Comparing spatial analysis methods for the definition of Functional Urban Regions

The case of Bahia, Brazil

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Abstract: The definition of the so-called Metropolitan Regions (MRs) or Functional Urban Regions (FURs) is not a trivial process, due to the inherent complexity of the concept. As a consequence, several approaches to tackle the problem, some of which based on spatial analysis methods, can be found in the literature. However, as some of these approaches are based on different analysis methods, their outcomes can lead to different conclusions. The objective of this study is to compare the results of two spatial analysis methods that can be used in the identification of FURs. The methods were applied with population density data in the state of Bahia, Brazil. Initially, Exploratory Spatial Data Analyses tools were used in the definition of regions that are uniform regarding that specific variable. A Moran scatterplot allowed the identification of the relative importance of the quadrants to which neighbour municipalities belong to. Finally, the representation of those values as *Box Maps* helped in the identification of clusters of municipalities with similar densities. The other approach used the same variable and the spatial analysis technique available in the computer program *SKATER - Spatial 'K'luster Analysis by Tree Edge Removal*. Assuming that those classifications of regions with similar characteristics can be used for identifying potential FURs, the results of both analyses were compared with one another and with the 'official' MR. A combined approach was also considered for comparison, but the results did not match the official MR boundaries. However, as the results were based only on one variable, it is difficult to conclude that the official boundaries are not adequate. Further studies should be conducted with the inclusion of other variables.

1. INTRODUCTION

In 2008, for the first time in history, more than half of the world population (i.e., over 3.3 billion people) was living in urban settlements spread in all continents (UNFPA, 2007). Despite the different geographical and cultural environments, cities of distinct sizes are connected in networks with a clear internal hierarchy. The higher hierarchical component of those networks is typically a combination of several adjacent cities, which offers a privileged space for interaction and innovation. More than that, the strength of those regions is not only a consequence of the geographical proximity of municipalities, but also a result of economic, political, social and demographic relationships.

This brings a challenge to urban managers and planners, given that the administrative limits of those conurbations go well beyond the limits of the individual cities that form them. However, they are often not large enough to match the boundaries of the superior administrative subdivisions, such as states or provinces. One of the alternatives to deal with that administrative problem is the definition of the so-called Metropolitan Regions (MRs), or Functional Urban Regions (FURs). Their definition is not a trivial process due to the inherent complexity of the concept. Several approaches can be found in the literature, as discussed in Manzato and Rodrigues da Silva (2010). Nevertheless, as some of those approaches are based on different spatial analysis methods, their outcomes can lead to different conclusions.

The objective of this study is to compare the results of two spatial analysis methods that can be used in the identification of FURs. The methods were applied with population density data in the state of Bahia, Brazil. Initially, Exploratory Spatial Data Analyses tools were used in the definition of regions that are uniform regarding that specific variable. A Moran scatterplot allowed the identification of the relative importance of the quadrants to which neighbour municipalities belong to. Finally, the representation of those values as *Box Maps* helped in the identification of clusters of municipalities with similar densities. The other approach used the same variable and the spatial analysis technique available in the computer program *SKATER - Spatial 'K'luster Analysis by Tree Edge Removal*.

We assumed that the classification of regions with similar characteristics can be used for identifying potential FURs. Thus, the results of both analyses were compared with one another and with the 'official' metropolitan regions, in order to confirm if the administrative divisions match the observations on the territory, at least regarding the selected variable.

This paper is structured as follows. We initially discuss basic theoretical aspects regarding FURs and MRs in section 2. Essential concepts of he spatial analyses methods applied are briefly introduced in section 3, in which the methodology is presented. The results of the application in the state of Bahia, Brazil, are presented and discussed in section 4, right before the conclusions.

2. THEORETICAL BACKGROUND

Given the worldwide trend of urbanization, the spatial distribution of the urban population needs to be analyzed. Adjacent and contiguous areas have in some cases been continuously developed in a process that combines, quite often in a large urbanized area, several distinct municipalities. They can be simply conurbations without strong political, economic or other relevant connections, but they can otherwise be identified as Functional Urban Regions (FURs) or Metropolitan Areas (MAs).

According to Manzato and Rodrigues da Silva (2010), the definition of FURs or MAs is not always an easy task for planners and decision-makers. It is not just a simple combination of adjacent municipalities or areas, but it can be a very complex process with distinct implications (see, for example, the works of Cheshire and Carbonaro, 1996; Duranton and Puga, 2004). As a consequence, different methods were created for the characterization of urban agglomerations, either conurbations or FURs. They are constantly being improved, as discussed in the work of Champion and Hugo (2004). Some of these methods are presented in the sequence.

In Europe, the FURs comprise at least one core "urbanized area" with 20,000 or more jobs as well as any adjacent NUTS3 (NUTS, or Nomenclature of Units for Territorial Statistics, is a hierarchical classification of administrative boundaries developed by Eurostat, the European Office for Statistics) regions from where more workers commute to that core than to any other core (Cheshire and Hay, 1989). The approach, however, faces some criticisms. Bode (2008), for example, argue that the commuting intensity alone is not able to show the degree of economic integration between a metropolitan center and its hinterland. His argument is supported by the works of other authors (e.g., Coombes and Overman, 2004; Duranton and Puga, 2004; Rosenthal and Strange, 2004; Duranton, 2006).

In the United States, the Metropolitan Statistical Areas comprise at least one core city with a population of 50,000 or more, as well as any adjacent counties from where at least 25 % of the employed residents commute to the core city's county (Office of Management and Budget, 2000).

In Brazil, although the Federal Constitution passed in 1988 suggested that the states can create metropolitan areas, urban agglomerations and micro regions, those terms were not defined then. Most states also did not establish clear criteria or even discuss those definitions. One exception is the state of São Paulo. In 1989, the state Constitution established definitions for the terms cited in the Federal Constitution, as follows. A *Metropolitan Region* is considered a group of adjacent municipalities with national expression due to the high population density, intense conurbation, and urban and regional functions with high level of diversity, specialization and socioeconomic integration. An *Urban Agglomeration* is considered a group of adjacent municipalities with socioeconomic relationships and a continuous urbanized area. A *Micro Region* is considered a group of adjacent municipalities with territorial, socioeconomic and administrative relationships (Gouvêa, 2005).

In terms of research on the issue, Weber (2001) proposed the analyses of satellite images to classify areas as "urban" or "non-urban". Although the analyses of the empirical study presented in the paper led to promising results, classifying an area as "urban" or "non-urban" may give only an indication of the delineation of a large urbanized area. Statistical factors that really show the mutual influence of urban settlements, such as economic relationships, commuting flows, etc., should also be considered. Regardless the 'official' administrative limits, which are sometimes larger than the urban areas, a clear advantage of the approach is the exact delimitation of the entire urbanized area. That is clearly an improvement if compared to the methods that associate the population density of the urbanized areas with the entire municipalities, no matter where the urban areas are located within the municipal boundaries.

The approach developed by Bode (2008) for the delineation of metropolitan areas uses the fraction of land prices attributable to economies of urban agglomeration. Despite the theoretical robustness of his model and the good results obtained in his empirical study, the approach is not easily applied because the data needed for its application is often unavailable or outdated in some countries. That is precisely the same problem observed with the commuting flows. As a consequence, the authors of Office of Management and Budget (1998) also defended another alternative for defining metropolitan areas based on population density values. They stated that "residential population density can serve as a surrogate for other measures of activity in the absence of nationally consistent and reliable datasets describing all daily and weekly movements of individuals". Some other alternative approaches have been presented for proxying commuting data, as suggested by Coombes (2004). Although some of the approaches he suggested still rely on data that are usually unavailable in developing countries, such as the distribution of jobs, he also lists feasible alternatives, such as using roads or service networks like bus services as a proxy for data on actual patterns of interaction.

In summary, given the difficulties for getting more specific data, the variable used for the definition of urban agglomerations in developing countries is essentially the population density. Although easily available in most census datasets, the variable "residential population density", however, can be analyzed in many different ways when applied to the definition of FURs. That was shown by Ramos and Rodrigues da Silva (2003 and 2007), Ramos *et al.* (2004) and Manzato *et al.* (2007), who have explored the use of the variable with spatial analyses tools. They based their approach on branches of spatial analyses like spatial statistics and spatial modeling. The spatial statistics concepts used Exploratory Spatial Data Analysis techniques. Their method also allowed analyses throughout time. Those works led to interesting and promising results for the definition of FURs using only population density values. Furthermore, they pointed out some ideas for improvements in the method.

Some of these ideas were tested by Manzato and Rodrigues da Silva (2010), who explored alternatives for defining FURs based on the population density, on an infrastructure supply index and on a combination of them in a case study carried out in the state of São Paulo, Brazil. They used, however essentially the same spatial analyses tools applied in the works of Ramos and Rodrigues da Silva (2007). In this study we tried to extend the previous approaches by testing different methods of spatial analyses, such as the clustering method proposed by Assunção *et al.* (2002). Their method is available in the computer program *SKATER*, which was here applied in a case study in the state of Bahia, also in Brazil. This meets one of the suggestions presented by Hugo and Champion (2004), who recommended that the research community should give urgent attention to the "the need to experiment with GIS methods of delineating hinterlands and functional urban regions".

3. METHODOLOGY

The study started with the acquisition of the census data collected by the Brazilian Institute of Geography and Statistics, which is the national census bureau, in the years 1970 and 2000. The variable explored in the applications presented here was essentially the number of inhabitants per municipality, although in the form of gross population density.

Two techniques of spatial analysis were then explored: Exploratory Spatial Data Analysis (ESDA) tools and the clustering method based on tree edge removal. Although several computer packages can be used to conduct the aforementioned analysis, we used the freeware packages *GeoDA* and *SKATER*. The GIS-T *TransCAD* was later on used to generate maps with the outcomes of the other packages. As the analysis methods are based on specific spatial analyses techniques, some basic concepts of the applied approaches are discussed in the following paragraphs.

In the case of ESDA, the Moran's I index can be applied to provide a general measure of spatial association within a dataset. Also, it can be used to test if the areas under analysis show a certain degree of similarity regarding one or more attributes that is larger than observed with values randomly distributed (Anselin, 1995). In addition to the calculation of the Moran's I value of spatial autocorrelation, the method allowed the classification of areas regarding the attribute value of a zone in relation to the overall average value and also in relation to the average value of the adjacent zones. The results, which can be represented in four quadrants of the Moran scatterplot and also in maps (i.e., *Box Maps*), can be classified as follows:

1. *High-High* (HH): in that quadrant are represented the zones with positive value for the zone and positive average value for contiguous neighbours. A positive value in that case means that the value is above the overall average value.
2. *Low-Low* (LL): in that quadrant are represented the zones with negative value for the zone and negative average value for contiguous neighbours. A negative value in that case means that the value is below the overall average value.
3. *Low-High* (LH): in that quadrant are represented the zones with negative value for the zone and positive average value for contiguous neighbours.
4. *High-Low* (HL): in that quadrant are represented the zones with positive value for the zone and negative average value for contiguous neighbours.

Another possible development of ESDA is to identify zones that have a spatial dynamics particularly distinct from the other zones, what can be explored through *Moran Maps* (Anselin, 1995).

The other approach used for exploring the data was based on cluster analysis, which is an efficient data management technique for finding homogeneous groups of elements in a heterogeneous dataset. Berkhin (2002) discusses several clustering techniques. The usual methods of cluster analysis can be adapted to consider elements that have a spatial location, as suggested by Carvalho *et al.* (1996, 1998). In this study we have used the computer program *SKATER*, which uses the clustering method proposed by Assunção *et al.* (2002).

In the first analysis, the focus was on the analysis of Moran scatterplots and the associated *Box Maps*. The combination of adjacent municipalities in the *High-High* and *High-Low* quadrants of a Moran scatterplot was seen as a potential FUR, as suggested by Ramos and Rodrigues da Silva (2007) and Manzato and Rodrigues da Silva (2010). In the case of the clusters generated with the software *SKATER*, we considered different numbers of clusters. The initial setting was for four clusters, just to match the number of quadrants of the Moran scatterplot and *Box Maps*. Different numbers of clusters (up to seven) were formed subsequently, in order to evaluate the incremental changes. As the clusters were formed by adjacent municipalities with similar values of population density, we assumed that the clusters with the highest values could also be seen as potential FURs.

The results of the two analyses were than compared with the boundaries of the 'official' state metropolitan region (or RMS, which in Portuguese stands for Metropolitan Region of Salvador), as defined in the years 1973 and in the latest years of the 2000 decade. Another complementary analysis combined the results of the two methods used before for identifying the municipalities that were in both cases strongly associated with the potential FURs. The outcome was also compared with the RMS.

4. RESULTS

Three procedures provided the elements for the initial analyses. The first analysis explored the results of ESDA in the years 1970 and 2000 (Figure 1). In the second and third procedures, the clustering method was applied in the 1970 and 2000 datasets, respectively (Figures 2 and 3). In order to allow a comparison of the results of those procedures with the boundaries of the RMS of 1973 and 2009, they were also depicted in the figures. The RMS was first established in 1973 with eight municipalities: Salvador (the state capital), Camaçari, Candeias, Simões Filho, Lauro de Freitas, Dias D'Ávila, Vera Cruz and Itaparica. Mata de São João and São Sebastião do Passe were added in 2008, and Pojuca in 2009.

A visual inspection of the Figures 1 to 3 shows that the potential FURs, which could be formed by the clusters of municipalities classified as *High-High* + *High-Low* in Figure 1 or by the clusters with the highest values of population density in Figures 2 and 3, do not match the boundaries of the RMS. The results represented in Figures 1 to 3 also indicate the presence of two major clusters in the state. The largest one, which is in the upper part of the zoom-in maps, is formed by municipalities around Salvador, but there is another one around the municipalities of Ilhéus and Itabuna in the south-eastern part of the state.

The municipalities that were selected with either one of the techniques are identified in Table 1. In the case of the clusters, we marked in Table 1 the municipalities that were grouped in all but the cluster with the lowest densities. For example, the 21 municipalities checked in the column '4' of 'Cluster 1970" are in either one of the three clusters with the highest density values.

When comparing the clusters of municipalities in Figure 1, the area of the cluster identified as *High-High* decreased from 1970 to 2000. That reduction can be a consequence of the migration and urbanization processes that took place in the country during the latest decades of the twentieth century. Particularly in the 1970s and 1980s, the population growth rate of large cities and adjacent municipalities was larger than the rates observed in small and medium-sized cities.

It is interesting to notice that all municipalities that formed the RMS in 1973 were identified as a potential FUR in the year 2000 with the ESDA approach. The changes in the population densities of these municipalities along those years may have been produced precisely because they were part of the RMS. Another possible explanation may be in the fact that the criteria used by the census bureau to identify the municipalities that should constitute the RMS were not based on the same variable we have used in our study (i. e., population density).

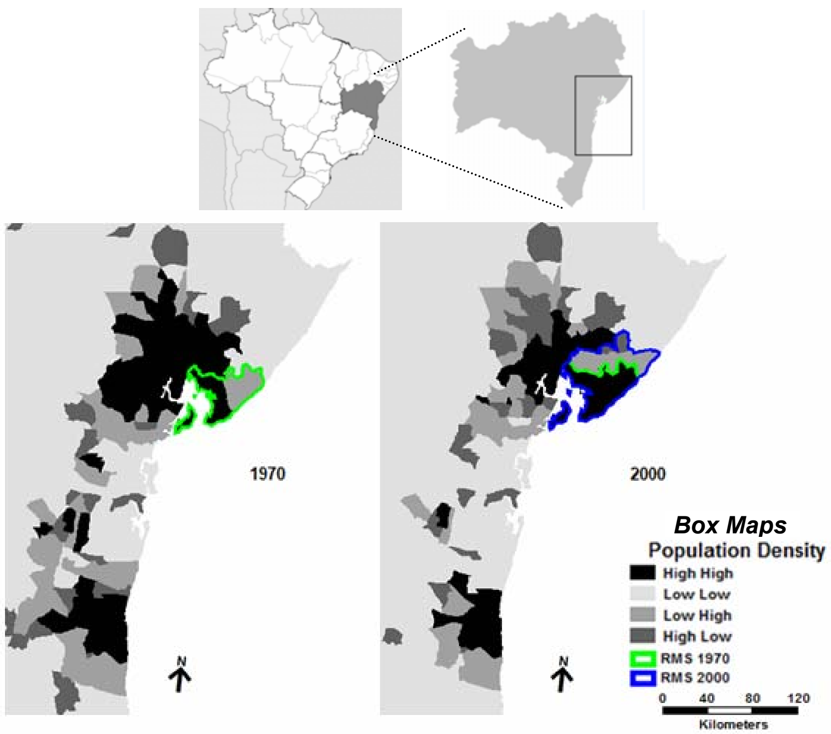

Figure 1. Box maps of the variable population density in the years 1970 and 2000

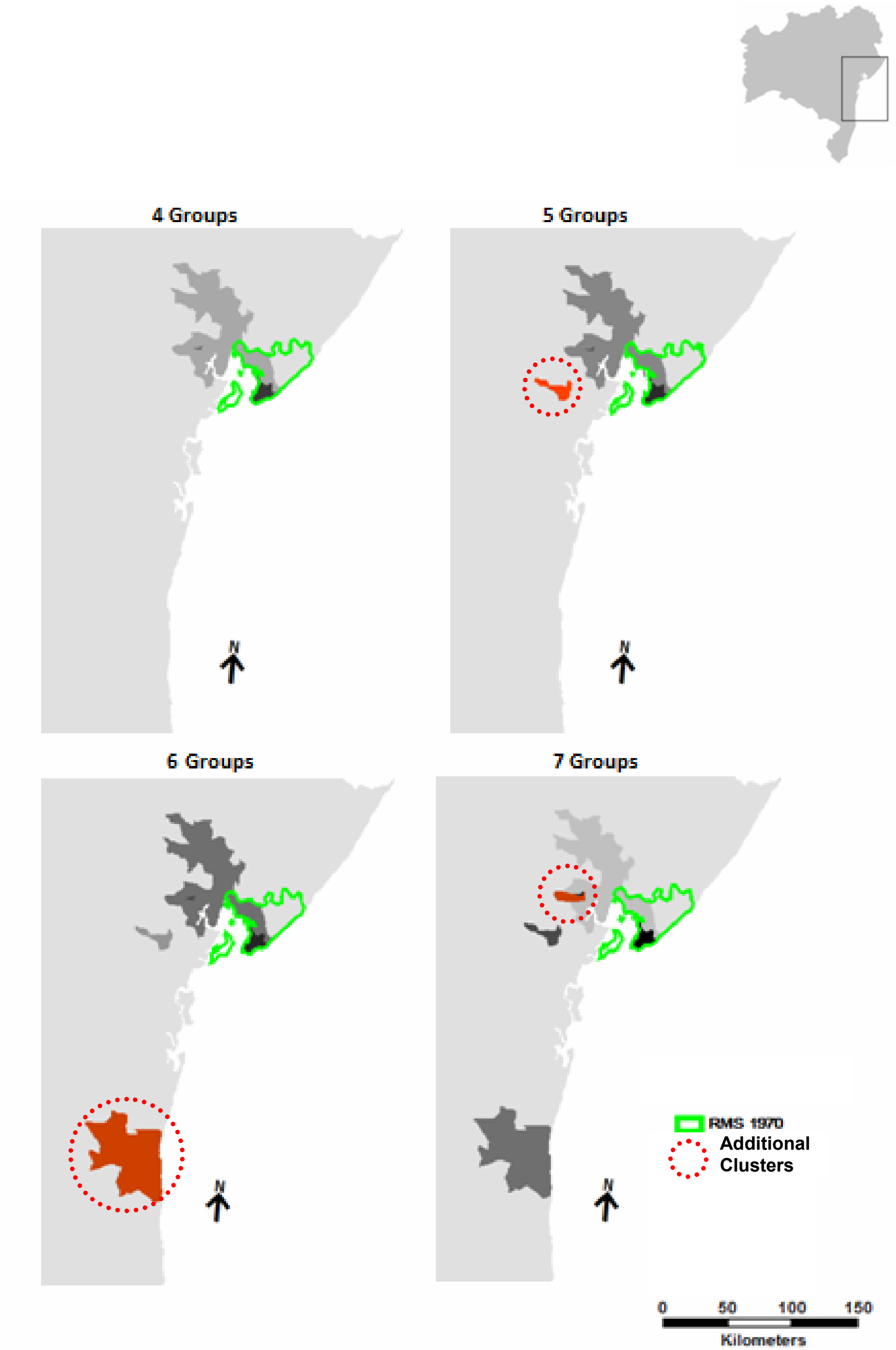

Figure 2. Clusters generated by the software *SKATER* in the year 1970

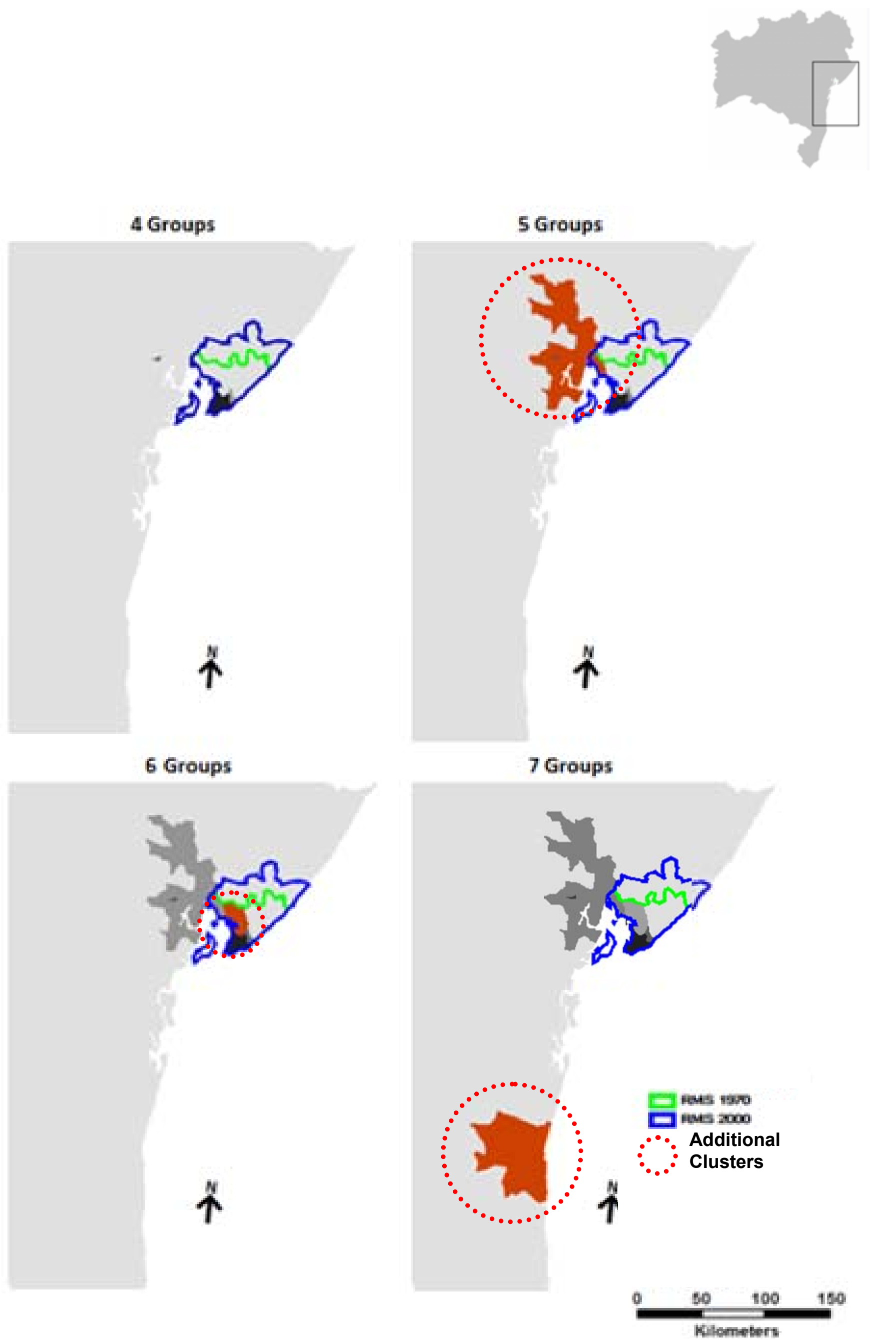

Figure 3. Clusters generated by the software *SKATER* in the year 2000

Table 1. Municipalities selected with the two spatial analyses techniques

Municipalities	1970		2000		Clusters 1970				Clusters 2000				RMS	RMS	Count
	HH	HL	HH	HL	4	5	6	7	4	5	6	7	1970	2000	
Salvador	X		X		X	X	X	X	X	X	X	X	X	X	10
Feira de Santana	X			X	X	X	X	X		X	X	X			9
Itabuna	X		X				X	X				X			5
Ilhéus	X		X				X	X				X			5
Alagoinhas		X		X											2
Camaçari			X										X	X	3
Serrinha		X		X											2
Candeias	X		X		X	X	X	X			X	X	X	X	8
S. Antonio Jesus	X			X		X	X	X							5
Castro Alves	X			X											2
Santo Amaro	X		X		X	X	X	X		X	X	X			9
Simões Filho	X		X		X	X	X	X			X	X	X	X	8
Maragogipe	X		X		X	X	X	X		X	X	X			9
Camacan		X		X											2
Ipiau		X		X											2
Catu	X		X												2
Cruz das Almas	X		X		X	X	X	X		X	X	X			9
R. do Pombal		X		X											2
Lauro de Freitas	X		X		X	X	X	X	X	X	X	X	X	X	10
Irece		X		X											2
Mata de S. João			X											X	1
S. Seb. do Passe	X			X										X	2
Ibicarai	X		X				X	X				X			5
Paripiranga		X		X											2
Pindobacu		X		X											2
Cachoeira	X		X		X	X	X	X		X	X	X			9
Amargosa		X		X											2
Itajuipe	X			X			X	X				X			5
Buerarema	X		X				X	X				X			5
Nazaré	X			X						X	X	X			5
Ubata	X			X											2
Itororó		X		X											2
S. G. Campos	X		X												2
Gandu		X		X											2
Coração Maria	X		X		X	X	X	X							6
Irara		X		X											2
Itubera		X		X											2
Ibirataia	X		X												2
Muritiba	X		X		X	X	X	X	X	X	X	X			10
Dias D'ávila			X										X	X	1
C. do Jacuipe	X		X		X	X	X	X		X	X	X			9
São Felipe	X			X											2
Floresta Azul	X			X											2
C. do Almeida	X			X											2
A. Rodrigues	X		X		X	X	X	X		X	X	X			9

Table 1 (cont.). Municipalities selected with the two spatial analyses techniques

Municipalities	1970		2000		Clusters 1970				Clusters 2000				RMS	RMS	Count
	HH	HL	HH	HL	4	5	6	7	4	5	6	7	1970	2000	
S. F. do Conde	X		X		X	X	X	X		X	X	X			9
Ipecaeta	X			X											2
G. Mangabeira	X		X		X	X	X	X		X	X	X			9
Pojuca			X											X	1
Ubaitaba		X		X											2
São Felix	X		X		X	X	X	X		X	X	X			9
Santa Bárbara	X			X											2
Teofilandia		X		X											2
Fátima		X		X											2
Conc.da Feira	X		X		X	X	X	X		X	X	X			9
Pres. T. Neves	X			X											2
Botupora		X		X											2
Vera Cruz	X		X		X	X	X	X	X	X	X	X	X	X	10
Nova Canaã		X		X											2
Antas		X		X											2
Sapeacu	X		X												2
Terra Nova	X		X		X	X	X	X							6
Varzedo	X		X			X	X	X							5
C. do Paraguaçu	X			X											2
Antonio Cardoso	X			X											2
Itaparica	X		X		X	X	X	X	X	X	X	X	X	X	10
Retirolandia		X		X											2
Várzea do Poço		X		X											2
Teod. Sampaio	X			X											2
Jiquirica		X		X											2
Cipó		X		X											2
Novo Triunfo		X		X											2
Barro Preto	X			X			X	X				X			5
Itamari		X		X											2
S. da Margarida	X			X						X	X	X			5
Pedrão	X			X											2
Aratuipe		X		X											2
Saubara	X		X		X	X	X	X		X	X	X			9
Aiquara	X			X											2
S. C. da Vitória		X		X											2
S. J. da Vitória		X		X			X	X				X			5
Firmino Alves		X		X											2
D. M. Costa	X		X			X	X	X							5
Madre de Deus	X		X			X	X	X					X	X	7

In the second and third analyses we determined clusters of municipalities that have similar values of population density in the years 1970 and 2000, respectively. For each of those years, the following numbers of clusters were generated with the program *SKATER*: four, five, six and seven. The new clusters added when going from one condition to the following are always highlighted in Figures 2 and 3. A comparison of the results found in the years 1970 and 2000 did not indicate significant changes in terms of the distribution of the selected municipalities and shape of the respective clusters groups. In addition, a cluster of municipalities with high densities around Ilhéus and Itabuna was also found. This group of cities, however, is not recognized as another 'official' state metropolitan region.

A summary of the results is presented in Table 2. When comparing the values of the official RMS and the values of the groups defined with the two techniques, the results obtained with ESDA approach the actual values in the density range, but are quite different in the number of municipalities. We tried to combine the municipalities selected with both techniques by counting the number of times they were included in the groups created with both techniques. The count is shown in the last column of Table 1. All municipalities that were marked 7 times or more were selected as part of another potential FUR, as shown in Figure 4. The selected municipalities are marked in grey in Table 1. However, not even in this case they matched the previous or current boundaries of the official RMS.

Table 2. Summary of results

Selected Groups of Municipalities	Number of Municipalities	Total Population	Population range (inhabitants)	Population Density range (inhab./km^2)
State of Bahia 1970	379	7728070	1940 - 1002758	2 - 8470
State of Bahia 2000	415	13070250	3092 - 2443107	3 - 20636
RMS 1973	8	1128823	6616 - 1002758	83 - 8470
RMS 2009	13	3094021	12036 - 2443107	113 - 20636
ESDA HH + LH 1970	51 (HH) + 29 (LH)	2797429	5472 - 1002758	89 - 20636
ESDA HH + LH 2000	35 (HH) + 49 (LH)	5666094	3748 - 2443107	103 - 8470
Six clusters with the highest density values in 1970	32	1911612	4437 - 1002758	110 - 8470
Six clusters with the highest density values in 2000	29	4158043	6210 - 2443107	158 - 20636

5. CONCLUSIONS

This study discussed the application of two spatial analyses techniques for the identification of Functional Urban Regions (FURs) in the state of Bahia, Brazil, through: the first one relied on Exploratory Spatial Data Analysis (ESDA) tools, while the second one used a clustering technique available in the computer program *SKATER - Spatial 'K'luster Analysis by Tree Edge Removal*. The results showed that both approaches can be used to identify regions that are considered homogeneous when regarding the variable population density. The resulting potential FURs were then compared with the limits of the RMS, which is the 'official' state metropolitan region.

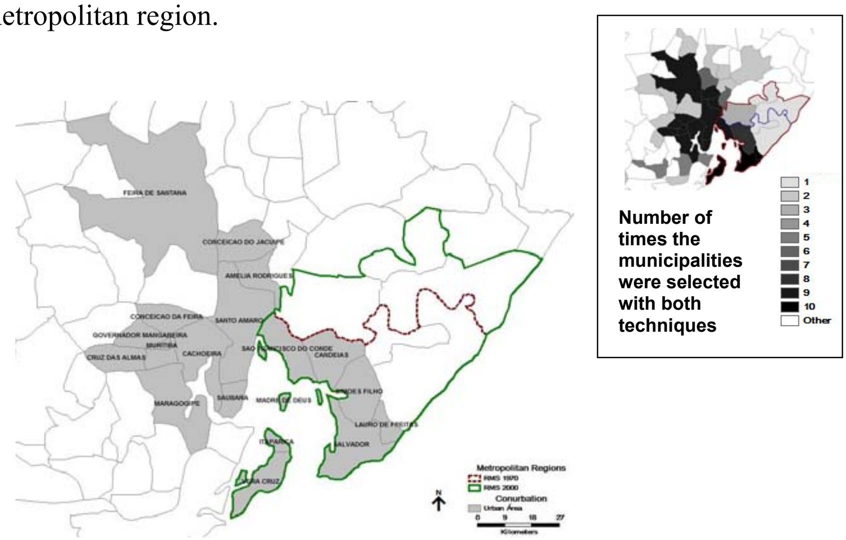

Figure 4. Comparison of the RMS in 1973 and 2008 with the potential FUR resulting from the combination of the two analyses methods explored

A first conclusion drawn from the results was that none of the spatial analysis methods produced a cluster of municipalities matching the single official state metropolitan region located around the state capital, which is the city of Salvador. In addition, both techniques applied have suggested the existence of two large urbanized clusters. The largest one is located around Salvador and encompasses the adjacent western municipalities, while the other one is formed by municipalities clustered around the cities of Ilhéus and Itabuna, over 400 km south from Salvador.

The results found with the ESDA technique have shown a reduction in the size of the identified homogeneous regions from 1970 to 2000. This finding is somehow in line with the trend of population concentration observed in and around large cities in Brazil in that time period. Also, the boundaries of the official metropolitan region were detected with the technique, but I this case with a 'delay' of about thirty years. The official metropolitan region created in 1973 matched the *High-High* and *High-High + High-Low* clusters found in the year 2000. Two possible explanations for that are: the consideration of an inadequate (or limited, for that matter) variable in our analyses, or the use of different criteria (for instance, political aspects) in the definition of the official region. That condition was found again in the year 2000. The municipalities officially added at that moment were classified in our analysis as *Low-High*. Therefore, they would not be part of the homogenous region defined with ESDA tools.

The combination of the results obtained with the two techniques also did not match the official boundaries. However, as the results were based only on one variable, it is difficult to conclude that the official boundaries are not really representing a FUR. Further studies should be conducted with the inclusion of other variables, such as socioeconomic attributes or transportation infrastructure.

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