WPS8702

Policy Research Working Paper 8702

Spatio-Temporal Dynamics of Urban Growth in Latin American Cities

An Analysis Using Nighttime Lights Imagery

Juan C. Duque
Nancy Lozano-Gracia
Jorge E. Patino
Paula Restrepo
Wilson A. Velasquez

World Bank Group
Social, Urban, Rural and Resilience Global Practice
January 2019

Abstract

The impact of urban form on economic performance and quality of life has been extensively recognized. The studies on urban form have focused in developed countries; only a few cities in developing countries have been studied. This paper utilizes nighttime lights imagery and information on street networks, automatically retrieved from OpenStreetMap, to calculate a series of spatial metrics that capture different aspects of the urban form of 919 Latin American and Caribbean cities. The paper classifies these cities into clusters according to these spatial metrics. It also studies the relationship between the urban form metrics and some factors that can correlate with urban form (topography, size, colony, and economic performance) and performs a spatio-temporal analysis of urban growth from 1996 to 2010. Among the results, the paper highlights the identification of five typologies of cities, the tendency of a group of cities to grow at a steeper slope, some worrying cases of urban growth over protected areas, and a trend toward increasing sprawl in some Latin American and Caribbean cities.

This paper is a product of the Social, Urban, Rural and Resilience Global Practice. It is part of a larger effort by the World Bank to provide open access to its research and make a contribution to development policy discussions around the world. Policy Research Working Papers are also posted on the Web at http://www.worldbank.org/research. The authors may be contacted at nlozano@worldbank.org and prestrepocadavid@worldbank.org.

Spatio-Temporal Dynamics of Urban Growth in Latin American Cities: An Analysis Using Nighttime Lights Imagery

Juan C. Duque (✉)

Research in Spatial Economics (RiSE-group), Department of Economics, Universidad EAFIT, Medellin, Colombia.e-mail: jduquec1@eafit.edu.co

Nancy Lozano-Gracia, Social, Urban, Rural and Resilience.The World Bank. Washington, USA. e-mail: nlozano@worldbank.org

Jorge E. Patino, Research in Spatial Economics (RiSE-group), Department of Economics, Universidad EAFIT, Medellin, Colombia.e-mail: jpatinoq@eafit.edu.co

Paula Restrepo, Social, Urban, Rural and Resilience. The World Bank. Washington, USA. e-mail: prestrepocadavid@worldbank.org

Wilson A. Velasquez, Research in Spatial Economics (RiSE-group), Department of Economics, Universidad EAFIT, Medellin, Colombia.e-mail: wavelasquezh@unal.edu.co

Keywords: Urban form · Latin American and Caribbean cities · Remote sensing, Cluster Analysis

JEL: N96, O18, O21, C38, R14

1 Introduction

In 2007 the global urban population exceeded the global rural population, and it is projected that urban dwellers will double the rural dwellers by 2050 (United Nations, 2014). Latin America and the Caribbean (LAC) is the most urbanized region on the planet, with 80% of its population living in cities (UN-Habitat, 2012). This growth has not stopped, according to the World Development Indicators, LAC cities added 206 million people between 1960 and 1990, and 191 million people between 1990 and 2015 (The World Bank, 2017). This rapid level of urbanization imposes challenges for local authorities, as many cannot provide services and infrastructure for the new urban areas at the same speed as the urban growth. Urban form has an important influence on the emergence of agglomeration economies and congestion costs, and on cities' economic productivity, as well as quality of life and environmental sustainability (Squires, 2002). The economies of agglomeration is strongly associated with intraurban connectivity levels, the level of compactness, and land use patterns (Ciccone and Hall, 1996; Cervero, 2001; Rosenthal and Strange, 2004). LAC cities are still spatially growing despite the deceleration in population growth (UN-Habitat, 2012).

However, there is a lack of empirical studies about the characteristics of LAC cities and their changes over time. The challenges of topography may have prevented dense development in some cases, as many Latin American cities are located in rugged topographies with natural barriers. Some of the urbanization in the region is in fact occurring over steep terrain, with slopes greater than 15%, and we verified the trend of urbanizing even steeper terrains in recent years. According to Gencer (2013), these levels of urban concentration of population increase the potential for disasters and most of the cities exposed to at least one natural hazard are located in Asia and Latin America. In some instances, the urbanization occurs at the cost of occupying adjacent protected areas. More than 2,400 square kilometers of protected areas have been lost to urban growth in the region from 1996 to 2010 according to the findings in this work. Rapid urbanization combined with limited infrastructure investments may have also led to urban forms that pose a barrier to the rise of agglomeration economies, limit firm interaction, and make it hard for workers to reach their jobs. A better understanding about the dynamics of urban form in the region can shed light on whether urban policy has a role to play in supporting city productivity, quality of life, and urban sustainability, while mitigating the increased vulnerability that usually comes with urban expansion.

In this paper we use nighttime lights (NTL) radiance-calibrated annual image composites, for 1996, 2000 and 2010, to provide a standardized characterization of the urban form of 919 Latin American cities. We make a descriptive analysis of the urban form variables, and their relationships with the potential factors that affect the urban form. We then look for differences in the data across countries and regions and identify the trends of change over time.

The rest of the paper is organized as follows. Section 2 presents a literature review. Section 3 describes the data used in this analysis, and the definitions of urban form variables and factors. Section 4 shows the descriptive analysis of the set of LAC cities, the differences across countries, and the interplay with the factors that affect urban form. Section 5 shows the space-time analysis of urban growth in the region and Section 6 presents the main conclusions of this work.

2 Literature review

The importance of urban form has been extensively recognized in the urban economics literature. The form of cities affects their economic performance (Parr, 1979), sustainability levels (Breheny, 1992; De Roo and Miller, 2000), quality of life (Squires, 2002), commuting costs (Wheeler, 2001), costs of transporting intermediate goods (Ciccone and Hall, 1996), the level of knowledge spillovers through human interactions (Lynch, 1981; Jaffe et al 1993 and Glaeser 1998), and the level of matching of firms and workers (Ciccone and Hall, 1996; Rosenthal and Strange, 2004; Cervero, 2001). All this together makes urban form a key factor from an urban policy standpoint.

However, the literature on urban form is not extensive, and it is mainly focused in North American cities (Hasse and Lathrop, 2003; Ewing et al., 2002; Filion, 2001; Tsai, 2005); European cities (Schwarz, 2010; Kasanko et al., 2006, Antrop, 2004; Cheshire, 1995; CEC, 1992; Champion, 1992), and Asian cities (Deng and Huang, 2004; Lin, 2002; Sorensen, 2000). In these studies, the main focus has been to measure the spatio-temporal patterns of urban sprawl.

Developing countries have been much less studied. Most of them treat specific cases such as Lagos, Nigeria (Barredo et al., 2004); Morelia city, Mexico (Lopez et al., 2001); or Cairo, Arab Republic of Egypt (Sutton and Fahmi, 2001). From the best of our knowledge there is evidence of three cross-country studies that include LA cities in their sample: Huang et al. (2007) study 17 Latin American cities that are part of a total sample of 77 metropolitan areas in Asia, the United States, Europe, and Australia. Using a semi-automatic process for delineating the urban extents from Landsat ETM imagery, the authors calculate seven spatial metrics that capture five dimensions of urban form: compactness, centrality, complexity, porosity and density. Angel et al. (2010a) include 17 Latin American cities in a total sample of 120 cities from all around the world. Using also satellite images the authors calculate four urban fragmentation metrics: edge index, openness index, core open space ratio, and city footprint ratio. Finally, Inostroza et al. (2013) use Landsat imagery to study urban sprawl and fragmentation in 10 Latin American cities. The metrics for measuring the sprawl are: built-up area, density, spatial configuration, and speed. The common finding in these three studies is that Latin American cities are more compact and denser than their counterparts in either Europe or North America.

In our paper we contribute to the literature on urban form in three ways: First, we combine the use of NTL imagery, for urban extent delineation, with recently developed software on computational geometry and network topology (Angel et al., 2010b; Boeing, 2017), to generate a highly automated procedure that makes possible to analyze 919 urban extents in Latin America and the Caribbean. This is the most comprehensive study of urban form for this region. Second, the indicators used to describe urban form are tightly connected to the definition of urban form from the urban planning perspective, which describes urban form as a combination of external shape and internal structure (Whyte, 1968). In this paper we implement a definition of urban form that includes three dimensions: Shape of the urban extent, internal urban structure and land use pattern (Prosperi et al., 2009; Batty, 2008). This definition allows us to go beyond the debate sprawl vs. compact and cover other important aspects of urban form. Finally, we explore the relationship between urban form and factors such as topography, size of the city, economic strength (measured with NTL), and heritage of colonial urban planning.

3 Data

3.1 Study region

This analysis focuses on Latin American and Caribbean (LAC) cities with more than 50,000 people in 2010. According to (UN-Habitat, 2012), Latin America and the Caribbean is the most urbanized region on the planet with more than 80% of the population living in urban areas, and built-up area continues to expand despite deceleration in population growth. The LAC region is characterized by large diversity of climatic conditions, including from tropical to temperate climates; and the terrain also shows high variability in altitudes due to the presence of the Andean Mountain Range. That diversity in climate and topographic conditions translates into a high diversity in the shape that urban areas have taken. On the one hand, there are cities located in the mountains constrained by hilly terrain; on the other hand, there are also some cities located in the lower lands in flat areas, constrained only by the presence of large rivers or lakes, and yet other cities have grown located at the Caribbean and Pacific coasts, whose shapes reflect the coastline. Speaking of urbanized area, in the region it accounts for 0.4% of the land, a much lower value than Europe (2.3%) and the United States (1.2%), somehow closer to Asia (0.7%), but higher than the former Soviet Union region (0.2%) and Oceania (0.1%) (Y. Zhou et al., 2015). When compared to other regions of the world, LAC cities show denser populations than Europe and the United States, greater regularity and lower open space (Angel et al., 2010a; Huang et al., 2007). However, Inostroza et al. (2013) reported a general trend towards low density growing for some of the largest LAC cities.

3.2 Use of Night-time Lights Data for urban extents delineation

The nighttime lights data (NTL) are based on nighttime imagery recorded by the Defense Meteorological Satellite Programs - Operational Linescan System (DMSP-OLS), which reports the recorded intensity of Earth’s surface lights. Nighttime lights products have high correlation to human activities (Hsu et al, 2015), and have been previously used for regional and global analysis of urbanization (Cheng et al., 2016; Pandey et al., 2013; Sutton et al., 2006; Zhang and Seto, 2011; Zhou et al., 2015a; Zhou et al., 2015), population modeling (Anderson et al., 2010; Lo, 2001), and economic performance (Cao et al.,2016; Forbes, 2013).

There are two different nighttime light products from DMSP-OLS that can be used to delineate urban areas: the stable or ordinary product (NTL), and the radiance-calibrated (RC) product. For this work we use the latter, given that such data include a correction for the saturation issue likely to be an important issue for most large cities in the region. Further, previous work has suggested that the RC information provides a better proxy for socioeconomic variables than the stable products (Hsu et al., 2015; Ma et al., 2014). Radiance-calibrated annual composites for 1996, 2000 and 2010 obtained from NOAA National Centers for Environmental Information[1] were used to delineate urban extents. These composites have a spatial resolution of 30 arc-seconds (about 1 km at the Equator).

Another known issue of the DMSP-OLS products is the "overglow" effect: dim lighting detected from light in surrounding areas of cities because of the scattering of lights in the atmosphere (Wu et al., 2014). A novel deblurring process was applied to address the issue of over glow in the radiance-calibrated products. This process involves the use of two sequential filters, a standard deconvolution and the frequency of illumination maxima, to withdraw the light from the surroundings back and restacking it vertically on its source pixels at city centers (Abrahams et al., 2016).

3.2.1 Calibration and interannual correction of deblurred RC data

Deblurred DSMP-OLS RC annual composites for the years 1996, 2000 and 2010 were previously inter-calibrated and corrected for a multi-temporal analysis of urban form and city productivity in Latin America (Duque et al., 2017a). In that work, the three nighttime images were used to delineate urban extents in each year for most of the Latin American and Caribbean cities that had more than 50,000 people in 2010 using a threshold approach. Figure 1 shows the workflow of urban extent delineation in Duque et al. (2017a). Figure 2 shows three examples of the obtained urban extents from the 2010 NTL image composite. Figure 3 shows the location of the obtained urban extents in Latin America and the Caribbean region.

[1] Image and Data processing by NOAA's National Geophysical Data Center. DMSP data collected by the US Air Force Weather Agency. https://ngdc.noaa.gov/eog/dmsp/download V4composites.html.

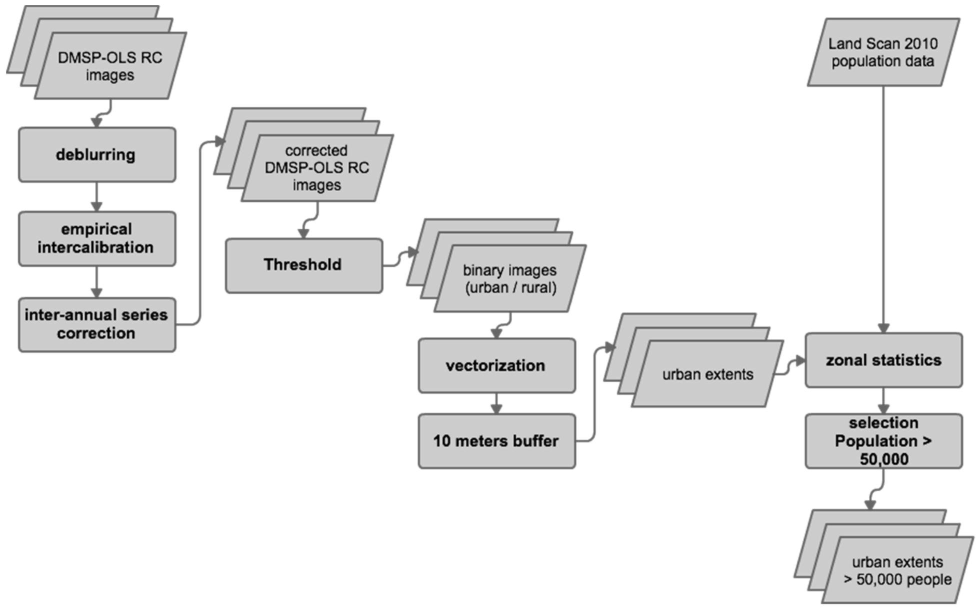


Figure 1. Workflow for urban extent delineation from NTL data (Duque et al., 2017a).

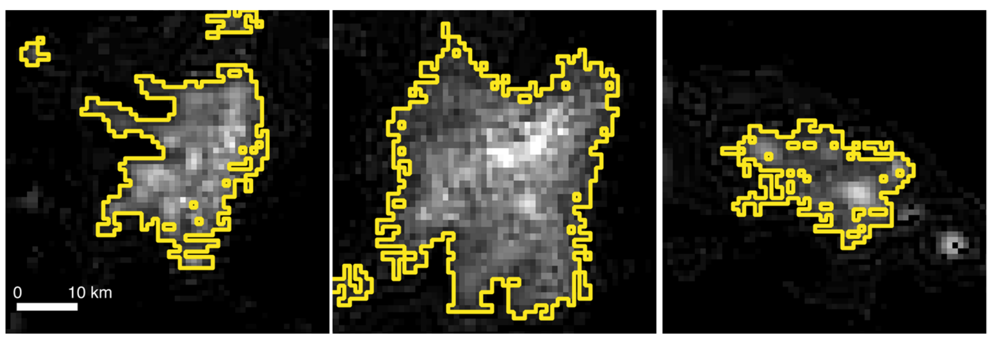


Figure 2. Examples of obtained urban extents over the DSMP-OLS RC 2010 composite. From left to right: Bogota (Colombia), Santiago (Chile), and San Jose (Costa Rica); at the same spatial scale. The yellow line shows de urban boundary.

Figure 3. Location of the 919 obtained urban extents in Duque et al., (2017a).

3.3 Measuring urban form

In this paper we adopt an integral definition of urban form from the urban planning literature. According to contributions such as Whyte (1968), Batty and Longley (1994) and Prosperi et al. (2009), the characterization of urban form should include information on the following three dimensions: shape of the border, urban texture, and land use patterns. This multidimensional definition of urban form allows going beyond the differentiation between sprawl and compactness into a definition that differentiates between natural/organic and planned/regular/artificial/geometric cities. In this paper we propose a series of seven indicators that to cover these three dimensions.

According to Angel et al. (2010b), the geometric characterization of a shape includes three aspects: degree of roundness, smoothness of the perimeter, and fullness. Using a perfect circle as the perfect benchmark shape, the degree of roundness is measured with the *Exchange_index* that measures the degree in which the shape of a polygon deviates from its equal-area circle. It is calculated as the share of the total area of the urban extent that is inside the equal-area circle about its center of gravity (Angel et al., 2010b). An *Exchange_index* equal to 1 corresponds to a perfect circle. As the *Exchange_index* moves towards 0, the shape of the polygon becomes irregular, elongated, and non-compact. The smoothness of the perimeter is measured with the *Perimeter_index*, which indicates how smooth is the perimeter of the urban extent. It is calculated as the ratio of the perimeter of the equal-area circle and the perimeter of the shape (Angel et al., 2010b). A *Perimeter_index* equal to 1 indicates a totally smooth perimeter, found in a perfect circle. A *Perimeter_index* close to 0 indicates a highly irregular perimeter, which is very common in natural/organic cities located in rugged topography. Finally, the level of fullness is quantified with the *Fullness_index*, which measures the presence of built-up areas within the urban extent as a fraction of the urban extent area. It is calculated as the fraction of the total area of the urban extent that is built-up. This measure can be understood as the complement of measures such as porosity or sprawling (Burchfield et al., 2006). A *Fullness_index* equal to 1 corresponds to a totally compact/built-up city. A *Fullness_index* close to 0 represents a sprawling city with lots of empty spaces within its borders. In this study, the *Fullness_index* was calculated using the built-up presence by epoch layers from Global Human Settlement Layer project (GHSL) at 250 meters of spatial resolution for 1990, 2000 and 2014 (Pesaresi et al., 2015; Pesaresi et al., 2016).

Next, we study two dimensions of a city structure related to two dimensions of connectivity: first, the structure given by the layout of the road network, and second, the connectedness of its segments. We measure urban structure with the *Circuity_avg*, which takes values close to 1 when the streets in the network are mostly straight lines, and greater than 1 when the streets are curvier/organic. This metric is calculated as the average ratio between an edge length and the straight-line distance between the two nodes it links (Boeing, 2017). Regarding the connectivity we applied the two most popular metrics for assessing connectivity: *Intersection_density* and the *Street_density*; *Intersection_density* is calculated as the sum of all edge lengths divided by the area (Boeing, 2017), and *Street_density* is calculated as the sum of all edges in the undirected representation of the graph (in km) divided by the area in Km^2 (Boeing, 2017). Both metrics inform about the ease of movement across the city (Boeing, 2017). High values of these two measures are associated to high rates of walking and use of non-motorized transport modes (Cervero, 1997).

Finally, in order to measure the third dimension, the land use pattern, we use the metric proposed by Fallah et al (2011), the *Sprawl_index*, which approaches the land use pattern by measuring the level of evenness in the distribution of population within the urban extent. When the population is evenly distributed, the *Sprawl_index* takes values close to 0; when the population is highly concentrated in a portion of the urban extent, the *Sprawl_index* takes values close to 1. It is calculated as the normalized difference between the share of areas with population density below the regional average density and the share of areas with population density above the regional average density (Fallah et al., 2011). We implemented this metric using population counts at pixel level retrieved from GHS population raster layers for 1990, 2000 and 2015 at 250 meters of spatial resolution (Freire and Pesaresi, 2015; Pesaresi et al., 2016) within the urban extents extracted from DMSP-OLS NTL RC images.

As one of our goals is to generate highly automated methods, we used the “Shape Metrics Toolbox”, which is a Python script that runs in ArcGIS, to calculate two of the three the shape metrics of the urban extents (Exchange index, and Perimeter index). This software is intellectual property of the Center for Land Use Education and Research (CLEAR) at the University of Connecticut (http://clear.uconn.edu/tools/Shape_Metrics/index.htm). We used the OSMnx Python library to compute three network topology variables (Circuity, Intersection_density, and Street_density) (Boeing, 2017). This library uses OpenStreetMap to retrieve, automatically, the street networks within a given polygon, and calculates a series of network-based metrics.

Table 1 presents examples of urban areas with high, medium and low values of these seven variables that describe urban form; and Figure 4 shows the Pearson's correlation coefficients among the implemented measures of urban form with 2010 data. There is high and positive correlation between the *Exchange_index* and the *Perimeter_index,* which describe the perimeter of the urban extent (0.74); and between *Intersection_density* and *Street_density* (0.95)*,* both measuring connectivity within the urban extent. *Fullness_index* and *Sprawl_index* show high and negative correlation (-0.82), with *Fullness* being easier to calculate. *Circuity_avg* shows low to moderate correlation coefficients with the rest of variables, which indicates that it captures a different aspect of the urban form and complements the information given by the other variables.

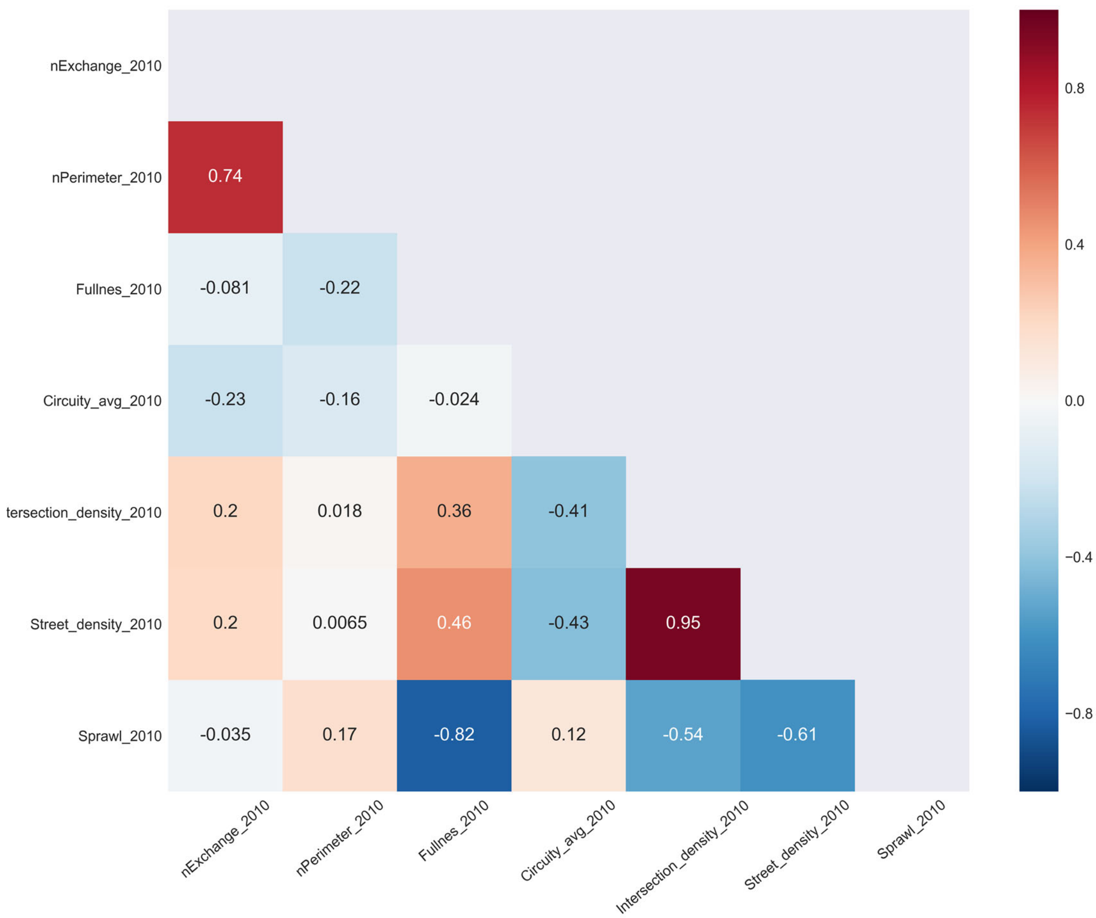
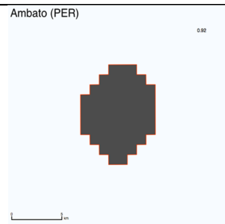
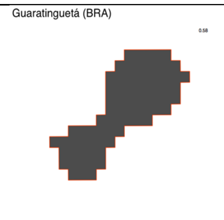
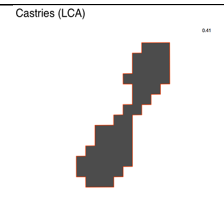
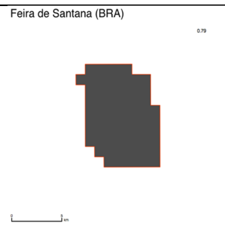
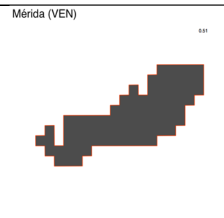
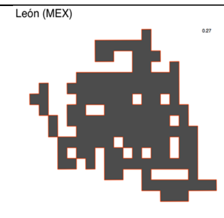
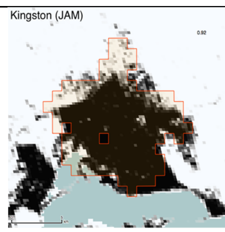
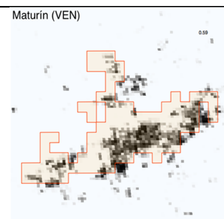
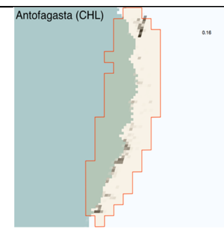
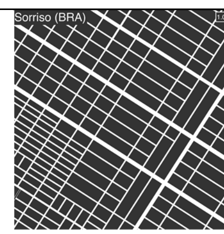
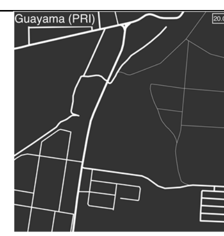
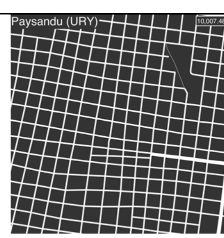
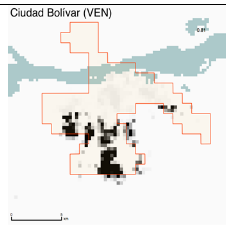
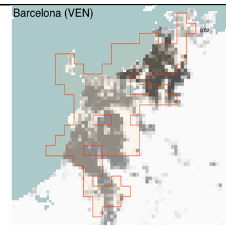
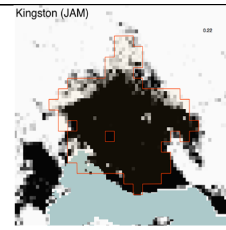


Figure 4. Correlation matrix (Pearson's r correlation coefficients) among spatial measures of urban form.

Table 1. Examples of urban areas with high, medium and low values of the indexes that describe urban form.

	High	Medium	Low
Exchange_index			
Perimeter_index			
Fullness_index			
Circuity_avg			
Intersection_ density			
Street_density			

Sprawl			

3.4 Factors that can affect urban form

We explore the relationship between the urban form variables and four factors that may affect the way in which an urban extent grows. The selected factors and the respective rationale are the following:

- Available land: The natural constraints to urbanization play an important role in defining urban form and structure. Cities with rugged topography located in the mountains should show more organic street networks and a less smooth perimeter than those with flat topography.

- Size of the city: As the city grows, the "best" land for urban growth may start to become scarce. In this situation, the city may consider occupying new areas that would not consider before, and its indicators of urban form may begin to deteriorate.

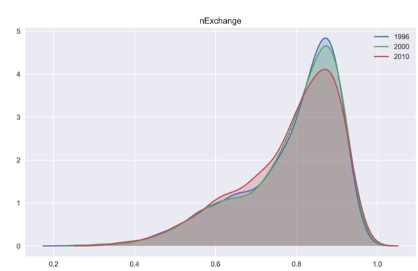
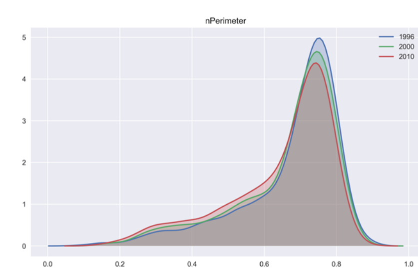
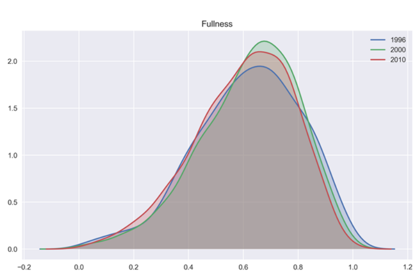
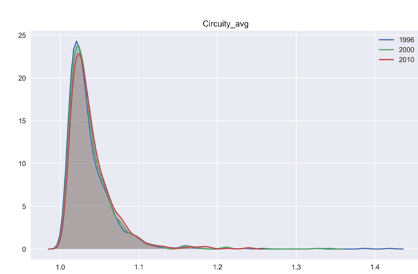
- Culture/Colonization history: The colonization history in Latin America is seen as proxy for cultural differences that translate to urban planning practices and ultimately to the resulting urban form today. Most historic centers of cities that were Spanish colonies show a more regular urban layout than cities that were colonies of other countries. We expect that the colonization differences may translate to differences in the urban structure in Latin American and Caribbean cities, with cities that were Iberian colonies showing more regular and organized urban layouts.

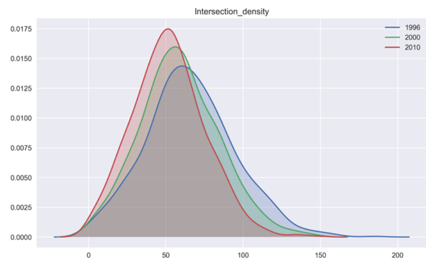
- GDP: Proxied with the density of radiance within the urban extent, as recorded by DMSP-OLS RC nighttime imagery. We expect that cities with high GDP can have the financial resources to ensure a planned and orderly urban growth and to provide, in a timely manner, the new areas with the required public services.

4 Results

4.1 Descriptive analysis

This section describes the whole set of LAC cities in terms of its urban shape, texture and land use variables. Figure shows the kernel density plots of urban form variables for each date: 1996, 2000, and 2010.

(a) nExchange	**(b) nPerimeter**
	
(c) Fullness	**(d) Circuity_avg**
	
(e) Intersection_density	**(f) Street_density**



(g) Sprawl

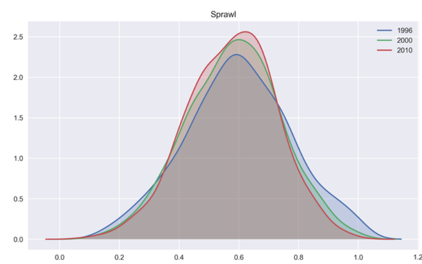


Figure 5. Kernel density distributions of urban form variables.

Table 2 contains the descriptive statistics for each variable in each date. While the distributions of the variables are very similar across dates, there are small changes that indicate how the set of LAC cities are evolving.

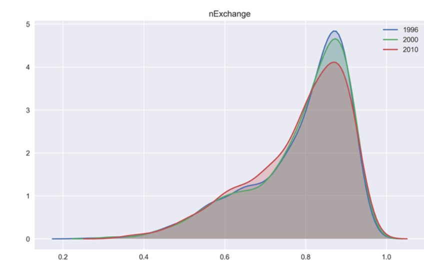
Generally speaking, urban shape variable values for 2010 indicate that LAC cities are more rounded than elongated; with urban perimeters more smoothed than complex, and little open space. The changes from 1996 to 2010 are small but point to some trends in the region. Roundness (*nExchange* in Figure 5a) values tend to be high, with median and mean values above 0.5 in the three dates. A slight decrease is observed from 1996 to 2010, which indicates a weak trend of change towards less round and more elongated urban extents. Smoothness of perimeter (*nPerimeter* in Figure 5b) values are high across all dates, and they also show a small decrease over time. This indicates the trend towards less smoothed urban perimeters that could be the result of the urban growth along corridors that link to other cities. *Fullness* values (Figure 5c) tend to be high, and they show a small increase from 1996 to 2000, and then a small decrease up to 2010, which could indicate the trend of low density growing in that period. These results are in agreement with previous findings (Angel et al., 2010a; Huang et al., 2007; Inostroza et al., 2013).

Urban texture variables indicate that LAC cities have a quite dense texture, with values of intersection density (Figure 5e) and street density (Figure 5f) that are rather high. The *Circuity_avg* values (Figure 5d) indicate that the street network layout in LAC cities is very regular: they are very close to 1, and 75% are below 1.05, meaning that most of their street networks are about only 5% longer than if they were all composed of straight lines. This regularity is in line with the findings by Huang et al. (2007). However, a general small increasing trend is observed in *Circuity_avg* values from 1996 to 2010, which might be due to recent occupation of rugged terrain in mountainous areas.

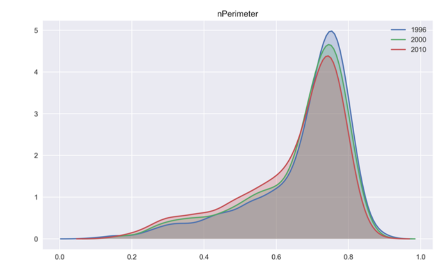
The land use variable, sprawl (Figure 5g), measures how uniform is the spatial distribution of population within the urban extents. In general, this variable shows medium values with a small decrease from 1996 to 2010. This could be a weak trend towards a more uniform distribution of the population within urban extents.

The diversity in climate and topographic conditions across the LAC region translates into a high diversity in the shape that urban areas have taken. We look at the 2010 data to highlight country level differences in urban areas (Figure 6). *nExchange* boxplots from Figure 6 show that Venezuelan cities tend to be more elongated than most of the other cities in the region, while Bolivian cities tend to be more rounded. Bolivian cities tend to have more smoothed perimeters (high values of *nPerimeter*), and the cities with less smoothed perimeters are in México, Brazil, Argentina and the República Bolivariana de Venezuela. *Fullness* boxplots show that lower values occur more frequently in Colombia, Ecuador and Peru than in other countries of the region, and the highest values are in Bolivia and Guatemala. Urban texture plots show that more regular networks are often denser than the organic ones: in general, the República Bolivariana de Venezuela and Guatemala have the cities with more organic street networks in the region (higher values of *Circuity_avg*), and they have also the lowest street and intersection densities. With respect to land use, the República Bolivariana de Venezuela and Peru exhibit higher values of *Sprawl*, which indicates less uniform distribution of urban population in their urban areas and more intra-urban differences, while Bolivia and Cuba exhibit lower values, which indicate a more uniform distribution of the population within their cities.

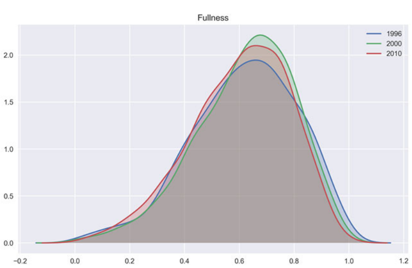
(a) nExchange



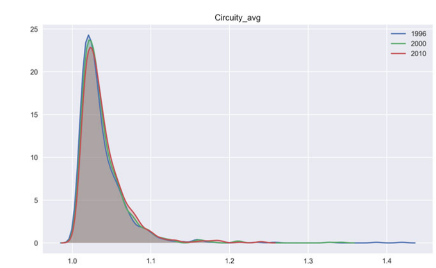
(b) nPerimeter



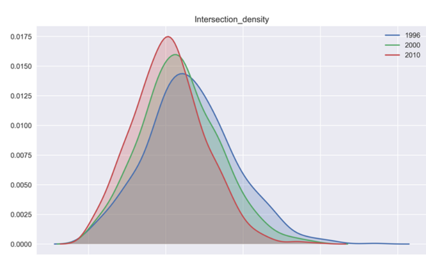
(c) Fullness



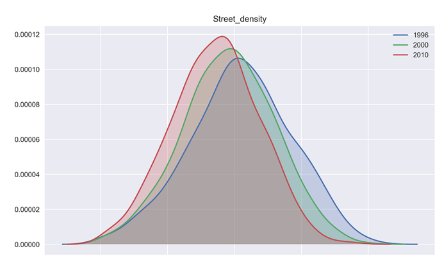
(d) Circuity_avg



(e) Intersection_density



(f) Street_density



(g) Sprawl

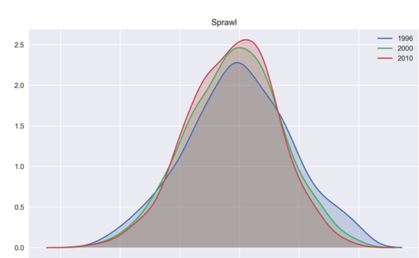
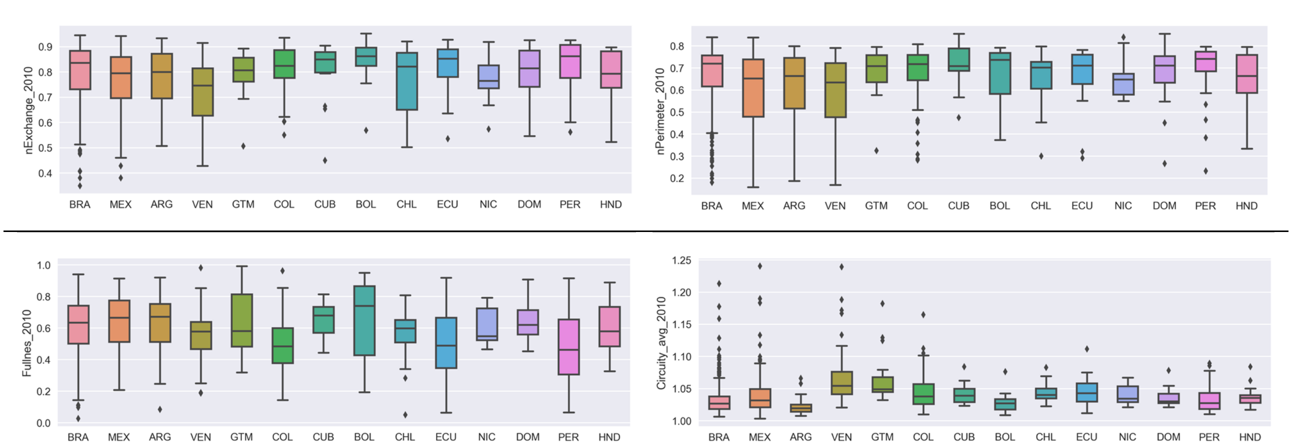


Figure 5. Kernel density distributions of urban form variables.

Table 2. Descriptive statistics of variables. N = 919.

Variable	date	p25	Median	p75	Mean	Std. Dev.	Min	Max
	1996	0.725	0.828	0.879	0.787	0.121	0.266	0.947
nExchange	2000	0.728	0.828	0.880	0.789	0.121	0.315	0.949
	2010	0.712	0.782	0.877	0.782	0.121	0.350	0.952
	1996	0.620	0.720	0.767	0.674	0.140	0.090	0.888
nPerimeter	2000	0.600	0.712	0.761	0.663	0.141	0.159	0.887
	2010	0.567	0.700	0.755	0.644	0.146	0.160	0.856
	1996	0.494	0.630	0.763	0.618	0.192	0.014	0.996
fullness	2000	0.509	0.645	0.758	0.623	0.180	0.006	0.992
	2010	0.482	0.623	0.739	0.602	0.181	0.028	0.993
	1996	46.96	64.90	84.13	65.87	28.88	0.33	184.97
intersection density	2000	41.87	57.78	75.69	59.01	25.78	0.19	147.25
	2010	36.02	51.26	66.59	51.93	23.51	0.20	148.01
	1996	7,988.8	10,452.4	12,985.5	10,474.4	3,791.5	135.9	20,669.2
street density	2000	7,245.7	9,643.5	11,990.9	9,591.8	3,447.6	198.5	19,961.4
	2010	6,428.3	8,643.8	10,773.7	8,582.4	3,249.5	87.1	19,040.0
	1996	1.019	1.028	1.046	1.037	0.034	1.002	1.419
circuity	2000	1.020	1.030	1.047	1.039	0.032	1.002	1.342
	2010	1.021	1.032	1.050	1.040	0.029	1.004	1.241
	1996	0.479	0.595	0.721	0.598	0.177	0.108	1.00
sprawl	2000	0.470	0.586	0.688	0.582	0.157	0.112	1.00
	2010	0.475	0.583	0.677	0.575	0.148	0.074	1.00



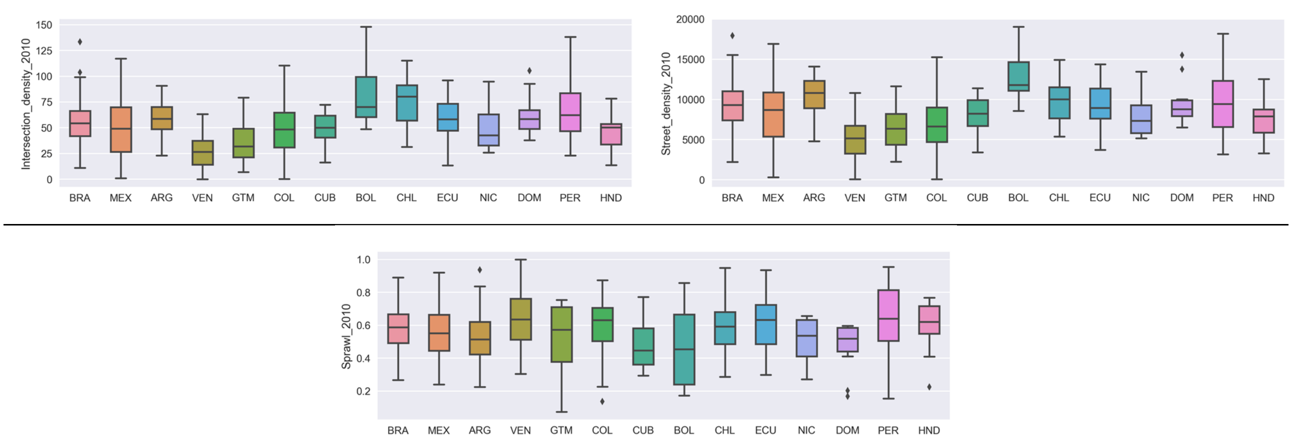


Figure 5. Box plots of urban form variables for 2010 by country (ISO3 code). Only showing countries with more than 9 detected urban extents from NTL.

4.2 Cluster Analysis

In this section we classify the cities into homogeneous groups according to their profile of values on the seven metrics. For this analysis we adopted the sequence proposed by Huang et al. (2007): First, we determine the number of clusters based on a visual inspection of the dendrogram that results from running a hierarchical clustering algorithm. The dendrogram in Figure 6 shows that four would be a proper number of clusters. Since the hierarchical cluster is a highly constrained algorithm (i.e., once two sets of areas are collapsed into one cluster, they are forced to remain together in further solutions, which can lead to suboptimal solutions). The second step consists of running a K-means clustering algorithm to aggregate the cities in four clusters. The profile of each cluster is presented in the parallel coordinate plot in

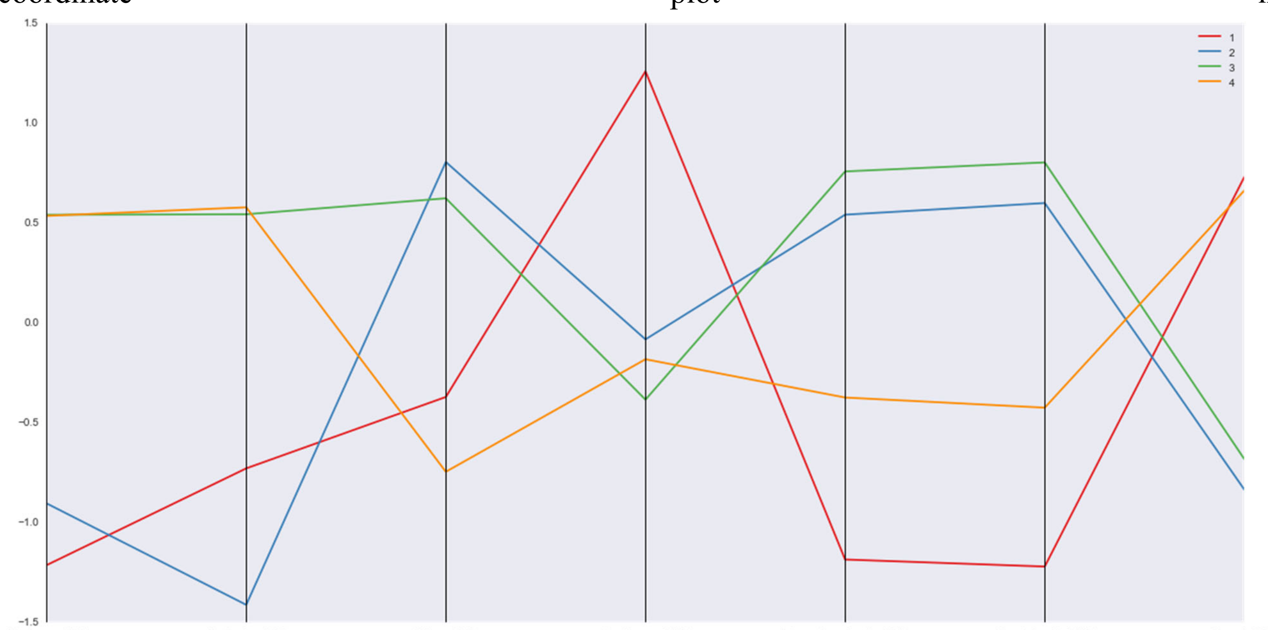


Figure 7. Cluster 1 is composed of cities with a highly organic street network, with poor connectivity and sprawled. Cluster 2 is composed of cities with organic perimeter, but with a street network with high level of connectivity and low sprawl. Cluster 3 is composed of compact cities with good connectivity and low sprawl. Finally, Cluster 4 is composed of compact cities with moderate level of connectivity and highly sprawled.

The mean and standard deviation of the variables for each cluster are presented in Table 3. Figure 8 shows the map of the spatial distribution of the cluster groups and Table 4 shows the proportion of cities in each cluster by country. Even though a clear spatial pattern is absent, there are some subtle patterns that help to understand the differences across countries shown in Figure 5. Most of the cities in the South (from Brazil and Ecuador southwards) are from clusters 2, 3 or 4, meaning that there are few in the group of densest and well-connected cities. And most of the urban extents that belong to cluster 1 are located either in the South-east of Brazil, or in the region that spans from Colombia and the República Bolivariana de Venezuela to the north up to Mexico.

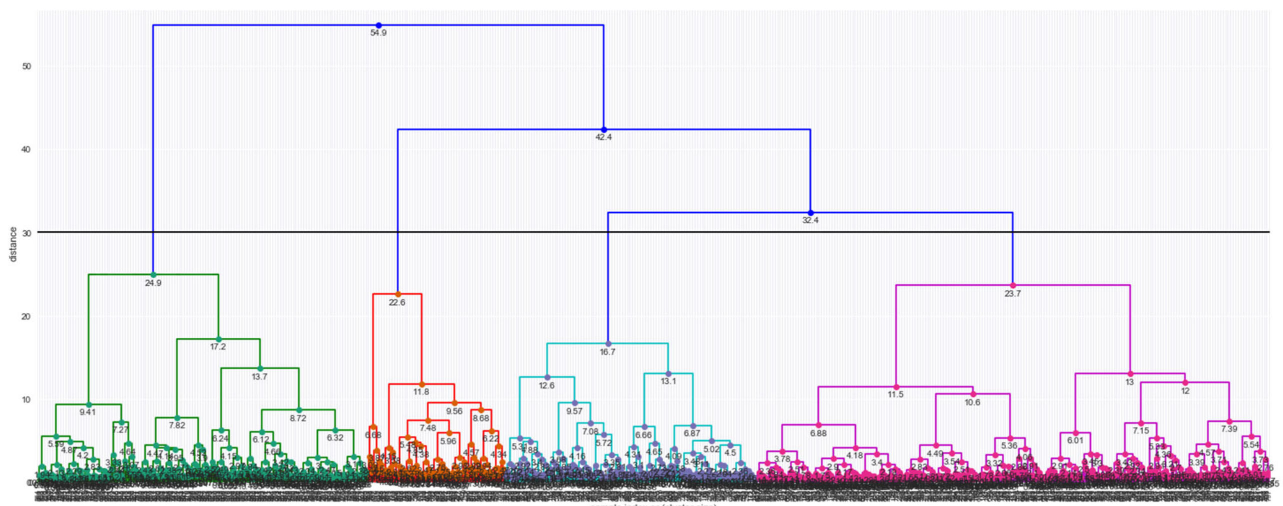


Figure 6. Hierarchical clustering dendogram (Note: Cophenetic correlation coefficient = 0.5176).

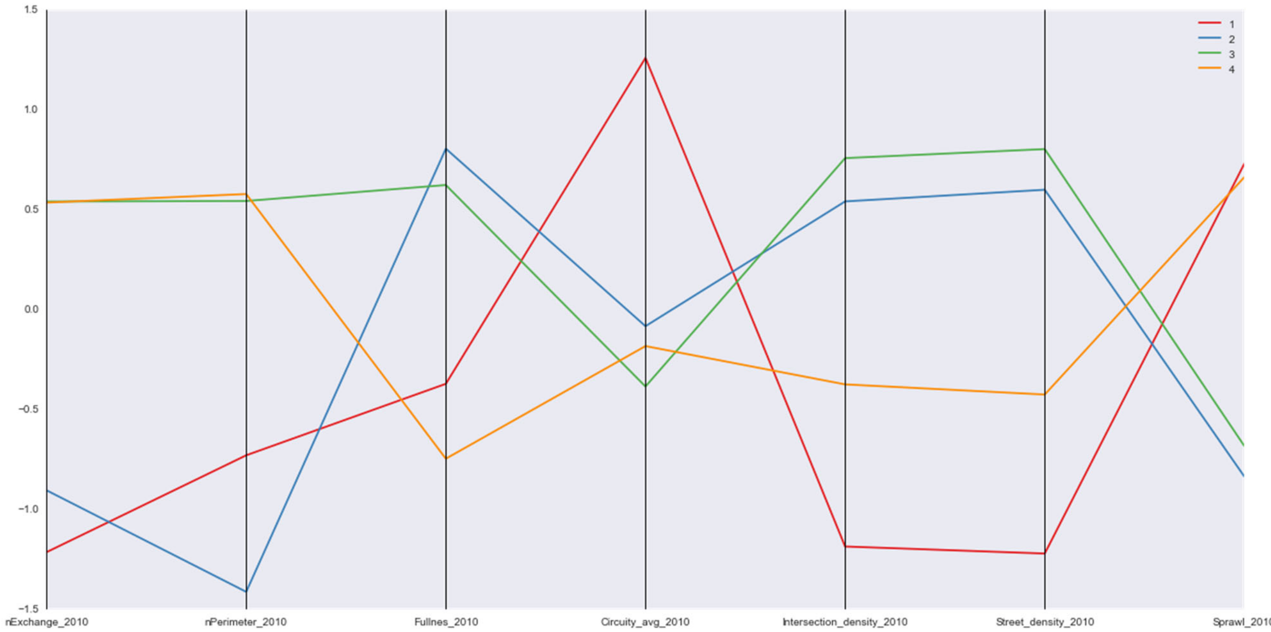


Figure 7. Cluster profiles. Note: All variables were standardized for the sake of comparability (mean=0, Std. Dev. = 1).

Table 3. Descriptive statistics by cluster (non-standardized values).

Cluster	Statistic	nExchange_2010	nPerimeter_2010	Fullnes_2010	Circuity_avg_2010	Intersection_density_2010	Street_density_2010	Sprawl_2010
1	count	144	144	144	144	144	144	144
	mean	0.635	0.538	0.534	1.076	24.040	4,611.875	0.683
	std	0.124	0.133	0.158	0.045	13.061	2,107.546	0.120
2	count	167	167	167	167	167	167	167
	mean	0.672	0.438	0.747	1.037	64.623	10,526.508	0.452
	std	0.089	0.117	0.111	0.018	19.482	2,294.134	0.120
3	count	273	273	273	273	273	273	273
	mean	0.848	0.724	0.714	1.029	69.715	11,187.477	0.474
	std	0.059	0.057	0.107	0.016	18.265	2,160.928	0.101
4	count	335	335	335	335	335	335	335
	mean	0.847	0.729	0.466	1.034	43.106	7,196.901	0.673
	std	0.063	0.056	0.151	0.019	15.252	2,131.492	0.090

4.3 Factors vs. urban form variables in LAC cities

In this section we analyze the urban form variables in regard to each of the factors that can correlate with urban form: topography, size, colony, and economic performance. Figure 9 shows the distributions of urban form variables (rows) grouped by factors (columns). Factor *slope* was grouped in two classes to differentiate between cities located in flat terrain and cities located in the mountains or rugged terrain: below 10% and above 10%. Factors *size of the city* (Area_km^2_2010) and *economic performance* (using the density or NTL radiance values within the urban extent as proxy) were grouped into quartiles to inspect differences between quartile groups. Factor *colony* was assigned according to the colony that the area was part of in 1700: Portugal, Spain, England, the Netherlands, and France (Gascoigne, 2001).

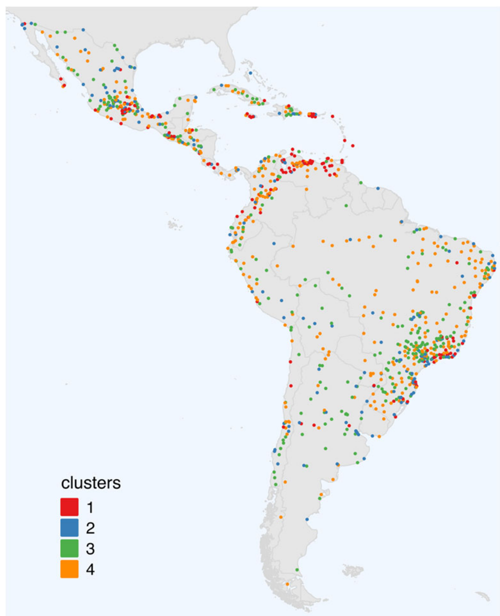
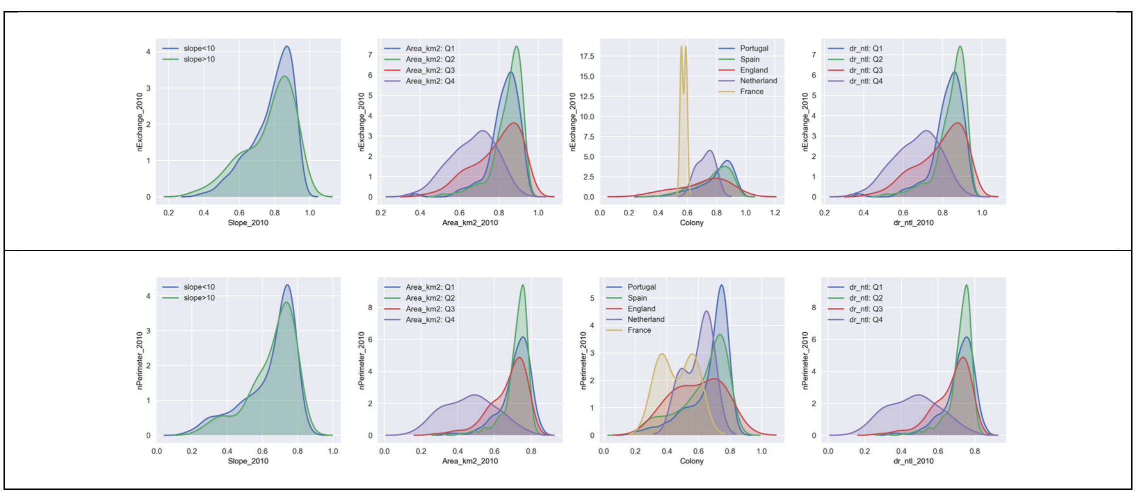


Figure 8. Urban extents classified into 4 cluster groups.

Table 4. Proportion of cities in each cluster.

		Cluster			
Country	Num.Cities	1	2	3	4
ABW	1	100.0%	0.0%	0.0%	0.0%
ARG	59	5.1%	27.1%	47.5%	20.3%
BHS	1	0.0%	100.0%	0.0%	0.0%
BLZ	1	0.0%	0.0%	0.0%	100.0%
BOL	11	0.0%	27.3%	36.4%	36.4%
BRA	355	9.0%	17.2%	34.6%	39.2%
BRB	1	100.0%	0.0%	0.0%	0.0%

CHL	31	9.7%	19.4%	38.7%	32.3%
COL	59	16.9%	10.2%	15.3%	57.6%
CRI	6	66.7%	16.7%	0.0%	16.7%
CUB	18	5.6%	5.6%	50.0%	38.9%
CUW	1	0.0%	0.0%	100.0%	0.0%
DOM	15	6.7%	20.0%	46.7%	26.7%
ECU	21	9.5%	14.3%	28.6%	47.6%
GTM	16	25.0%	12.5%	25.0%	37.5%
GUY	1	0.0%	0.0%	100.0%	0.0%
HND	12	16.7%	25.0%	16.7%	41.7%
HTI	1	0.0%	100.0%	0.0%	0.0%
JAM	6	66.7%	16.7%	0.0%	16.7%
LCA	1	100.0%	0.0%	0.0%	0.0%
MEX	157	17.8%	24.2%	28.7%	29.3%
NIC	10	10.0%	20.0%	30.0%	40.0%
PAN	6	0.0%	33.3%	0.0%	66.7%
PER	32	3.1%	15.6%	37.5%	43.8%
PRI	8	75.0%	12.5%	0.0%	12.5%
PRY	9	11.1%	22.2%	11.1%	55.6%
SLV	8	0.0%	12.5%	37.5%	50.0%
SUR	1	0.0%	100.0%	0.0%	0.0%
SXM	1	100.0%	0.0%	0.0%	0.0%
TTO	3	100.0%	0.0%	0.0%	0.0%
URY	5	0.0%	20.0%	20.0%	60.0%
VEN	62	54.8%	9.7%	3.2%	32.3%



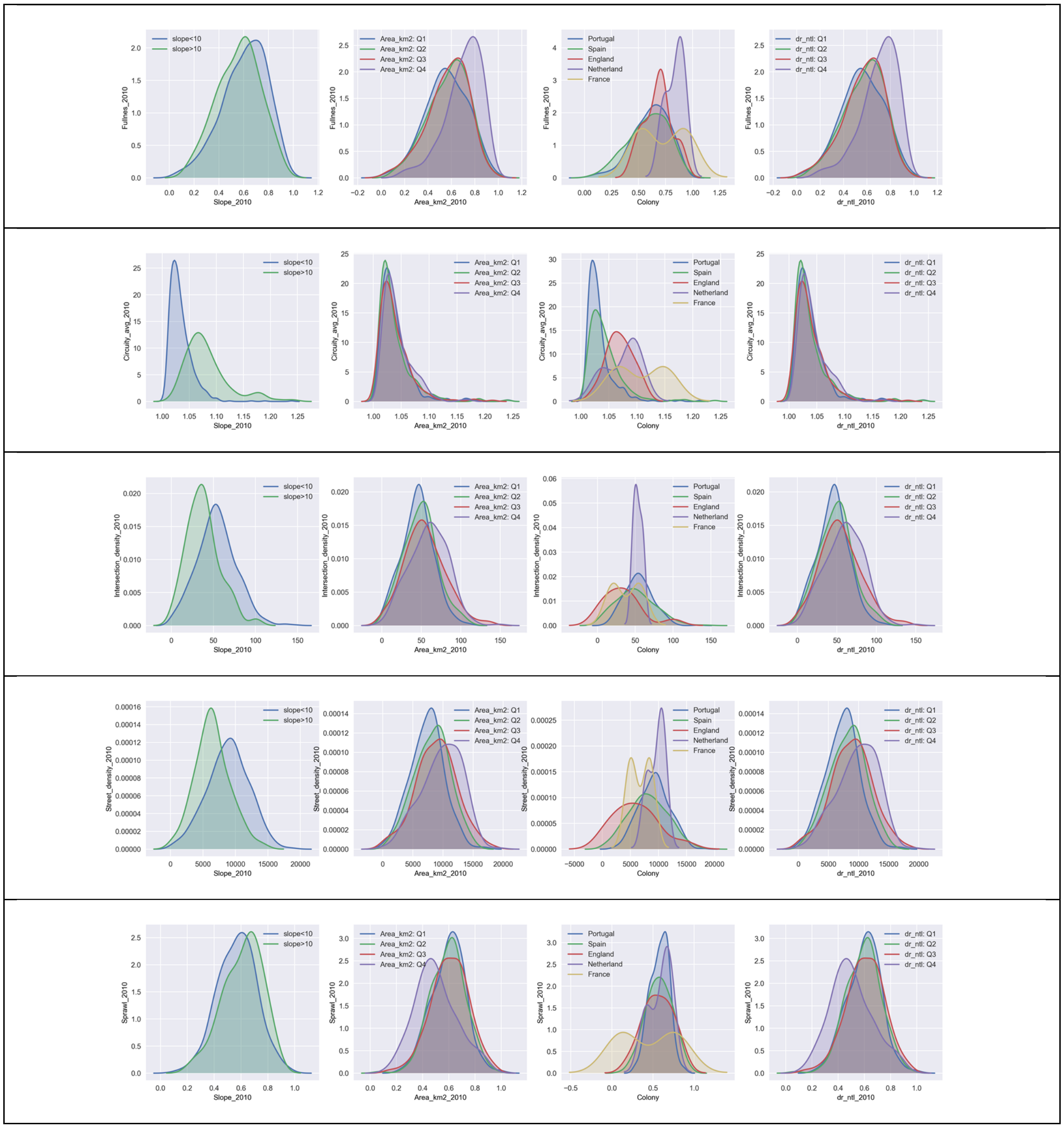


Figure 9. Urban form variables distributions for 2010 data according to the factors that can affect urban form.

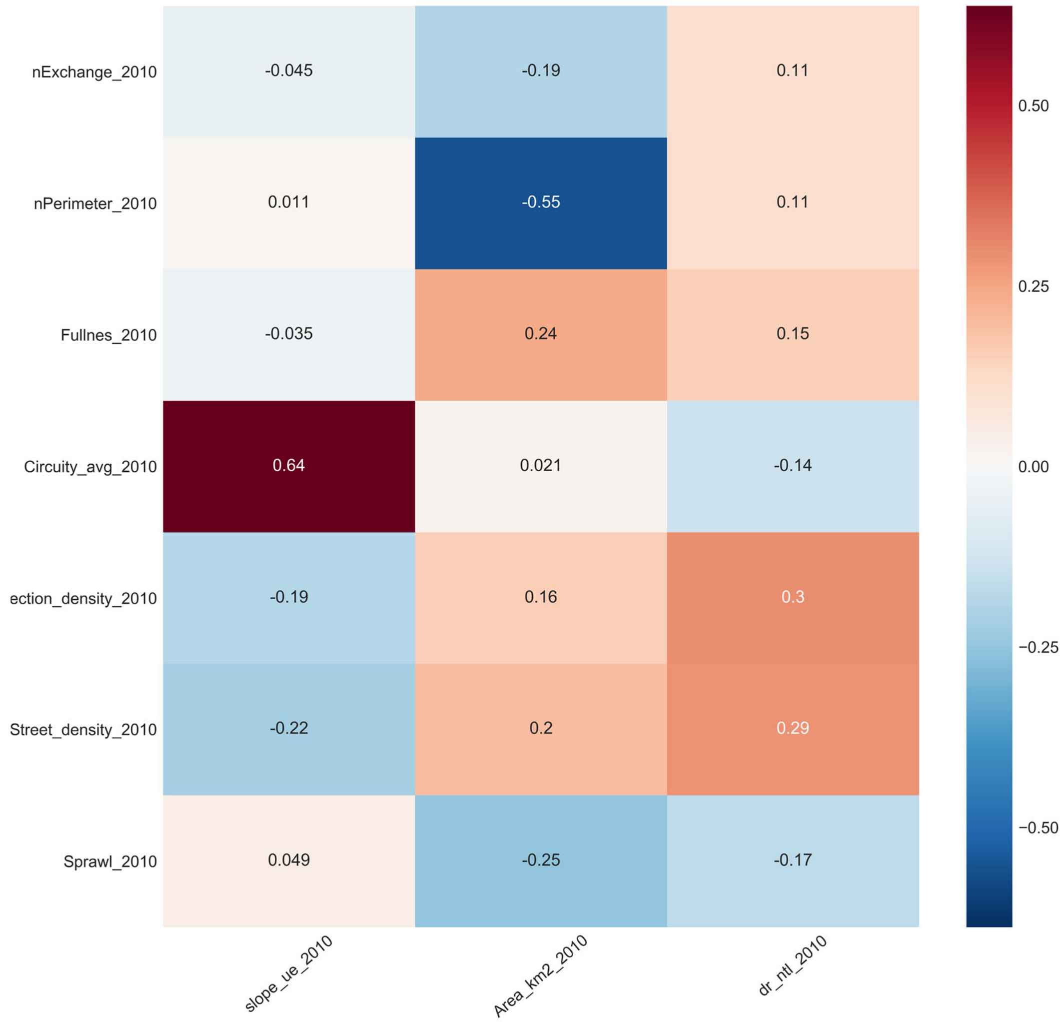


Figure 10. Correlations between urban form variables and the factors that affect them.

4.3.1 Topography

We analyze the topography using the mean slope (%) within the urban extent (Figure 10), first column). While roundness variables *nExchange* and *nPerimeter* do not show important differences between the two classes, *Fullness* does show a small but legible difference: urban extents with slopes above 10% tend to lower values than those with slopes below 10%. This indicates that the cities located in rugged terrain have more empty spaces than the cities located in flat terrain. Urban texture graphs corroborate that cities with steepest slopes have lower values of street and intersection densities, as well as more organic urban layouts, with higher values of *Circuity_avg*. This is an expected behavior because the street network in rugged terrain should adjust to the topography with curvy roads. Also, according to Batty and Longley (1994), organic cities, which area associated with high levels of *Circuity*_avg, fit their natural landscape. That explains the high and positive correlation between *Circuity*_avg and Slope (0.64). The relation with *Sprawl* indicates that cities with steeper slopes have a less uniform distribution of their population within the urban areas than cities located in flat terrain.

4.3.2 Size of the city

We classified the urban extent area in square kilometers into quartiles and built kernel density plots of the distribution of urban form variables for each group (Figure 10 second column). Roundness variables *nExchange* and *nPerimeter* are very similar for the first, second and third quartile; but the fourth quartile group shows a wider distribution with lower values in both cases. This and the moderate and negative correlation between *nPerimeter* and *Area_km*^{2} (-0.55) indicate that larger urban areas in the LAC region deviate more from the circular shape and have less smoothed perimeters (Figure 11). The trend in *Fullness* is quite the opposite: larger cities show higher values, indicating a more efficient use of urban space, with a low positive correlation (0.24). Urban texture does not seem to be affected by city size. *Circuity_avg* distributions of all groups are very similar; while *street density* and *intersection density* distributions show small differences indicating that larger cities have higher street and intersection densities, as expected from the inspection of *fullness* distributions. *Sprawl* distributions also show an interesting trend: larger cities have lower values than the rest and a low negative correlation (-0.25), which indicates that the population in those cities tends to be more uniformly distributed than in the smaller urban areas.

4.3.3 Culture/Colonization history

The colonization process influences urban design and growth trends. We classified the urban extents in LAC region according to the colony they belonged in 1700 (Gascoigne, 2001), and built the kernel density plots of urban form variables for each class (colony). Portugal, Spain, England, the Netherlands and France were the countries that had colonies in Latin America and the Caribbean by 1700. The third column of Figure 10 shows the distribution plots of urban form variables for the colony groups. English and Iberian (Spanish and Portuguese) colonies show a similar trend in roundness variables, while French and Dutch colonies show smaller values in both cases, indicating cities more elongated and with less smoothed perimeters than their English and Iberian counterparts. *Fullness* distributions also show some differences, with French and Dutch colonies showing higher values than the rest. Urban texture distributions show an interesting trend: Portuguese colonies have the lower values of *Circuity_avg*, followed by Spanish colonies, then English, then Dutch, and then the French ones. This corroborates the idea that LAC cities that were Iberian colonies have more regular urban layouts. The density of streets and intersections indicates that the English colonies have less density than the rest, with the higher densities in the Iberian colonies. *Sprawl* distributions show that French colonies have the lower values, indicating that the population is more uniformly distributed in those cities than in the rest of the groups.

4.3.4 GDP (proxy: density of radiance in NTL imagery, dr_ntl)

We used the density of radiance from the nighttime imagery as proxy for GDP (*dr_ntl*). We classified the LAC cities in quartiles according their registered radiance density in 2010. *nExchange* and *nPerimeter* do not show legible differences across quartiles, but *Fullness* does: the group of cities with lower density radiance values also show a trend towards lower values of *Fullness*. This indicates the trend that the cities with more open spaces within the urban extent are less productive, in agreement with the findings of Duque et al. (2017a, 2017b). The distributions of urban texture variables corroborate the same finding: street and intersection densities both increase with radiance density, and the group of higher values of radiance density has the more regular urban layouts (*Circuity_avg* values closer to 1). The distributions of *Sprawl* show that the most productive cities have the most uniform distributions of populations within the urban extent. The variable *dr_ntl* is positively correlated with variables capturing compactness and connectivity. This is in line with the finding by Duque et al (2017a) in which compact and well-connected cities show higher levels of productivity. Good mobility reduces transportation costs, and compactness reduces the cost-per-household of public service infrastructure.

5 Spatio-temporal analysis of urban growth, 1996, 2000 and 2010

We analyzed the urban growth between 1996 and 2010 looking at trends in the data of new urban areas in 2000 and 2010 with respect to the prior date. Here we tried to answer if there is a trend of growing in steeper terrain, how much fragmented is the growth, if the new areas occupy protected areas, and the relationship of urban growth with the initial size of the city and with the population density of the urban extent in the prior date.

5.1 Slope

Figure 11 shows the distribution of slope data for new areas in 2000 and 2010, aggregated in two groups: urban extents with mean slope < 10% (mostly flat), and urban extents with mean slope > 10% (located in rugged terrain). As expected, the initially flat urban extents grow most often over new flat areas (low slope values), and rarely over slopes greater than 10%, while urban extents in rugged terrain grow most of the time over areas with steeper slopes, from 5% to 25% in most of the cases. Moreover, the distribution of slope in new areas in 2010 is shifted to the right in regard to the slope of new areas in 2000. The mean value of the slope of rugged terrains in new areas shows a small increase: from 14.6% in 2000 to 16.3% in 2010. This points to the trend, also found by Gencer (2013), of urban growth over steeper terrains for the cities initially located in rugged terrain, which increases the potential for disasters related to the occurrence of landslides and flash floods.

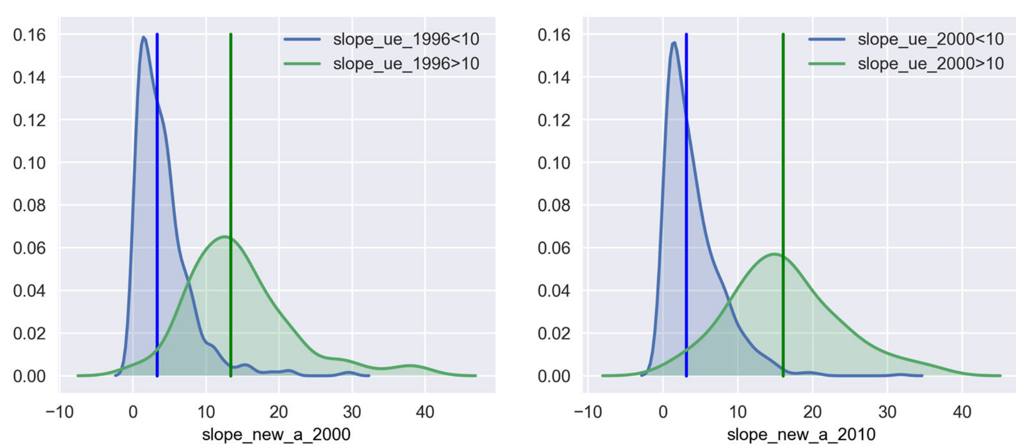


Figure 11. Kernel density distribution of slope (percent rise) of new areas. The vertical lines show the mean of each distribution.

5.2 Fragmentation

We counted the number of patches of the new urban areas in 2000 and 2010 to see if there is a trend toward more or less fragmented urban growth. Higher values of fragmentation indicate that the cities are growing in multiple directions over the prior urban extent boundary. Figure 13 shows the box plots of the number of new areas in 2000 and in 2010, grouped by region: North America (México): NAM, Central America (CAM), South America (SAM), and the Caribbean (CAR). This figure shows a weak trend toward a less fragmented urban growth between 2000 and 2010 than between 1996 and 2000, except for Central America that shows a small increase. When looking to the different groups' boxplots, it is clear that some Mexican cities, as well as some South American ones have the highest values of fragmentation within LAC.

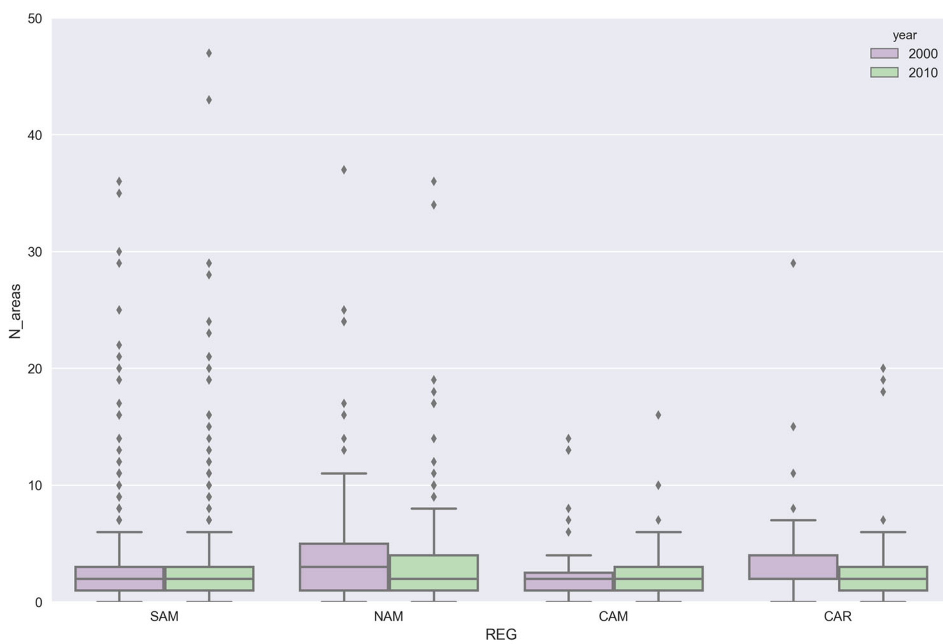


Figure 13. Boxplots of growth fragmentation (number of new areas) in 2000 and 2010, grouped by region.

5.3 Protected areas

A protected area is a protected geographical space to achieve long-term conservation of nature with the associated ecosystem services and cultural values (UNEP-WCMC, 2016). Urban growth over protected areas implies the loss of ecosystem services and cultural values and it jeopardizes the urban sustainability in the long term. We quantified urban growth over protected areas using the World Database on Protected Areas (WDPA) produced by the United Nations Environment Programme (UNEP-WCMC, 2016), which is the most comprehensive global database of marine and terrestrial protected areas. We considered all types of protected areas included in the WDPA and calculated the intersection with the new urban areas in 2000 and 2010 using geoprocessing tools in ArcGIS. Figure 14 shows the country average of percent urban growth on protected areas. Most countries in the LAC region show relatively low values (up to 6%). Bolivia has the highest values in both periods, both above 50%, which indicates a negative trend in terms of long-term sustainability. Venezuelan urban extents also show high values as well, up to 18%. According to UN (2014), it is expected that Bolivian cities will increase the urban population by 79% between 2014 and 2050; with the second largest annual rate of change in South America: 0.6%. This makes the detected trend an important issue to address in the near future.

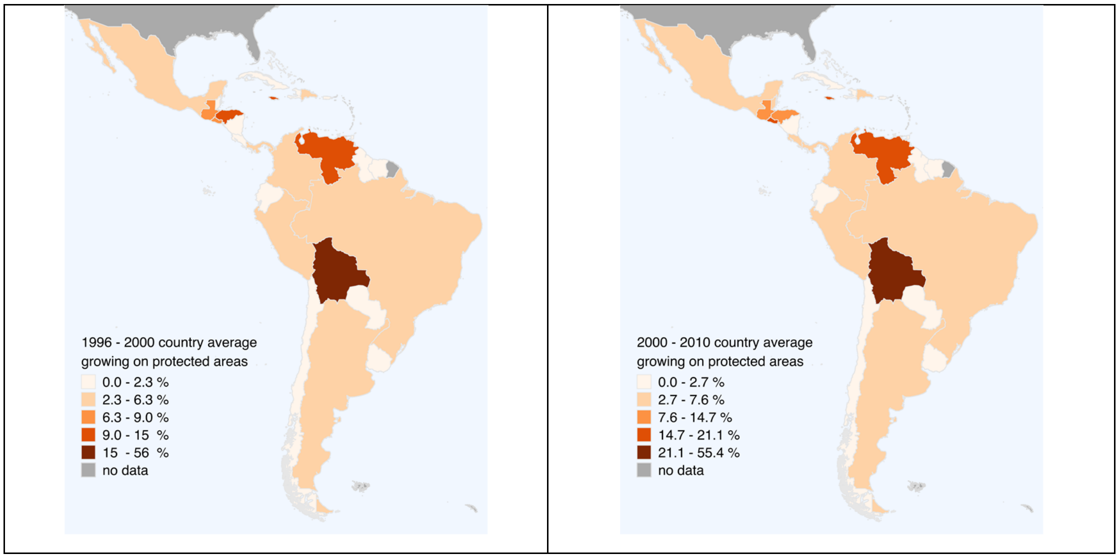


Figure 14. Country average urban growth on protected areas in LAC. Left: 1996 – 2000, right: 2000 – 2010.

5.4 Growth vs. initial spatial size

Initial spatial size of the urban extent does not seem to play an important role in the magnitude of urban growth. As shown in Figure 15, the initial area of the urban extent does not show significant differences between quartile groups in regard to urban growth: all four quartile groups have similar central values and their distributions have very similar shapes in both periods.

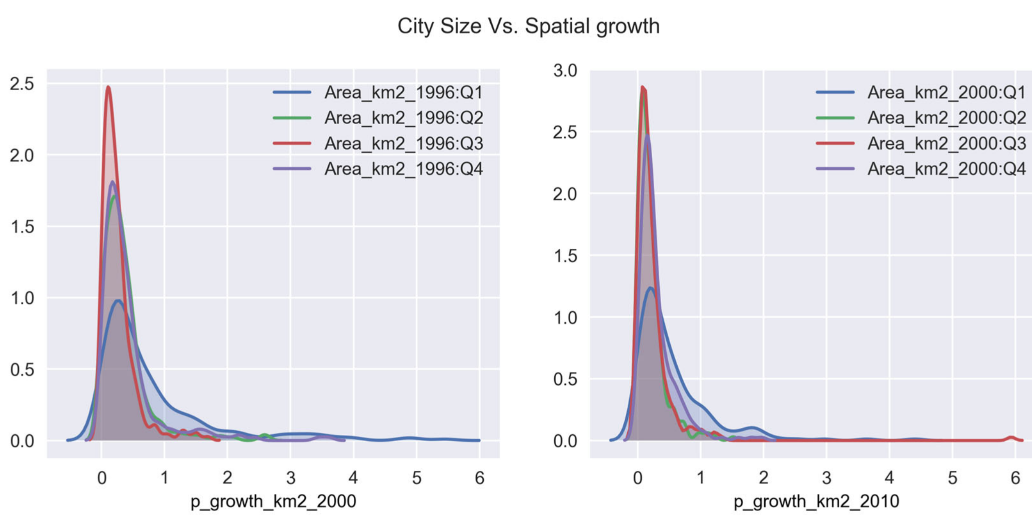


Figure 15. Initial urban extent size (area in Km2, classified in quartile groups) and urban growth (as percentage of initial size).

5.5 Growth vs. population density

In regard to the relationship between urban growth and population density, we analyzed the distributions of the initial population density (for years 1996 in the period 1996 – 2000, and 2000 for the period 2000 – 2010) divided in quartiles groups (Figure 16). Initial population density seems to play a weak role in the spatial growth of the urban extents: the denser urban areas (Q4 group) tend to grow about 0.1% to 0.2% more than the rest of urban extents. This was expected as the less dense urban areas can accommodate new people up to a saturation point without spatial growth. When the population density is close to reaching its physical limit or saturation point, spatial growth to new areas must accommodate the new population.

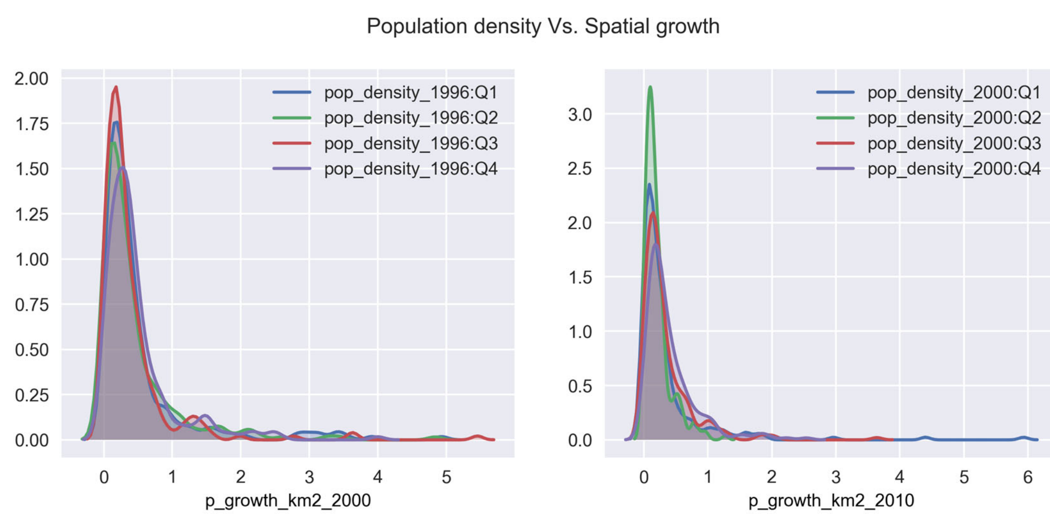


Figure 16. Initial population density (people/Km2, classified in quartile groups) and urban growth (as percentage of initial size).

5.6 Growth by saturation

As stated above, growth for saturation takes place when the urban population growth does not imply new spatial growth until a top population density is reached. This situation can take place when the population density in a city is below its upper limit for its urban carrying capacity.[2] In this scenario, the city can increase its population by infill of available spaces within the urban area, or via an increase in population density, before the occupation of new areas. When the population density has reached its maximum or saturation point, the only option left is growth on new adjacent areas. We analyzed if the urban growth is a consequence of saturation by comparing the highest population densities reached in the new urban areas in 2000 and 2010, with the population density reached in the respective date in the urban extent area for the initial date (1996). We built an indicator of saturation for each period as shown in Table 5, using population figures for the last date in each period (i.e., 2000 for the 1996 to 2000 period, and 2010 for the 2000 to 2010 period):

[2] For a comprehensive discussion on urban carrying capacity, see Li and Lian (2012).

Table 5. Growth by saturation metrics and rationale_means.

Metric	Rationale
$Saturation_{2000} = \dfrac{\dfrac{Pop_{2000} \in NUE_{1996,2000}}{NUE_{1996,2000}}}{\dfrac{Pop_{2000} \in UE_{1996}}{UE_{1996}}}$	If growth by saturation, this metric would take values below 1. Which means that the new area built between 1996 and 2000 has a population density lower that the population density within the polygon corresponding to the urban extent in 1996.
$Saturation_{2010} = \dfrac{\dfrac{Pop_{2010} \in NUE_{1996,2000}}{NUE_{1996,2000}}}{\dfrac{Pop_{2010} \in UE_{1996}}{UE_{1996}}}$	If growth by saturation, then the population density gap between the urban extent of the city in 1996 and the new area between 1996 and 2000 should be closer to 1 by 2010. Otherwise, the city's new area between 2000 and 2010 might be unnecessary or hasty.

Where:

- UE_t = Urban extent at year *t*
- $NUE_{(t-k),t}$ = New urban extent between years (*t-k*) and *t*.
- Pop_t = Population at year *t*

Saturation values above 1 indicate that the population density in the new areas is higher than the population density in the prior-date urban extent area. This indicates low saturation, as it can be assumed that the prior urban extent area can still increase its density to a similar level to those in the new areas. Values below 1 indicate that the population density in the new areas is lower than the population density in the prior-date urban extent, indicating that the prior urban extent area is denser and fuller than the new areas; and that growth could be the result of saturation. Figure 17 shows the distribution plots of the *saturation index* for both time periods. Both distributions are very similar and show that most of the cities have values below 1 (804 urban extents for 2000, and 809 for 2010), indicating growing by saturation in most of the LAC cities in both periods. However, about 12% of the urban extents show values above 1 in both periods, indicating not saturated growth. When comparing $Saturation_{2000}$ with $Saturation_{2010}$, we found a decreasing trend: most urban extents, about

60%, have lower values for 2010 than for 2000. This means that most of the cities are spatially growing on patches of denser areas than the urban extent area in 1996, leaving lower-density areas in the core. This finding is in agreement with Inostroza et al. (2013), which identified a trend towards increasing sprawl in some Latin American cities.

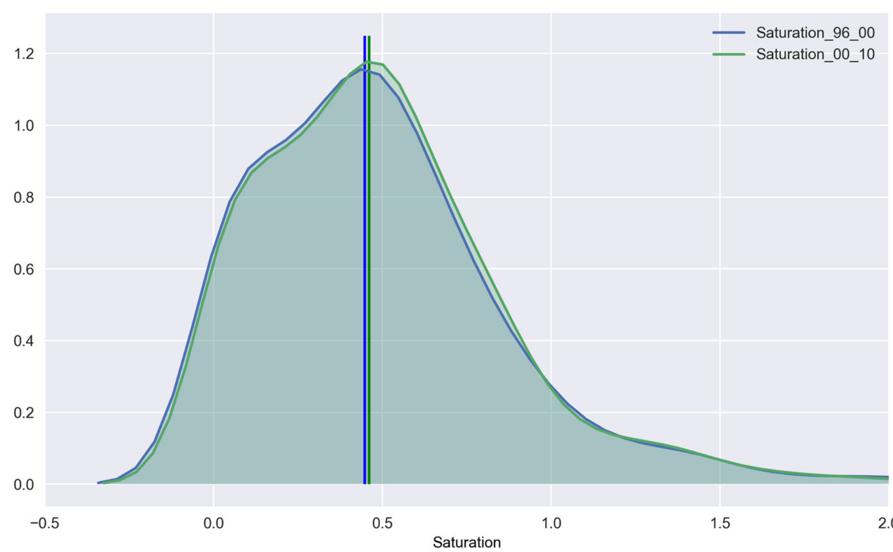


Figure 17. Kernel density plots of saturation for the periods 1996 - 2000 (96_00) and 2000 - 2010 (00_10). Vertical lines show the mean of each distribution.

6. Conclusions

Open spatial data, remote sensing imagery and automatic data retrieval systems like OSMnx, open a new horizon of possibilities of performing standardized and massive studies of urban form across cities and countries. A better, comparable and systematic study of the evolution of the form of urban extents can allow urban planners to monitor more closely the evolution of urban extents and make timely decisions on the way urban extents are evolving.

Based on the integral definition of urban form, from the urban planning literature, this paper approaches urban form as the combination of three dimensions: shape of the perimeter, urban structure and land use. Several indicators on each dimension where calculated using free data and highly automatized libraries for geometry and network analysis. Those indicators show that LAC cities are more rounded than elongated, with urban perimeters more smoothed than complex, and little open space. The street networks in LAC cities tend to be regular and dense. Using these indicators, LAC cities can be divided into four distinct clusters that range from compact and well-connected cities, to highly organic, sprawled and poorly connected cities. Cities in each cluster do not show a clear spatial pattern.

Regarding the factors that can be correlated to urban form, we found that factors such as topography and historical legacies linked to urban design (colony history) are highly correlated to urban form indicators. Organic/natural urban structures are usually located in rugged topography; and LAC cities that were Iberian colonies have more regular urban layouts and denser street networks. As found in previous literature, this study finds a positive correlation between compactness/connectivity and levels of productivity.

Finally, the spatiotemporal analysis detected some signs of urban growth over steeper terrains for the cities initially located in rugged terrain, as well as a weak trend toward less fragmented urban growth between 2000 and 2010. The cases of Bolivia and the República Bolivariana de Venezuela emerged as critical cases of urban growth over protected areas, which can jeopardize sustainable urban growth in those countries.

Future research will explore the possibility of using this input data and indicators to forecast the evolution of the urban extents, which can help urban planners and policy makers to identify in advance situations of potential exposure to natural hazards, invasion of aquifer reservoirs or other non-sustainable forms of urban growth.

7. References

Abrahams, A; Oram, C, Lozano-Gracia, N; (2018). Deblurring DSMP Nighttime Lights: A new method using Gaussian filters and frequencies of illumination. Remote Sensing of Environment. June 2018, 210, pp242-258.

Anderson, S. J., Tuttle, B. T., Powell, R. L., & Sutton, P. C. (2010). Characterizing relationships between population density and nighttime imagery for Denver, Colorado: issues of scale and representation. *International Journal of Remote Sensing*, *31*(21), 5733–5746. https://doi.org/10.1080/01431161.2010.496798

Angel, S., Parent, J., Civco, D. (2010a). The Fragmentation of Urban Footprints: Global Evidence of Urban Sprawl 1990-2000. Lincoln Institute of Land Policy Working Paper. Cambridge, MA, p. 104.

Angel, S; Parent, J; Civco, DL (2010b). Ten compactness properties of circles: Measuring shape in geography. Canadian Geographer, 54(4): 441–461. https://doi.org/10.1111/j.1541-0064.2009.00304.x

Antrop, M., 2004. Landscape change and the urbanization process in Europe. Landscape Urban Planning, 37 (1–4), 9–26.

Barredo, J., Demicheli, L., Lavalle, C., Kasanko, M.,McCormick, N., 2004. Modelling future urban scenarios in developing countries: an application case study in Lagos, Nigeria. Environ. Plan. B: Plan. Design 32, 65–84. Batty, M; Longley, P (1994). Fractal Cities: A Geometry of Form and Function Academic Press, London.

Batty, M (2008). The Size, Scale, and Shape of Cities. Science 319, 769

Batty, M; Longley, P (1994). Fractal Cities: A Geometry of Form and Function Academic Press, London.

Boeing, G (2017). OSMnx: New Methods for Acquiring, Constructing, Analyzing, and Visualizing Complex Street Networks. Available at SSRN: https://ssrn.com/abstract=2865501

Breheny, M., 1992. Sustainable development and urban form. Pion, London.

Burchfield M, Overman H, Puga D, Turner M (2006) Causes of sprawl: A portrait from space. *Quarterly Journal of Economics* 121: 587–633

Cao, Z., Wu, Z., Kuang, Y., Huang, N., & Wang, M. (2016). Coupling an intercalibration of radiance-calibrated nighttime light images and land use/cover data for modeling and analyzing the distribution of GDP in Guangdong, China. *Sustainability (Switzerland)*, *8*(2). https://doi.org/10.3390/su8020108

Cervero, R, Kockelman, K. (1997). Travel demand and the 3Ds: Density, Design and Diversity. *Transportation Research. Part D Transp. Environ*., 2(3):199–219.

Cervero, R (2001). Efficient Urbanisation: Economic Performance and the Shape of the Metropolis. *Urban Studies*, 38(10):1651-1671.

Champion, A.G., 1992. Urban and regional demographic trends in the developed world. Urban Stud. 29 (3/4), 461–482.

Cheng, Y., Zhao, L., Wan, W., Li, L., Yu, T., & Gu, X. (2016). Extracting urban areas in China using DMSP/OLS nighttime light data integrated with biophysical composition information. *Journal of Geographical Sciences*, *26*(3), 325–338. https://doi.org/10.1007/s11442-016-1271-6

Cheshire, P., 1995. A new phase of urban development in Western Europe? The evidence for the 1980s. Urban Stud. 32 (7), 1045–1063.

CEC, 1992. Commission of the European Communities. DG Regional Policy. Urbanisation and the Functions of Cities in the European Communities. European Institute of Urban Affairs. Liverpool John Moores University, Brussels/Luxembourg.

Ciccone A; Hall RE (1996). Productivity and the density of economic activity. *American Economic Review*, 86: 54–70.

de Roo, G. and Miller, D. (2000) Compact Cities and Sustainable Urban Development: a critical assessment of policies and plans from an international perspective, Aldershot: Ashgate.

Deng, F.F., Huang, Y., 2004. Uneven land reform and urban sprawl in China: the case of Beijing. Prog. Plan. 61, 211–236.

Duque, J. C., Lozano-Gracia, Patino, J. E., and Restrepo, P. 2017a. Urban form and productivity: in what shape are Latin American cities? LCR Flagship Report on Cities and Productivity. World Bank (*forthcoming*).

Duque, J. C., Lozano-Gracia, Patino, J. E., and Restrepo, P. 2017b. Institutional fragmentation and metropolitan coordination in Latin-American cities: What consequences for productivity and growth? LCR Flagship Report on Cities and Productivity. World Bank (*forthcoming*).

Ewing, R., Pendall, R., Chen, D., 2002. Measuring Sprawl and its Impact. Smart Growth America, Washington, DC.

Fallah, B; Partridge, M; Olfert, M (2011). Urban sprawl and productivity: Evidence from US metropolitan areas, Papers in Regional Science, 90(3): 451-473.

Filion, P., 2001. Suburban mixed-use centres and urban dispersion: what difference do they make? Environ. Plan. A 33, 141–160.

Forbes, D. J. (2013). Multi-scale analysis of the relationship between economic statistics and DMSP- OLS night light images. *GIScience & Remote Sensing*, *50*(5), 483–499. https://doi.org/10.1080/15481603.2013.823732

Freire, S; Pesaresi, M (2015): GHS population grid, derived from GPW4, multitemporal (1975, 1990, 2000, 2015). European Commission, Joint Research Centre (JRC) [Dataset] PID: http://data.europa.eu/89h/jrc-ghsl-ghs_pop_gpw4_globe_r2015a.

Gascoigne, Bamber. (2001) "History of Latin America" HistoryWorld. From 2001, ongoing. http://www.historyworld.net/wrldhis/PlainTextHistories.asp?groupid=850&HistoryID=aa87&gtrack=pthc (retrieved 2017-06-12).

Gencer, E. A. (2013). Natural Disasters, Urban Vulnerability, and Risk Management: A Theoretical Overview. In The Interplay between Urban Development, Vulnerability, and Risk Management. Volume 7 of the series SpringerBriefs in Environment, Security, Development and Peace (pp. 7-43). New York, NY: Springer Berlin Heidelberg.

Glaeser EL (1998) Are cities dying? *Journal of Economic Perspectives* 12: 139–160

Hasse, J. E. and Lathrop, R. G. (2003) Land resource impact indicators of urban sprawl, Applied Geography, *23*, 159–175.

Hsu, F. C., Baugh, K. E., Ghosh, T., Zhizhin, M., & Elvidge, C. D. (2015). DMSP-OLS radiance calibrated nighttime lights time series with intercalibration. *Remote Sensing*, *7*(2), 1855–1876. https://doi.org/10.3390/rs70201855

Huang, J., Lu, X. X., & Sellers, J. M. (2007). A global comparative analysis of urban form: Applying spatial metrics and remote sensing. *Landscape and Urban Planning*, *82*(4), 184–197. https://doi.org/10.1016/j.landurbplan.2007.02.010

Inostroza, L; Baur, R; Csaplovics, E (2013). Urban sprawl and fragmentation in Latin America: A dynamic quantification and characterization of spatial patterns. Journal of Environmental Management, 115: 87-97

Jaffe A, Trajtenberg M, Henderson R (1993) Geographic localization of knowledge spillovers as evidenced by patent citations. *Quarterly Journal of Economics* 108: 577–598

Kasanko, M; Barredo, JI; Lavalle, C; McCormick, N; Demicheli, L; Sagris, V; Brezger, A (2006). Are European cities becoming dispersed? A comparative analysis of 15 European urban áreas. Landscape and Urban Planning, 77:111–130

Li, C., & Lian, L. (2012). Theoretical Research of the Urban Comprehensive Carrying Capacity in the Epoch of Urbanization. International Journal of Financial Research, 3(1), 105–113. https://doi.org/10.5430/ijfr.v3n1p105

Lin, G.C.S., 2002. The growth and structural change of Chinese cities: a contextual and geographic analysis. Cities 19 (5), 299–316.

Lo, C. P. (2001). Modeling the Population of China Using DMSP Operational Linescan System Nighttime Data. *Photogrammetric Engineering and Remote Sensing*, *67*(9), 1037–1047.

Lopez, E., Bocco, G., Mendosa, M., Duhau, E., 2001. Predicting land-cover and land-use change in the urban fringe. A case in Morelia city, Mexico. Landscape Urban Plan. 55 (4), 271–285.

Lynch, K (1981) *A theory of good city form*. MIT Press, Cambridge, MA

Ma, L., Wu, J., Li, W., Peng, J., & Liu, H. (2014). Evaluating saturation correction methods for DMSP/OLS nighttime light data: A case study from China's cities. *Remote Sensing*, *6*(10), 9853–9872. https://doi.org/10.3390/rs6109853

Pandey, B., Joshi, P. K., & Seto, K. C. (2013). Monitoring urbanization dynamics in India using DMSP/OLS night time lights and SPOT-VGT data. *International Journal of Applied Earth Observation and Geoinformation*, *23*, 49–61. https://doi.org/10.1016/j.jag.2012.11.005

Parr, J.B. (1979). "Regional economic change and regional spatial structure: some interrelationships", Environment and Planning A 11(7), 825 – 837.

Pesaresi, Martino; Ehrilch, Daniele; Florczyk, Aneta J.; Freire, Sergio; Julea, Andreea; Kemper, Thomas; Soille, Pierre; Syrris, Vasileios (2015): GHS built-up grid, derived from Landsat, multitemporal (1975, 1990, 2000, 2014). European Commission, Joint Research Centre (JRC) [Dataset] PID: http://data.europa.eu/89h/jrc-ghsl-ghs_built_ldsmt_globe_r2015b

Pesaresi, M; Ehrlich, D; Ferri, S; Florczyk, A.J; Freire, S; Halkia, M; Syrris, V (2016). Operating procedure for the production of the Global Human Settlement Layer from Landsat data of the epochs 1975, 1990, 2000, and 2014; JRC Technical Report EUR 27741 EN. Ispra (VA), Italy. https://doi.org/10.2788/253582

Prosperi, D., Moudon, A. V., & Claessens, F. (2009). The Question of Metropolitan Form: Introduction. *Footprint*, *3*(2), 1-4.

Rosenthal, SS; Strange, WC (2004). Evidence on the nature and sources of agglomeration economies, in J.V. Henderson and J.-F. Thisse, eds., Handbook of Urban and Regional Economics, Volume 4, New York: North Holland, 2119-2171.

Schwarz, N (2010). Urban form revisited—Selecting indicators for characterising European cities. Landscape and Urban Planning, 96:29–47

Sorensen, A., 2000. Land readjustment and metropolitan growth: an examination of suburban land development and urban sprawl in the Tokyo metropolitan area. Prog. Plan. 53 (4), 217–330.

Squires, G.D. (2002). Sprawl: Causes and Consequences and Policy Responses. The Urban Institute Press, Washington, D.C.

Sutton, P. C., Cova, T. J., & Elvidge, C. D. (2006). Mapping ``Exurbia'' in the conterminous United States using nighttime satellite imagery. *Geocarto International*, *21*(2), 39–45. https://doi.org/10.1080/10106040608542382

Sutton, K., Fahmi,W., 2001. Cairo's urban growth and strategic master plan in the light of Egypt's

1996 population census results. Cities 18 (3), 135–149.

The World Bank (2017) World Development Indicators 2017. Available at: http://data.worldbank.org/data-catalog/world-development-indicators

Tsai, Y.H., 2005. Quantifying Urban Form: Compactness Versus 'Sprawl'. Urban Stud. 42 (1), 141–161.

UN-Habitat. (2012). *State of Latin American and Caribbean Cities 2012, Towards a new urban transition*. Naples: UN-Habitat.

United Nations, Department of Economic and Social Affairs, Population Division (2014). World Urbanization Prospects: The 2014 Revision, Highlights (ST/ESA/SER.A/352).

UNEP-WCMC (2016). World Database on Protected Areas User Manual 1.4. UNEP-WCMC: Cambridge, UK. Available at: http://wcmc.io/WDPA_Manual

Wheeler CH (2001) Search, sorting, and urban agglomeration. *Journal of Labour Economics* 19: 879–899

Whyte, W (1968). The Last Landscape, Garden City, NY: Doubleday.

Wu, J., Ma, L., Li, W., Peng, J., & Liu, H. (2014). Dynamics of urban density in china: Estimations based on DMSP/OLS nighttime light data. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, *7*(10), 4266–4275. https://doi.org/10.1109/JSTARS.2014.2367131

Zhang, Q., & Seto, K. C. (2011). Mapping urbanization dynamics at regional and global scales using multi-temporal DMSP/OLS nighttime light data. *Remote Sensing of Environment*, *115*(9), 2320–2329. https://doi.org/10.1016/j.rse.2011.04.032

Zhou, N., Hubacek, K., & Roberts, M. (2015a). Analysis of spatial patterns of urban growth across South Asia using DMSP-OLS nighttime lights data. *Applied Geography*, *63*, 292–303. https://doi.org/10.1016/j.apgeog.2015.06.016

Zhou, Y., Smith, S. J., Zhao, K., Imhoff, M., Thomson, A., Bond-Lamberty, B., … Elvidge, C. D. (2015b). A global map of urban extent from nightlights. *Environmental Research Letters*, *10*(5), 54011. https://doi.org/10.1088/1748-9326/10/5/054011