growth of the population in urban areas (Gouvêa, 2005). One of the reasons of concern is the fact that increases in the urban population figures have a direct impact in the occupation of the territory. Adjacent and contiguous areas are continuously developed in a process that often combines, in a large urbanized area, several distinct municipalities. Those conurbations can be identified as homogeneous urban areas or as Metropolitan Areas (MA).

One of the major challenges faced by urban planners and urban managers at a regional scale is the definition of those areas. The evidence of strong political and administrative relationships among the municipalities is one of the strategies used for their definition. That criterion, however, does not always effectively reflect all common aspects of the neighboring municipalities. Another suggested approach is based on the commuting flows among adjacent regions. That alternative, however, is not easily applied because the data needed for its application is often unavailable or outdated. Criteria based on population density values are also found in many studies. One specific work even suggests that "residential population density can serve as a surrogate for other measures of activity in the absence of nationally consistent and reliable data sets describing all daily and weekly movements of individuals".

An eventual problem behind different methodologies, however, is the fact they can produce different results. As a consequence, those results can lead to distinct definitions of MA. Planners need to know to what extent they differ from one another before suggesting the adoption of any of them. Thus, the objective of this paper is to present a comparison of two methodologies for the definition of metropolitan regions when applied in a developing country, both based on population density values. The first one considers an index I resulting from population density values normalized twice between zero and one, at the local and national levels. The second method considered is based on Exploratory Spatial Data Analyses (ESDA) techniques, which allow an analysis of the spatial distribution of population densities through the four quadrants of a Moran's scatterplot. In order to compare the outcomes of the two methodologies considered, they are applied in a case study in the state of São Paulo, Brazil.

This paper is structured as follows. Some methods for the definition of metropolitan areas found in the literature are presented and discussed in section 2. In section 3 is presented the method adopted here, followed by a discussion of the results found with it in section 4. Finally, the conclusions and some recommendations for further investigations are shown in section 5.

2. THE DEFINITION OF METROPOLITAN AREAS

The focus of the problem discussed here is the definition of the metropolitan regions in spatial terms, considering that they are larger than any single clustered city but often smaller than the upper administrative divisions (e.g., province, state, or region). This is not a recent problem and therefore it is not difficult to find discussions about the issue and methods for such a definition in the literature, as in the works of NUREC (1994), Lacour and Puissant (1999), Ferreira and Rosado (1999) and Ferrão *et al.* (2002). A number of authors even carried out theoretical applications of some of the reported methods for defining boundaries of metropolitan regions in the main Portuguese regions, namely Lisbon and Oporto (Ferrão and Vala, 2001; and Ferrão *et al.*, 2002). They used the differences in terms of area, population, and employment resulting from the application of various methods to point out the main problems of the approaches investigated.

There is also literature about the topic available in the United States (e.g., Office of Management and Budget, 1990; Office of Management and Budget, 1998; Office of Management and Budget, 1999; Metropolitan Area Standards Review Committee, 2000; and Office of Management and Budget, 2000), where the need of constant review of metropolitan area standards is often highlighted in order to ensure their continued usefulness and relevance. The current standard for defining metropolitan areas in the United States is essentially a commuting-based county-level approach (Office of Management and Budget, 2000), which was adopted after a discussion of four initial alternative approaches. They were: a commuting-based county-level approach, a commuting-based tract-level approach, a directional commuting tract-level approach and a comparative density county-level approach (Office of Management and Budget, 1998).

It is important to observe the presence of the population density as an alternative to defining metropolitan areas, since reliable and up-to-date commuting data are very hard to find in some countries. This was also defended by the authors of Office of Management and Budget (1998), who stated that "residential population density can serve as a surrogate for other measures of activity in the absence of nationally consistent and reliable data sets describing all daily and weekly movements of individuals".

In that context, recent studies using the population density for defining metropolitan areas have been carried out exploring spatial analyses tools. Ramos and Silva (2003a) have presented a data-driven approach based on the population density through two branches of Spatial Analyses: Spatial Statistics and Spatial Modeling. An alternative approach is found in Ramos and Silva (2003b), in which the authors use the building density instead of the population density. The spatial modeling concepts explored in the two studies were derived from the Cellular Automata (CA) theory.

It is important to notice that the approaches tested by Ramos and Silva (2003a, 2003b, 2007) are all looking at the local influence of the municipalities, rather than their national and local strengths altogether. The authors acknowledged that limitation of their studies and at a certain point they presented a comparison of two different methodologies for the definition of metropolitan areas (Ramos *et al.*, 2004). The first method followed their original studies and it was based on the ESDA techniques, while the second one considered an index I, which was built to represent the local and national influence of the municipalities, following the Office of Management and Budget (1998).

The study of Ramos *et al.* (2004) made possible a clear identification of the main differences between the approaches, from now on called ESDA and I, respectively. The ESDA approach allows a clear identification of clusters of municipalities with high values (i.e., areas in the Q1 quadrant of the Moran’s scatterplot) of a certain variable (in that case, population density) and surrounded by transition areas represented by zones in the quadrant Q3. The I method does not allow such a straightforward definition of homogeneous urban areas. Alternatively, it provides a quite flexible outcome of the analyses, in which the analyst is free to decide how to set the conditions for defining metropolitan areas based on the outcomes of the calculation.

However, the ESDA and I methods bring some inherent characteristics regarding their geographical comprehensiveness that are relevant for the present study. While the ESDA method looks only at the local vicinity (e.g., within state boundaries), the I method is able to simultaneously take into account the role played by each municipality at different scales, for example, at the local and national levels. Another important characteristic of the methods discussed is the way their outcomes are related to space and time. The ESDA techniques present results that are static, both in space and time. It means that the analyst is not able to set the conditions for the definition of which municipalities will join a metropolitan area without modifying the neighborhood criteria. The I method presents results that are static in time, but flexible in space. The flexibility in space comes from the fact that it is possible to change the conditions for the identification of municipalities that would form a metropolitan area.

Nevertheless, these two methods are stationary in time and that is a restriction for their implementation in practice. Thus, in order to avoid this restriction, spatial modeling tools can be an option for analyses of the phenomenon throughout time. In the studies of Ramos and Silva (2003a, 2003b and 2007) and Ramos *et al.* (2004) the authors built some models based on CA concepts for exploring different ways of getting the transition rules and for testing distinct variables as model outcomes. Basically, the first models developed by Ramos and Silva (2003a and 2003b) were built with a deterministic transition rule based on a structure *if, then, else*. The outcomes of these models were the quadrant of the Moran's scatterplot. Given the restrictions found by the authors in that approach, further studies were carried out. Ramos and Silva (2007) presented an alternative approach for establishing the transition rules based on Artificial Neural Networks (ANN), what made possible to set any variable to be a predicted outcome.

Although the work of Ramos and Silva (2007) led to interesting and promising results, once the population density could be estimated by a CA-like model during a specific period of time, they were limited to the case of Portugal, where the study was carried out. As a consequence, their approach is now used for an application in a case study in the state of São Paulo, Brazil, in combination with another method previously tested. In summary, the application explores two methodologies for the identification of metropolitan areas: the I index and ESDA techniques combined with CA models, as discussed in the next section in details.

3. METHOD

The method applied in the present study for the definition of metropolitan areas is based on two approaches: an index I and ESDA techniques combined with CA models. In order to compare the outcomes of the two methodologies considered, they are applied in a case study in the state of São Paulo, Brazil, which already has three "official" metropolitan regions, around the cities of Campinas, São Paulo and Santos.

The first method considers an index I resulting from population density values for the year 2000, normalized twice between zero and one, at the local and national levels, as in Equation (1). Once classified by the index I, each municipality can be represented in a thematic map giving an identification of clusters of municipalities with high population density values.

$$I_i = \left(\frac{PD_i - Min_L}{Max_L - Min_L} \right) \times \left(\frac{PD_i - Min_N}{Max_N - Min_N} \right) \tag{1}$$

Where:

PD_i is the population density of each municipality;
Min_L is the minimum value of the population density at the local level;
Max_L is the maximum value of the population density at the local level;

Min_N is the minimum value of the population density at the national level;
Max_N is the maximum value of the population density at the national level.

The second method considered is based on Exploratory Spatial Data Analyses (ESDA) techniques, which allow an analysis of the spatial distribution of population densities through the four quadrants of a Moran's scatterplot. Points located in quadrants Q1 and Q2 indicate that the attribute value of a particular zone is similar to the average value of the same attribute in neighbor zones (positive value for the zone and positive average value for neighbors in Q1 and negative value for the zone and negative average value for neighbors in Q2). Points are located in quadrants Q3 and Q4 if the attribute value of a particular zone is dissimilar to the average value of the same attribute in neighbor zones (positive value for the zone and negative average value for neighbors in Q4, and negative value for the zone and positive average value for neighbors in Q3). The representation of the quadrants in a map (which is called *Box Map*) allows a clear identification of clusters of municipalities with high population density values. According to that method, Q1 clusters can be used to define MAs. The results of the ESDA techniques were compared with the outcomes of the method based on the index I, both applied to the population density in the year 2000.

Regarding the ESDA method, CA models were built to analyze the metropolitan areas developments through time. It is important to notice that the models developed here explore only some concepts of CA. One of the most remarkable characteristics is their ability to simulate space-temporal changes. CA models are also able to represent complex phenomena related to the urban planning (Silva, 2002; Webster and Wu, 2001). The main inherent concept of CA is the possibility of getting global patterns from the local behavior of a reduced number of elements (Silva, 2002; Yeh and Li, 2002). A CA model also presents some important properties: cells with multiple formats to represent space, several state possibilities, neighborhood relationships, transition rules to represent changes and discrete temporal series. Thus, taking into account these characteristics and properties, the models developed in this study were built as follows.

Firstly, in addition to the calculation of the population density, other variables had to be determined: the average of the population density in the neighborhood of each municipality, the quadrant of the Moran's scatterplot and the number of neighbors in each quadrant (Q1, Q2, Q3 and Q4) for each municipality. These variables were calculated for the periods of 1960, 1970, 1980, 1990 and 2000. Secondly, these variables had to be organized in order to allow the use of neural nets, given the data available has to be used for training, validation and prediction. During the training phase, data from 1960, 1970 and 1980 were used as inputs of the model, and 1990 data was taken as the output. After this, in order to validate the model, data from 1970, 1980 and 1990 were used as inputs and the values of 2000 as the output. This step is very important, once the predicted values of the year 2000 can be compared with the real values of the same year. The comparison gives a feedback to the analyst about the performance of the model. Finally, in the prediction phase, it is possible to analyze data of a simulation in a future time step. It means that the population density can be predicted in a certain period of time. As the time step considered in this study was of ten years, the predicted values of the population density were for the year 2010.

The results of the application of this specific CA model in this study can be shown in thematic maps representing the quadrants of the predicted population density (*Box*

Map). Clusters of municipalities in Q1 can then be easily used to define metropolitan areas. This is discussed in the next section, along with the presentation of the main results obtained with the different methods applied.

4. RESULTS

The results of the method based on the index I are presented in Figure 1, which shows a thematic map with the outcomes of the population density classified by that index. The map on the top left of the figure presents the municipalities with the highest 10 % values for the index I. The map on the top right, the highest 20 %. At the bottom left, the map shows the municipalities with the 25 % highest values for the index I and, finally, at the bottom right, 30 % of the municipalities are highlighted because of their high I values.

A visual analysis of Figure 1 helps to understand the flexibility of the index I previously mentioned. By exploring different sets of municipalities with the highest index I values, the analyst can consider different groups of municipalities to conform one or more metropolitan areas. It also offers the possibility of generating different scenarios. In the examples displayed in Figure 1, the scenario with the 25 % highest values seems to contain the most adequate set for identifying the metropolitan regions in the case studied. That is only possible because an inherent characteristic of this method is the possibility of producing several outputs.

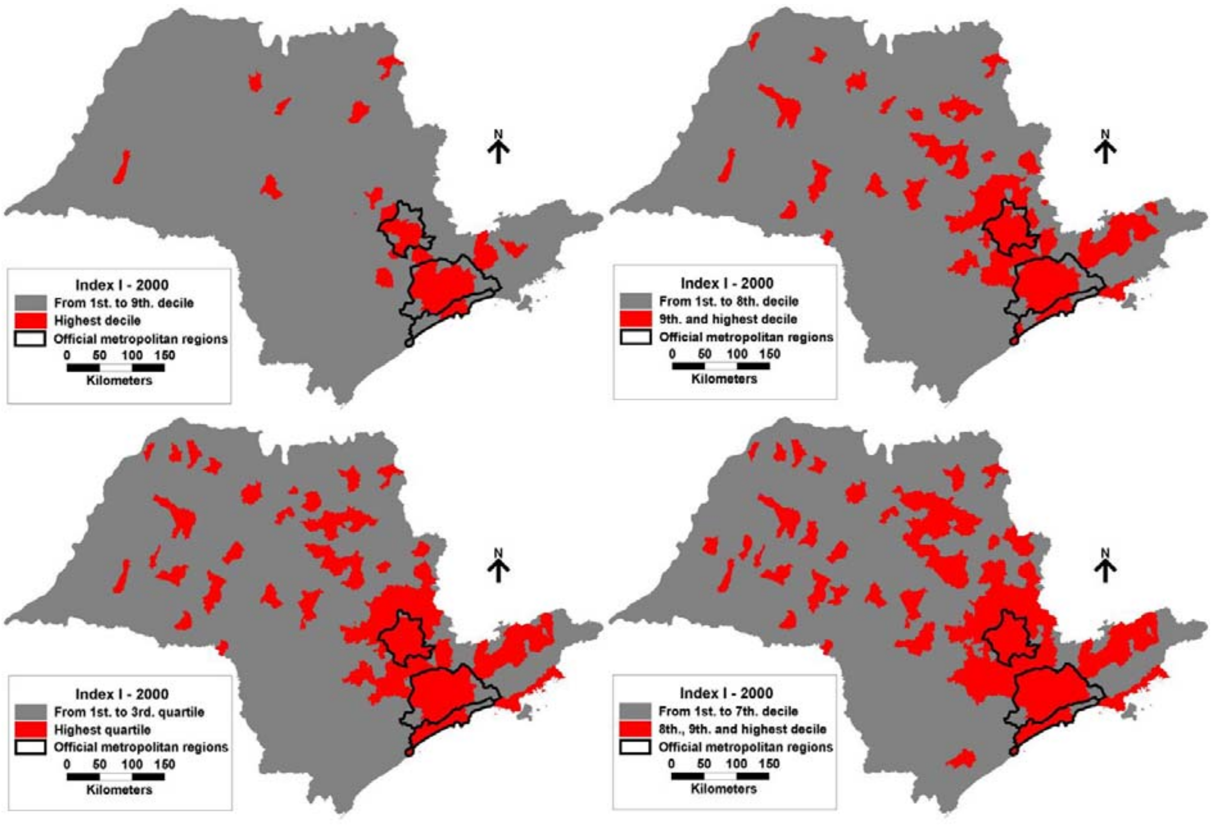

Figure 1: Thematic maps showing four different sets of municipalities with the highest values of the index I for the variable population density

Regarding the ESDA method, the results for the variable population density classified by the quadrants of the Moran's scatterplot are shown in Figure 2, which represents a

Box Map for the year 2000. It is possible to observe through Figure 2 that, differently from the method based on the index I, the ESDA approach allows a clear identification of clusters with high density municipalities, represented by Q1 areas. It is also important to notice the presence of Q3 areas surrounding the Q1 clusters, which is also an interesting outcome of the ESDA method. Although they have low density values when compared to the neighbors in Q1, their geographical locations and the strength of the Q1 neighbors suggest that they can become part of the Q1 clusters after some time.

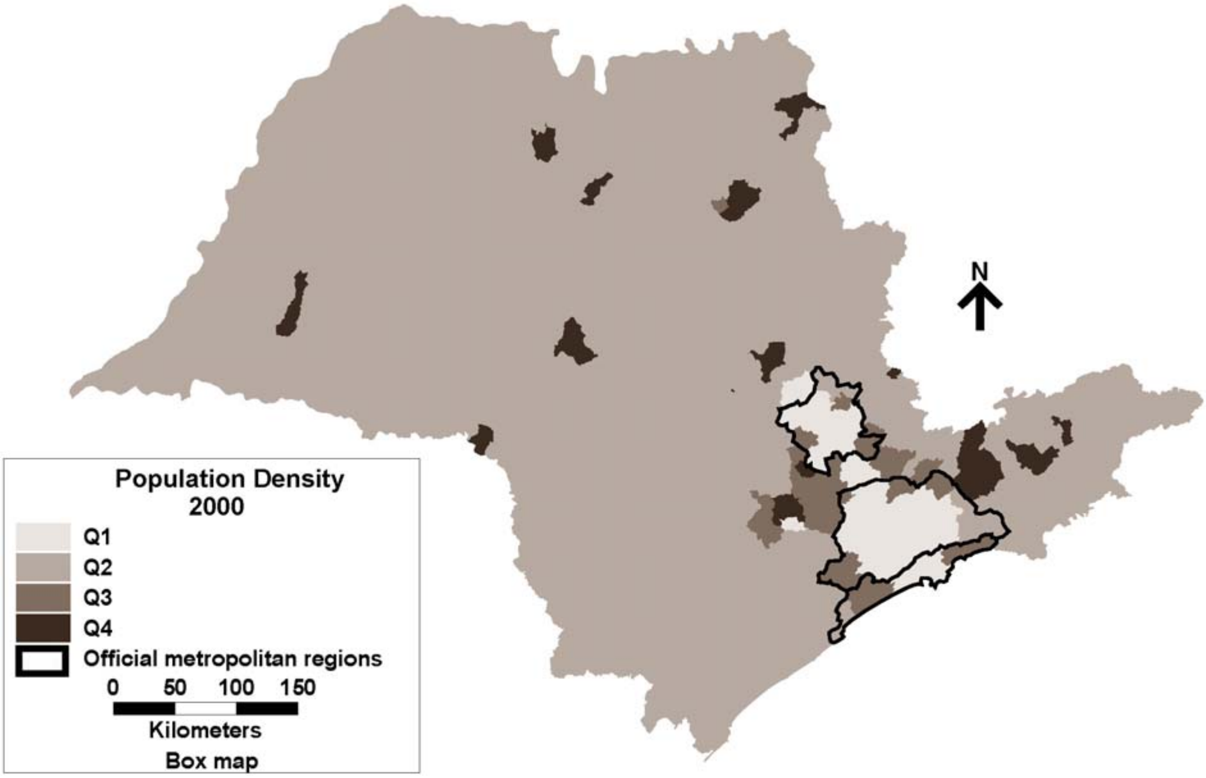

Figure 2: Box Map representing the variable population density in the year 2000

However, as these two approaches are stationary in time, it is not possible to use them for analyzing changes in the metropolitan areas throughout time. Therefore, analysts are not able to elaborate urban planning policies based on the evolution of the metropolitan areas, for example. Thus, models that could explain the patterns of change of those areas through time would be interesting. As suggested here, CA models are suitable for such a dynamic representation. The model we built with that purpose used data of several past periods for calibration and data of the year 2000 for validation. After the model was calibrated and validated, it was used for building a future scenario in the year 2010.

Before looking at the predicted values for the year 2000 and 2010, it is interesting to examine the results of an ESDA application for the years 1960, 1970, 1980 and 1990, once these periods were used in the model construction. They are presented in the *Box Maps* displayed in Figure 3, which were built using the variable population density in different periods of time.

In order to allow a direct comparison of the outcomes obtained with the CA model for the variable population density in the year 2000 with the actual values of the same variable in the same year, the *Box Maps* of both cases are presented in Figure 4. Next, making use of the dynamic nature of the CA model, it was used to generate a scenario for the year 2010. The distribution of the quadrants calculated using predicted values of population density is presented in the *Box Map* of Figure 5.

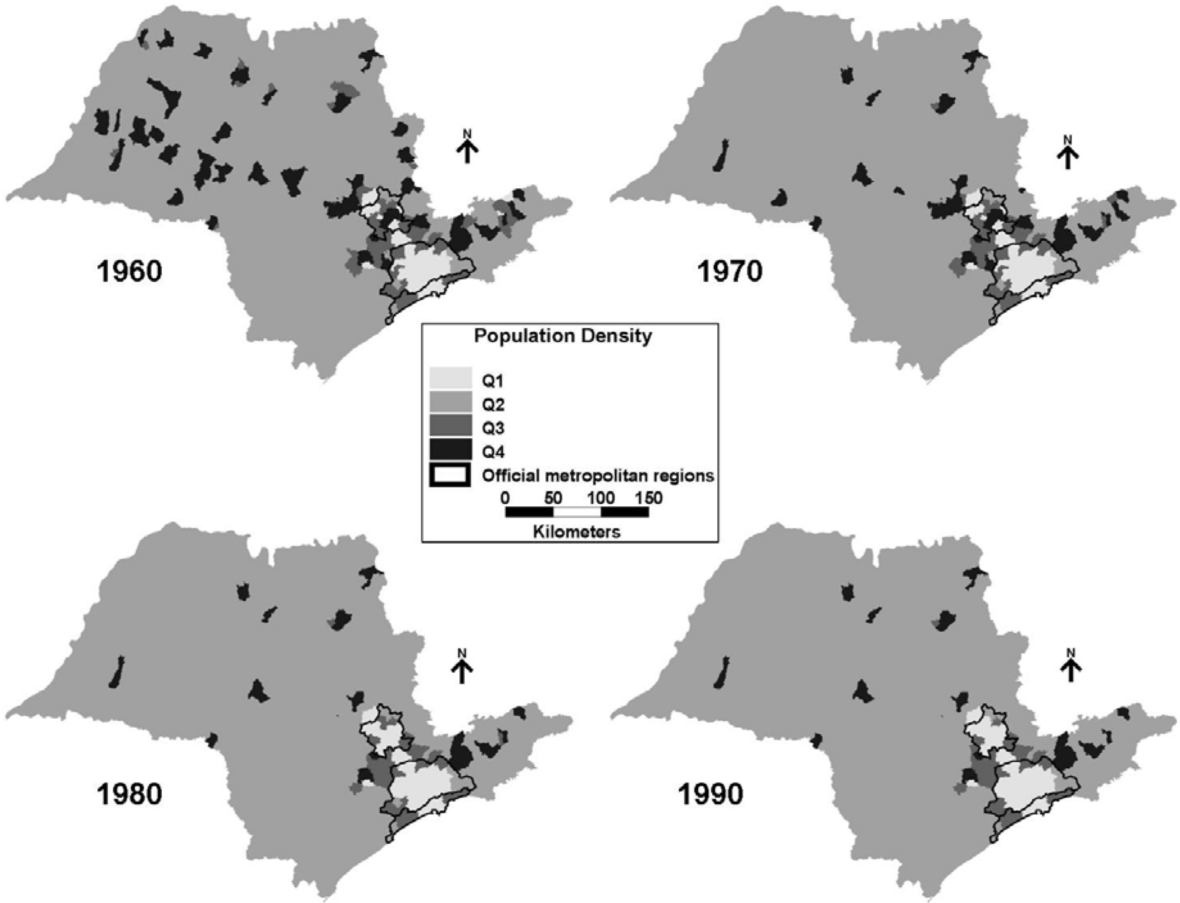

Figure 3: *Box Maps* representing the variable population density in the years 1960, 1970, 1980 and 1990

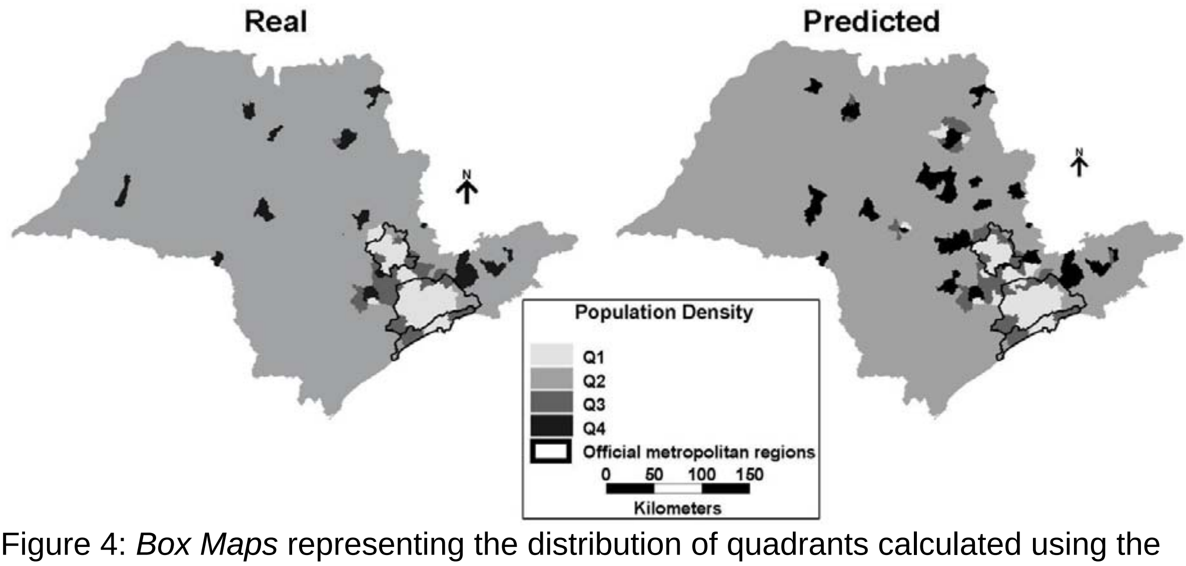

Figure 4: *Box Maps* representing the distribution of quadrants calculated using the variable population density in the year 2000 for real and predicted values

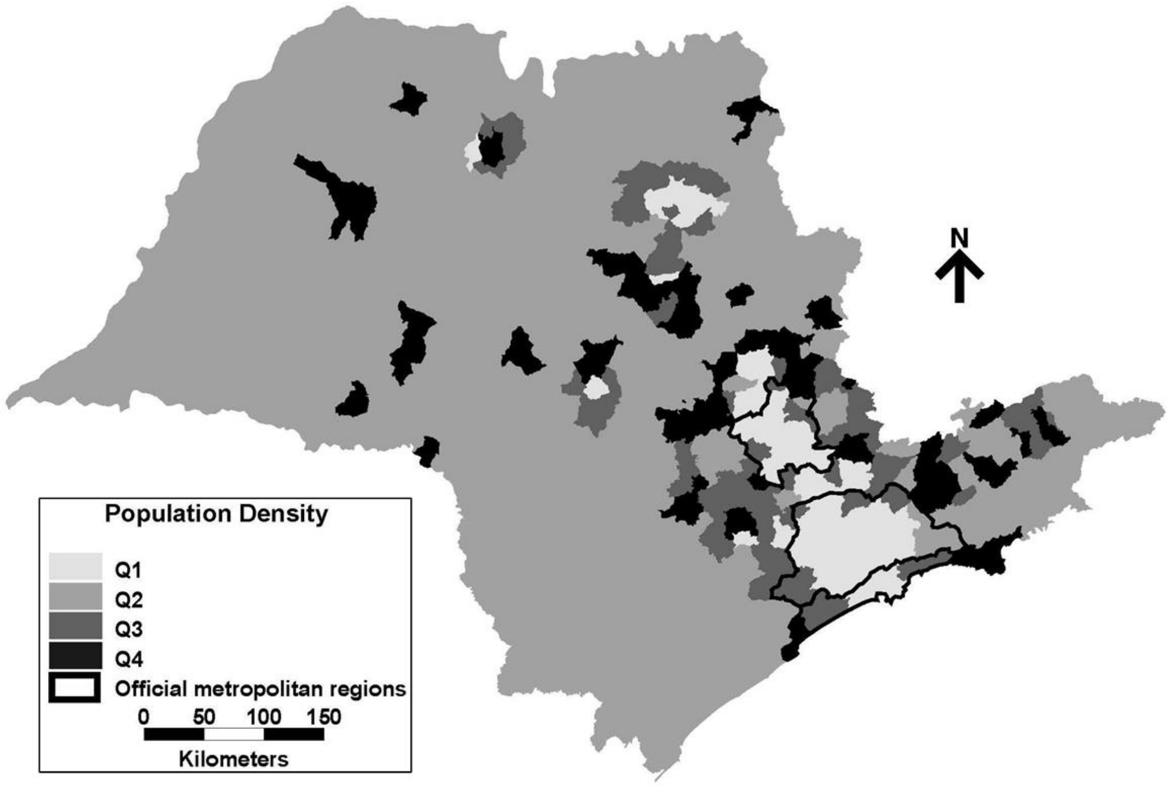

Figure 5: *Box Map* representing the distribution of quadrants calculated using predicted values of the variable population density in the year 2010

5. CONCLUSIONS

The objective of this paper was to present a comparison of two methodologies for the definition of metropolitan regions, both based on population density values, when applied in a developing country. The two methodologies can be used to highlight potential metropolitan areas. An important point to be highlighted is the different geographical comprehensiveness of the applications conducted.

The output of the first method tested, which is based on a single index that represents both the local and national weights of population density values of the municipalities, is not so well defined as the ESDA output. However, it is more flexible for analyses. The flexibility comes from the fact that the analyst can choose the percentage (or number) of municipalities to be considered in the definition of the metropolitan region.

The ESDA approach allows a clear identification of clusters of high density municipalities represented by Q1 areas. The presence of Q3 areas around those clusters is also an interesting outcome of the method. Although they have low density values when compared to the neighbors in Q1, their geographical locations suggest that they can become part of the clusters after some time.

However, as the two methods are not able to explore the changes of metropolitan areas through time, a CA-based approach was also discussed. In this case, the application of CA concepts in the development of models that can be used in temporal analyses is interesting for the formulation of urban planning policies. Once the combination of CA and ANN tools allows the prediction of distinct variables, many alternative variables can be explored in further studies. An example is the analysis of a similar approach using the index I itself instead of the variable population density. The advantage of that variable is the fact that the index I considers both national and local influences of the density. When applied in combination with ESDA techniques it could deliver interesting outcomes. While the ESDA method would take into account the local importance of the municipalities of the state analyzed, the national influence of the municipality would be captured by the index I.

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REFERENCES

Ferrão, J. and Vala, F. (2001) Delimitação das aglomerações metropolitanas de Lisboa e Porto com base no critério de continuidade de espaço construído, **Revista de Estudos Regionais – Região Lisboa e Vale do Tejo, No. 2**, 7-35.

Ferrão, J., Rodrigues, D. and Vala, F. (2002) As regiões metropolitanas portuguesas no contexto ibérico. **DGOTDU**, Lisbon.

Ferreira, M.J. and Rosado, A.R. (1999) As grandes áreas urbanas portuguesas. Conceitos e delimitação espacial. In M. Pereira (ed.), **Grandes Áreas Urbanas. Reorganização institucional e territorial. O caso da Área Metropolitana de Lisboa.** Centro de Estudos de Geografia e Planeamento, Universidade Nova de Lisboa, Portugal.

Gouvêa, R.G. (2005) **A Questão Metropolitana no Brasil**. First edition. Fundação Getúlio Vargas, Rio de Janeiro, RJ.

Lacour, C. and Puissant, S. (1999) **La métropolisation. Croissance, diversité, fractures**. Anthropos, Paris.

Metropolitan Area Standards Review Committee (2000) Final Report and Recommendations From the Metropolitan Area Standards Review Committee to the Office of Management and Budget Concerning Changes to the Standards for Defining Metropolitan Areas, Federal Register, Vol. 65, No. 163, August 22.

NUREC (1994) Atlas of Agglomerations in the European Union. Network on Urban Research in the European Union, Duisburg.

Office of Management and Budget (1998) Alternative Approaches to Defining Metropolitan and Non-metropolitan Areas. Federal Register, Vol. 63, No. 244, December 21.

Office of Management and Budget (1999) Recommendations from the Metropolitan Area Standards Review Committee to the Office of Management and Budget Concerning Changes to the Standards for Defining Metropolitan Areas. Federal Register, Vol. 64, No. 202, October 20.

Office of Management and Budget (2000) Standards for Defining Metropolitan and Micropolitan Statistical Areas. Federal Register, Vol. 65, No. 249, December 27

Ramos, R.A.R. and Silva, A.N.R. (2003a) A data-driven approach for the definition of metropolitan regions. **Proceedings VIII International Conference on Computers in Urban Planning and Urban Management**, CUPUM, Sendai, Japan.

Ramos, R.A.R. and Silva, A.N.R. (2003b) Um contributo para a delimitação da área metropolitana do noroeste de Portugal. **Revista Portuguesa de Estudos Regionais,** 61-82.

Ramos, R.A.R. and Silva, A.N.R. (2007) A spatial analysis approach for the definition of metropolitan regions – the case of Portugal. **Environment and Planning B, Vol. 34**, **No. 1**, 171-185.

Ramos, R.A.R.; Silva, A.N.R. and Miranda, V.P. (2004) A comparison of two methods for the definition of regional metropolitan areas through an application in the North of Portugal. **Proceedings 44th European Congress of the European Regional Science Association**, Oporto, Portugal.

Silva, E.A. (2002) Cenários da expansão urbana na área metropolitana de Lisboa. **Revista de Estudos Regionais - Região Lisboa e Vale do Tejo, n. 5**, 23-41.

Webster, C. and Wu, F. (2001) Coase, spatial pricing and self-organising cities. **Urban Studies, Vol. 38, No. 11**, 2037-2054.

Yeh, A.G. and Li, X. (2002) A Cellular Automata model to simulate development density for urban planning. **Environment and Planning B, v. 29**, 431-450.