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Research Paper

Spatiotemporal dynamics of urban growth in Latin American cities: An analysis using nighttime light imagery

Juan C. Duque[a,*], Nancy Lozano-Gracia[b], Jorge E. Patino[a], Paula Restrepo[b], Wilson A. Velasquez[a]

[a] Research in Spatial Economics (RiSE-group), Department of Mathematical Sciences, Universidad EAFIT, Medellin, Colombia
[b] Social, Urban, Rural and Resilience, The World Bank. Washington, USA

ABSTRACT

The impact of urban form on economic performance and quality of life has been widely recognized. Studies regarding urban form have focused on developed countries; only a small number of cities in developing countries have been studied. This paper utilizes nighttime light imagery and information regarding 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. We study the relationship between the urban form metrics and several factors that can correlate with urban form (topography, size, colony, and economic performance) and perform a spatiotemporal analysis of urban growth from 1996 to 2010. Among the results, we highlight the tendency of a group of cities to grow on steeper slopes and several worrying aspects, specifically urban growth in protected areas and a trend to sprawl-growing in certain Latin American and Caribbean cities.

1. Introduction

In 2007, the global urban population exceeded the global rural population, and UN projects that the number of urban dwellers will be twice the number of rural dwellers by 2050 (United Nations, 2014). Latin America and the Caribbean (LAC) is the second most urbanized region on the planet, with 81% of its population living in cities (United Nations, 2018). 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), and they are still spatially growing despite the deceleration in population growth (UN-Habitat, 2012). In many cases, the high urbanization rates in the region overcame the capacity of local authorities to deliver services and infrastructure to the new urban areas, causing the appearance of substandard urban areas. Urban form has an important influence on the emergence of agglomeration economies and congestion costs (Squires, 2002), in addition to influencing public health (Coppel & Wüstemann, 2017; Xu & Gao, 2017), quality of life (Squires, 2002; Wissen Hayek et al., 2015), and environmental sustainability (Panagopoulos, González Duque, & Bostenaru Dan, 2016). Agglomeration economies are strongly associated with intraurban connectivity levels, the level of compactness, and land use patterns (Cervero, 2001; Ciccone & Hall, 1996; Rosenthal & Strange, 2004). Furthermore, different types of urban growth are thought to affect the urban fabric features that foster economic performance, sustainability, and quality of life. These growth types are infill growth and spatial growth either by edge expansion or by outlying expansion (Duwal, Amer, & Kuffer, 2019; Liu et al., 2010; Shi, Sun, Zhu, Li, & Mei, 2012).

However, there is a lack of empirical studies looking at urban form in LAC cities and their evolution over time. Many Latin American cities are located in rugged topographies with natural barriers limiting urban development; some of the urbanization in the region is occurring over steep terrain (e.g., Medellin, Colombia) (Parés-Ramos, Álvarez-Berríos, & Aide, 2013). There are cities located in the lower lands in flat areas, where growth is only constrained by the presence of large rivers or lakes (e.g., Manaus, Brazil), and other cities grew along the Caribbean and Pacific coasts and matched the shape of the coastlines (e.g., Antofagasta, Chile). According to Gencer (2013), high levels of population concentration in urban areas increase the likelihood of having disasters, and most of the cities exposed to at least one natural hazard are located in Asia and in Latin America. In some instances, urbanization occurs at the cost of occupying adjacent protected areas, jeopardizing biodiversity and environmental sustainability. Regarding urbanized area, the LAC region accounts for a 0.4% of its land, a much lower value than Europe (2.3%) and the US (1.2%), somewhat closer to Asia (0.7%), but higher than the former Soviet Union region (0.2%) and Oceania (0.1%) (Zhou, Smith, et al., 2015). Compared to other regions of the world, LAC cities have higher population densities than cities in Europe and in the US, have greater regularity and less open space (Angel, Parent, & Civco, 2010a; Huang, Lu, & Sellers, 2007). However, Inostroza, Baur,

* Corresponding author.
E-mail addresses: jduquec1@eafit.edu.co (J.C. Duque), nlozano@worldbank.org (N. Lozano-Gracia), jpatinoq@eafit.edu.co (J.E. Patino), prestrepocadavid@worldbank.org (P. Restrepo), wavelasquezh@unal.edu.co (W.A. Velasquez).

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and Csaplovics (2013) reported a general trend towards lower-density growth in some of the largest LAC cities. Hence the importance of analyzing this trend and knowing whether LAC cities are making an efficient use of land by infill development before expanding the urbanized land.

Rapid urbanization combined with limited infrastructure investments may have also led to urban form features that pose a barrier to the rise of agglomeration economies, firm interaction, and worsen the spatial mismatch. A better understanding of the dynamics of urban form in the LAC region is an important contribution to the achievement of sustainable development goal (SDG) 11, "Make cities and human settlements inclusive, safe, resilient and sustainable," since it 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.

The main objective of this work is to reduce the gap in empirical studies about urban form in Latin American and Caribbean cities, analyzing a wide sample of cities in three different points in time using standardized data and methods. The second objective is to contribute to the discussion between urban form and sustainable development by analyzing urban form using a comprehensive definition that goes beyond the traditional debate between compact and sprawling cities. In this paper, we use nighttime lights radiance-calibrated annual image composites of 1996, 2000 and 2010 to provide a standardized characterization of the urban form of 919 Latin American cities that had more than 50,000 people in 2010. We perform 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 presents the descriptive analyses of the set of LAC cities, the differences across countries, and the interplay with the factors that affect urban form. Section 5 reports the spatiotemporal analysis of urban growth in the region, and Section 6 presents the conclusions of this work.

2. Literature review

The importance of urban form has been extensively recognized in the urban economics literature. Citie's form affects their economic performance (Parr, 1979), sustainability levels (Breheny, 1992; de Roo & Miller, 2000), quality of life (Squires, 2002), costs of commuting (Wheeler, 2001) and costs of transporting intermediate goods (Ciccone & Hall, 1996), knowledge spillovers through human interactions (Glaeser, 1998; Jaffe, Trajtenberg, & Henderson, 1993; Lynch, 1981), and matching between firms and workers (Cervero, 2001; Ciccone & Hall, 1996; Rosenthal & Strange, 2004). All of these aspects together make urban form a key factor for urban policy.

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

Developing countries have been studied to a lesser extent. Earlier work in these countries focuses on modelling urban growth scenarios for one city, quantifying land cover and land use change, and revisiting urban master plans in the light of their analyses (Barredo, Demicheli, Lavalle, Kasanko, & McCormick, 2004; Lopez, Bocco, Mendosa, & Duhau, 2001; Sutton & Fahmi, 2001). To the best of our knowledge, there are four cross-country studies that include LAC cities in their sample: Huang et al. (2007) study 17 Latin American cities that are part of a total sample of 77 metropolitan areas from Asia, US, Europe, and Australia. Using a semiautomatic 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. Also using satellite images, the authors calculate four urban fragmentation metrics: edge index, openness index, core open space ratio, and city footprint ratio. Parés-Ramos et al. (2013) use nighttime satellite imagery and Google Earth to map the urbanization dynamics of the major cities of Colombia, Ecuador, Peru and Bolivia. They find three dominant urban development patterns: high-density compact in Bogotá, Cali, and Medellin (Colombia), and Guayaquil (Ecuador); high-density expansive growth in La Paz/El Alto (Bolivia); low-density expansive in Quito (Ecuador) and Santa Cruz (Bolivia); and a mixture of high-density compact and suburban growth in Lima (Peru). They also state that urban density in Colombia is among the highest in the world. 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 (of land consumption per year). We reviewed the urban form metrics in these studies and used some of them in our analysis. The common finding in these studies is that Latin American cities are more compact and denser than their counterparts in either Europe or North America. This is because cities from developed regions in general feature higher levels of sprawl than those found in Asia or Latin America (Huang et al., 2007).

In our paper, we contribute to the literature about urban form in three aspects: firstly, we combine the use of nighttime lights imagery for urban extent delineation with recently developed software for computational geometry and network topology (Angel, Parent, & Civco, 2010b; Boeing, 2017) in a highly automated procedure that makes it possible to analyze 919 urban extents in Latin America and the Caribbean. Therefore, this work is the most comprehensive study of urban form for this region. Secondly, the indicators used to describe urban form are tightly connected to the definition of urban form from the urban planning literature, which describes urban form as a combination of external shape and internal structure (Whyte, 1968). This definition allows us to go beyond the classic debate of sprawl vs. compact, to cover other important aspects of urban form. In this paper, we measure urban form including three dimensions: shape of the urban extent, internal urban structure, and land occupation pattern (Batty, 2008; Prosperi, Moudon, & Claessens, 2009). In this way, we can analyze the interplay between these dimensions to provide better recommendations for policy makers beyond the compact/sprawl disjunctive. Finally, we explore the relationships between urban form and factors such as topography, city size, economic strength (measured with nighttime lights imagery), and legacy of colonial urban planning.

3. Methods

3.1. Use of nighttime light data for urban extents delineation

The nighttime light data are based on nighttime imagery recorded by the Defense Meteorological Satellite Programs - Operational Linescan System (DMSP-OLS); they report the recorded intensity of Earth's surface lights. Nighttime lights data products have high correlation with human activities (Hsu, Baugh, Ghosh, Zhizhin, & Elvidge, 2015) and have been previously used for regional and global analyses of urbanization (Cheng et al., 2016; Pandey, Joshi, & Seto, 2013; Sutton, Cova, & Elvidge, 2006; Zhang & Seto, 2011; Zhou, Hubacek & Roberts, 2015; Zhou, Smith, et al., 2015), population modelling (Anderson, Tuttle, Powell, & Sutton, 2010; Lo, 2001), and economic performance (Cao, Wu, Kuang, Huang, & Wang, 2016; Forbes, 2013).

There are two different nighttime light data 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 saturation (Hsu et al., 2015), which is likely to be present in most of the largest cities in the region. Furthermore, previous work has suggested that the RC products provide better proxies for socioeconomic variables than the stable products (Hsu et al., 2015; Ma, Wu, Li, Peng, & Liu, 2014). The radiance-calibrated annual composites for 1996, 2000 and 2010 obtained from NOAA National Centers for Environmental Information were used to delineate urban extents. These composites have a spatial resolution of 30 arc-seconds (approximately 1 km at the Equator).

Another technical challenge with the DMSP-OLS products is the "overglow" effect, which creates a dim lighting in surrounding areas of cities due to scattering of light in the atmosphere (Wu, Ma, Li, Peng, & Liu, 2014). A novel deblurring process was applied to address the issue of overglow in the radiance-calibrated products (Abrahams, Oram, & Lozano-Gracia, 2018). This method deblurs the images using a sequence of two filters. First, a standard Wiener Deconvolution is used to invert the blurring process, assuming light was blurred via a symmetric Gaussian point-spread function (PSF). The second filter is informed by the re-creation of the satellite's step-by-step on-board data collection and data storage process, which suggest that the pixel at which a light source is located will always be a local maximum in the pct image.[1] Hence, the second filter described by Abrahams et al. (2018) sets to zero all pixels that are not local maxima in the pct image. In their work, Abrahams et al. (2018) apply this filter to outline urban extents of 15 cities across regions and geographies. Their results suggest that their two-part sequence filter provides roughly a 5.5-fold improvement over NOAA's stable lights filtered images, and a 9-fold improvement over the blurred images in terms of delineation of urban areas.

3.1.1. Calibration and interannual correction of deblurred RC data

We used the deblurred DSMP-OLS RC yearly composites for the years 1996, 2000 and 2010 to delineate urban extents in Latin America. DMSP-OLS RC NTL from different years can't be compared because of the lack of sensor's on-board calibration (Cao et al., 2016; Hsu et al., 2015; Pandey et al., 2013; Zhang & Seto, 2011). An empirical intercalibration was performed to enable the comparison of these images. We followed Hsu et al. (2015) and used the same area as reference: Los Angeles metropolitan area. This area was selected for two reasons: firstly, it has been a mature metropolis for a long time and hence its light change is negligible; secondly, because of its size and the large variability of light intensity within its extent, it provides samples of high DN values in the city center, as well as low DN values in suburban areas. We used the 2000 image as reference and estimated linear and second-order regression models. The second-order models showed only negligible improvements compared to the linear models, which were preferred because of their simplicity (see Table 1).

Table 1
Intercalibration linear models.

Year	Slope	Intercept	R^2	Sample (pixels)
1996	0.83744	21.6868	0.663	26,208
2000	1.000	0.0000	1.000	26,208
2010	0.835163	32.0772	0.589	26,208

We set the intercept as 0 in the calibration models to ensure that all the background areas have the same zero value in the three images. While the calibration solves the comparison issue, there are additional inconsistences in lit pixels among the three dates that needed to be addressed. These inconsistences are seen as lit pixels that change to unlit pixels in the next date image at the same geographic location, and as abnormal fluctuations in pixel values across dates (Cao et al., 2016). We applied the inter-annual series correction proposed by (Cao et al., 2016) to ensure that the lit pixels detected in an image do not disappear in a later date, and that the lit pixel DN values for each date are not smaller than the pixel DN value at the same location of a previous date. The inter-annual correction model after intercalibration is composed of two rules: (1) when a pixel DN value is equal to zero in an image, that pixel DN value for the previous date at the same geographic location should also be equal to zero, and (2) when a pixel DN value is not equal to zero in an image, the pixel DN value must be greater than the DN value of the lit pixel in the same geographic location in the previous date. This correction model is described in equation (1).

$$DN_{(n,\ i)} = \begin{cases} 0, & DN(n+1,\ n) = 0 \\ DN(n-1,\ i), & DN(n+1,\ i) > 0 \ and \ DN(n-1, \\ & i) > DN(n,\ i) \\ DN(n,\ i), & \text{otherwise} \end{cases} \quad (1)$$

were $DN_{(n\text{-}1,\ i)}$, $DN_{(n\ i)}$, *and* $DN_{(n+1.\ i)}$ are the DN values of the *i*-th lit pixel in the deblurred RC NTL image after intercalibration in the *(n-1)*-th, the *n*-th, and *(n + 1)*-th years, respectively. And *n* = 1996, 2000, and 2010.

3.1.2. Urban extent delineation

We used the inter-annual corrected deblurred DMSP-OLS NTL RC images to outline urban extents in Latin America and the Caribbean (Fig. 1). We applied a DN threshold to define what is considered an urban area in the NTL imagery. Threshold-based methods have been extensively used to extract urban areas from NTL data (Ellis & Roberts, 2015; Harari, 2016; Li & Zhou, 2017; Pandey et al., 2013; Sutton, Goetz, Fildes, Forster, & Ghosh, 2010; Zhang & Seto, 2011). The central premise in this method is that urban areas are generally a concentration of people and income, and therefore, there is a DN value (a threshold) that can be used to define and delineate urban areas from nighttime imagery (Tewari, Alder, & Roberts, 2016). The threshold was chosen after a careful evaluation of the longitudinal profiles for the year 2000 using a sample of LAC cities; as an additional check, the extents were compared to the Built-up Global Human Settlements Layer (GHS) for the same year at 250 m of spatial resolution (Freire & Pesaresi, 2015). For this work we found a threshold of DN equal to 110 (unitless) in the processed RC images (i.e., after deblurring, and interannual calibration and correction). Because the GHS built-up layer uses Landsat images as input and does not consider at any point layers of nighttime lights, we feel confident of using it as an independent data source to set the threshold. Fig. 2 shows five examples of the extracted urban extents and the built-up layer used as reference.

We applied the threshold and obtained binary images of urban extents in LAC. The three images were converted to vector format to create the polygons that outline the extent of cities. Further, we applied a buffer of 10 m to the outlined polygons to encompass all the image cells that belonged to the same urban area, even when they were connected only by pixel corners. As a city can have more than one continuous patch on-ground, we decided to keep only the larger patch for this analysis. We used the LandScan 2012 data set (Bright, Rose, & Urban, 2013) as reference to identify and extract the urban extents with more than 50,000 people in 2010. We obtained 940 urban extents with more than 50,000 people in Latin America for the year 2010 and extracted the urban extents for the same locations from the processed NTL images of the years 1996 and 2000. According to (Chuvieco, 2016), an object must be several times larger than the pixel size to be delineated properly from a remote sensing image. Since the pixel size of the DMSP-OLS NTL RC images is 30 arc seconds (almost 1 by 1 Km near the Equator), we feel justified to exclude those urban extents that were

[1] The "pct image" refers to the image that records the percentage of cloud-free nights on which each pixel was observed to be lit ("pct.tif"), and that accompanies every blurred DMSP avg_vis image; both these files are freely available for each satellite-year from the NOAA's website.

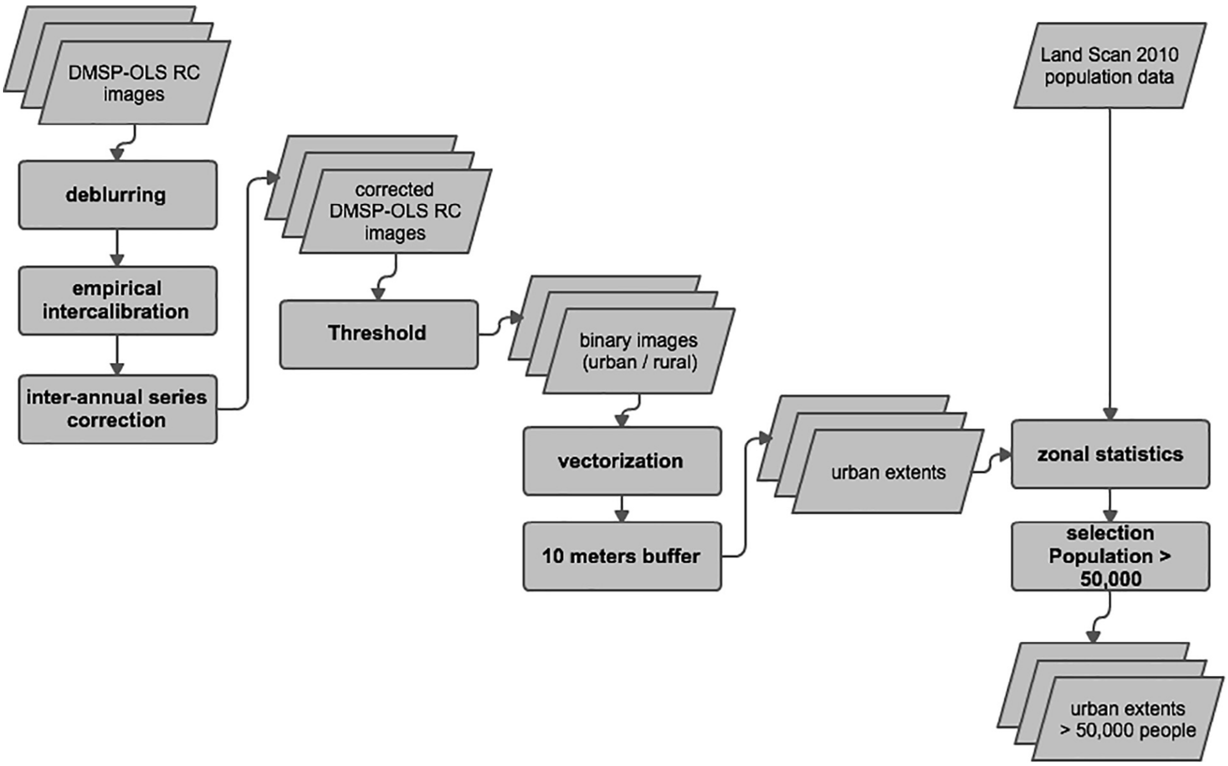

Fig. 1. Workflow for urban extent delineation from deblurred and corrected NTL RC imagery.

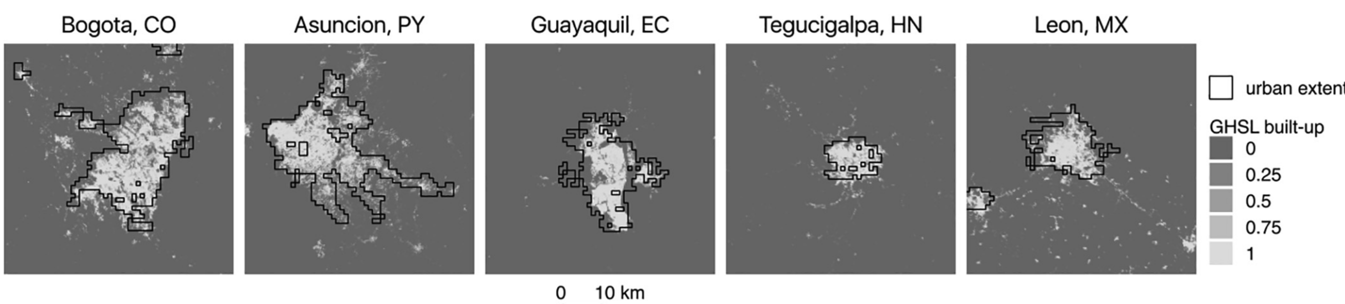

Fig. 2. Examples of urban extents extracted from the 2000 NTL image over the reference 2000 GHS Built-up layer.

smaller than 3 Km^2 in 1996. That resulting final sample therefore includes 919 urban extents in each year. Some of these urban extents correspond on-ground with urban agglomerations, including more than one city as defined by the cities' administrative boundaries.

3.2. Measuring urban form

There is a strong interest in urban form across multiple academic disciplines, and the specific questions of these disciplines often dictates the type of the analysis and the data source (Clifton, Ewing, Knaap, & Song, 2008). Some have focused on the neighborhood scale using a wide set of metrics and then reducing them using factor analysis (Song, Popkin, & Gordon-Larsen, 2013), while others implemented different sets of metrics to analyze cities and metropolitan areas (Schwarz, 2010; Song & Knaap, 2004; Tsai, 2005). In this work, we implemented a set of seven metrics to measure the urban form at the urban agglomeration scale. We adopt an integral definition of urban form from the urban planning and geography 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 about the following three dimensions: shape of the border, urban texture, and land occupation 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 use a series of seven indicators that intent to cover these three dimensions (Table 2).

3.2.1. Shape of the border

According to Angel et al. (2010b), the geometric characterization of a shape includes three aspects: degree of roundness, smoothness of the perimeter, and fullness. The first two help to characterize the shape of the border, whereas the third is useful to characterize the land

Table 2
Urban form metrics used in this study.

Dimension	Metric	Reference
Shape of the border	Roundness index Smoothness index	Angel et al., 2010b
Urban texture (connectivity)	Circuity index Intersection density Street density	Boeing, 2017
Land occupation pattern	Sprawl index Fullness index	Fallah et al., 2011 Angel et al., 2010b

occupation pattern.

- *Roundness index.*

Using a circle as the perfect benchmark shape, the roundness index measures the degree of roundness, as the degree by 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). A roundness index equal to 1 corresponds to a circle. As the roundness index moves towards 0, the shape of the polygon becomes irregular, elongated, and noncompact.

- *Smoothness index.*

The smoothness of the perimeter is measured with the smoothness index. It is calculated as the ratio of the perimeter of the equal-area circle to the perimeter of the shape (Angel et al., 2010b). A smoothness index equal to 1 indicates a totally smooth perimeter, found in a circle. A smoothness index close to 0 indicates a highly irregular perimeter, which is very common in natural/organic cities located in rugged topography.

3.2.2. Urban texture

Next, we study urban texture using descriptors of a city structure related to the street network: firstly, the structure given by the layout of the road network (named circuity), and secondly, the connectedness of its segments. We measure urban structure with the circuity index. Regarding the connectivity, we applied the two most popular metrics for assessing connectivity: intersection density and street density.

- *Circuity index*

This metric takes values close to 1 when the streets in the network are mostly straight lines and values greater than 1 when the streets are curvier and more organic. This metric is calculated as the average ratio between the length of a segment and the straight-line distance between the two nodes it links (Boeing, 2017).

- *Intersection density*

Intersection density is calculated as the number of nodes divided by the area of the urban extent, considering only the set of nodes with more than one street connected to them, thus including only street intersections and excluding dead ends (Boeing, 2017).

- *Street density*

Street density is calculated as the sum of all segments of the street network in the undirected representation of the graph (in km) divided by the area in km^2 (Boeing, 2017). The segments are defined by their starting and ending nodes from the street network, and they are defined using the same data source (the OpenStreetMap street network) and the same process for every urban extent (with the OSMnx Python library). Both metrics, intersection and street density, inform about the ease of movement across the city (Boeing, 2017). High values of these two measures are associated with high rates of walking and use of non-motorized transport modes (Cervero & Kockelman, 1997). These metrics were used recently, along with other metrics, in the analysis of 27,000 urban areas in the United States at different scales (Boeing, 2018). A general finding of that analysis is that the planning, and design paradigms, transportation technologies, topography, and economics, influenced the street networks arrangement and appearance observed today, and the results of the descriptive analysis shows how the street networks change from place to place across the US.

3.2.3. Land occupation pattern

Finally, to measure the land use pattern, we use two metrics: sprawl and fullness.

- *Sprawl index*

The sprawl index (Fallah, Partridge, & Olfert, 2011) 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 the pixel level retrieved from GHSL population raster layers for 1990, 2000 and 2015 at a spatial resolution of 250 m (Freire & Pesaresi, 2015; Pesaresi, Ehrlich, Ferri, Florczyk, Freire, Halkia, & Syrris, 2016) within the urban extents extracted from DMSP-OLS NTL RC images.

- *Fullness index*

The level of fullness is quantified with the fullness index (Angel et al., 2010b), 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, Overman, Puga, & Turner, 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 a spatial resolution of 250 m for 1990, 2000 and 2014 (Pesaresi et al., 2016; Pesaresi, Ehrilch, Florczyk, Freire, & Julea, 2015).[2]

We used a Python script that runs in ArcGIS known as the "Shape Metrics Toolbox" to calculate two of the three the shape metrics of the urban extents (using the nExchange index as the roundness index, and the nPerimeter index as the smoothness index). The intellectual property of this software belongs to the Center for Land Use Education and Research (CLEAR) at the University of Connecticut[3]. The OSMnx Python library was used to compute three network topology variables (circuity index, intersection density, and street density) (Boeing, 2017, 2018). This library uses OpenStreetMap to retrieve the street networks within a given polygon and calculates a series of network-based metrics. Fig. 3 presents examples of urban areas with high, medium and low values for these seven variables that describe urban form, and Fig. 4 shows the Spearman's rank-order correlation coefficients among the implemented metrics of urban form with the data from 2010. There is a strong positive correlation between the roundness index and the smoothness index, which describe the shape of the perimeter of the urban extent, and between intersection density and street density, both of which measure connectivity within the urban extent. The fullness index and sprawl index exhibit a strong negative correlation. Circuity exhibits low to moderate correlation coefficients with the rest of variables, indicating that it captures a different aspect of the urban form and complements the information provided by the other metrics.

[2] We left the urban extent polygons as they resulted from the urban extent delineation process. Which means that there are some polygons with holes. The presence of those holes within the urban extents could add some bias to the fullness index, making the figures a bit higher than if those holes were treated as developed areas within the cities.

[3] http://clear.uconn.edu/tools/Shape_Metrics/index.htm.

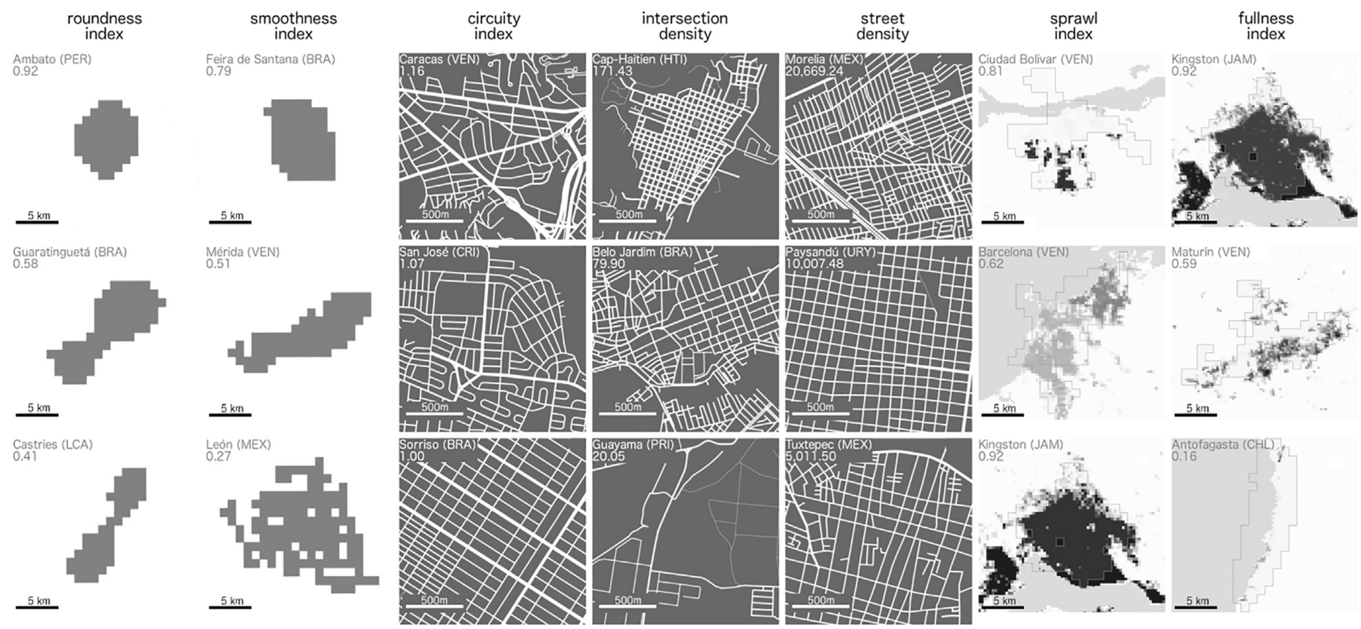

Fig. 3. Examples of urban areas with high (top), medium (middle), and low (bottom) values of urban form metrics.

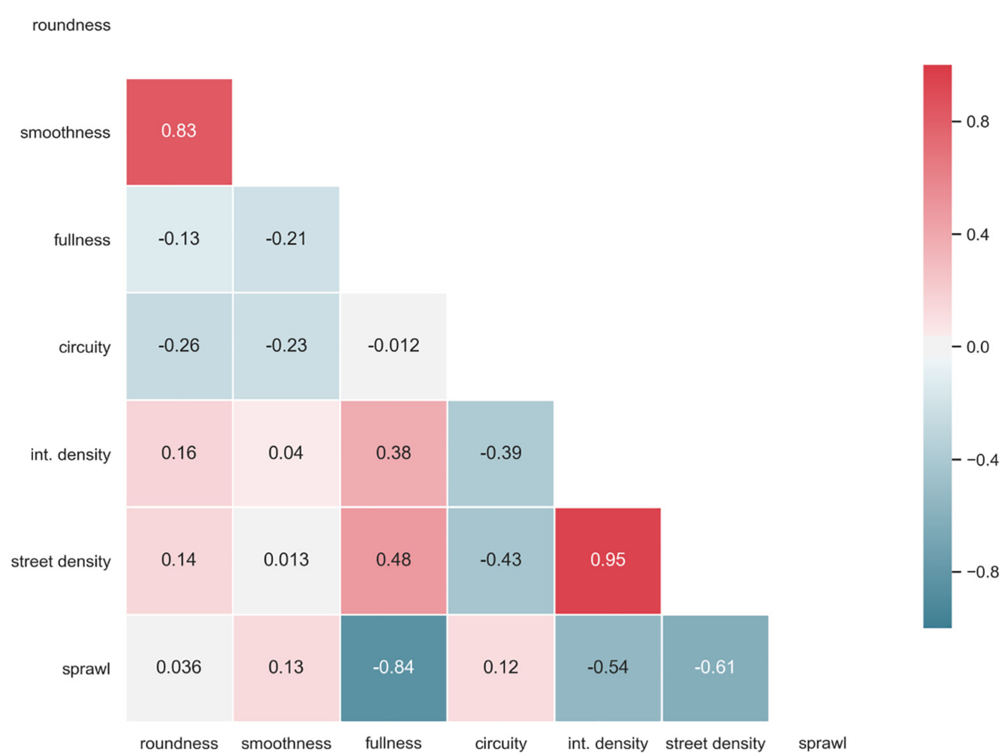

Fig. 4. Correlation matrix (Spearman's rank-order correlation coefficients) among metrics of urban form (2010 data).

3.3. Factors that can affect urban form

A review of the literature on urban form across disciplines, suggests four factors that may determine the manner in which a city grows:

- Topography: The natural constraints on urbanization play an important role in defining urban form and structure (Herold, Goldstein, & Clarke, 2003). Cities with rugged topographies located in the mountains should exhibit more-organic street networks and a less smooth perimeter than those with flat topographies (Batty & Longley, 1994; Batty, 2008).
- Size of the city: According to Harari (2016), exogenous changes in city form over time can result from encountering topographic obstacles along its expansion path. 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 it would not consider before, and its indicators of urban form may begin to deteriorate.
- Culture/colonization legacy: The first premise that justifies the use of remote sensing data to describe socio-economic conditions is that the physical appearance of an urban settlement is a reflection of the society that created it (Taubenbock et al., 2009). The colonization history in Latin America is observed as a proxy for cultural

differences that translate into urban planning practices and ultimately the resulting urban form today. Most historic centers of cities that were Spanish colonies exhibit a more regular urban layout than cities that were colonies of other countries (Irazábal, 2009). We expect that the colonization differences may translate into differences in the urban structure in Latin American and Caribbean cities, with cities that were Iberian colonies exhibiting more regular and organized urban layouts.

- Economic performance: The economic performance of the city is approximated by the density of radiance within the urban extent, as recorded by DMSP-OLS RC nighttime imagery. We expect that certain urban form aspects may provide better grounds for agglomeration economies to emerge; such as a better-connected urban fabric, urban compactness, land use, among others (Cervero, 2001; Duranton & Puga, 2004; Parr, 1979).

Although there can be other factors that affect urban form, the four factors listed above have associated metrics that we can compute for our sample of cities using open data. See Batty and Longley (1994) for a comprehensive analysis of the factors that shape cities.

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. For this we present in Table 3 the basic descriptive statistics for each urban form variable in 1996, 2000, and 2010, and in Fig. 5 the kernel density plots of these variables to visually identify changes over time in mean, variance, peakedness, symmetry or modality. Whereas the distributions of the variables are very similar across dates, there are small changes that indicate how the set of LAC cities are evolving (see Fig. 5).

4.1.1. Urban shape

Generally, urban shape variables values for 2010 indicate that LAC cities are more rounded than elongated, with urban perimeters more smooth than complex, and little open space within the urban extent. The changes from 1996 to 2010 are small but point to some trends in the region. The roundness index values are high, with median and mean values greater than 0.5 on the three dates. A small decrease is observed from 1996 to 2010, which indicates a weak trend of change towards more elongated urban extents. The smoothness index values are high across all dates, and they also exhibit a small decrease over time. This indicates a trend towards less-smooth urban perimeters that could be the result of urban growth along corridors that link to other cities.

4.1.2. Urban texture

Urban texture variables indicate that LAC cities have a dense texture, with high values of intersection density and street density. The circuity index values indicate that the street network layout in LAC cities is very regular: they are very close to 1, and 75% of the analyzed urban extents have values less than 1.05, meaning that most of their street networks are only up to approximately 5% longer than if they were all composed of straight lines. This regularity is in line with the findings of Huang et al. (2007). However, a small increasing trend is observed in circuity index values from 1996 to 2010, which might be due to recent occupation of rugged terrain in mountainous areas.

4.1.3. Land occupation pattern

The land occupation pattern variables indicate that cities in LAC are rather compact, with high densities. The sprawl index measures how uniform the spatial distribution of population is within the urban extents. In general, this variable exhibits 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 fullness index values tend to be high, and they exhibit a small increase from 1996 to 2000 and then a small decrease up to 2010, which could indicate a trend of low-density growth in that period. These results are in agreement with previous findings (Angel et al., 2010a; Huang et al., 2007; Inostroza et al., 2013).

We looked deeper at three indexes distributions, one by dimension, to see which cities have high, average, and low values of the respective metric. Cities with high smoothness values are Santa Cruz (Bolivia), and Puebla (Mexico), while Medellin (Colombia) and Sao Paulo (Brazil) have low values. San Luis Potosi (Bolivia) is an example of the average LAC city in regard to smoothness. Looking at the street density index, La Paz (Bolivia), Lima (Peru), and Santiago (Chile) are examples of cities with high values of street density, while San Salvador (Salvador) and Panama City (Panama) show low values of this metric. Maceio (Brazil) has the average street density in the LAC region. High fullness values are met in Sao Paulo (Brazil), Puebla, and Mexico City (Mexico). The average fullness value is met in Belem (Brazil), while Brasilia (Brazil) and Cali (Colombia) have low fullness values, with higher proportion of

Table 3
Descriptive statistics of variables. N = 919.

Variable	date	p25	Median	p75	Mean	Std. Dev.	Min	Max
Roundness index	1996	0.725	0.828	0.879	0.787	0.121	0.266	0.947
	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
Smoothness index	1996	0.620	0.720	0.767	0.674	0.140	0.090	0.888
	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
Intersection density	1996	46.96	64.90	84.13	65.87	28.88	0.33	184.97
	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
Street density	1996	7,988.8	10,452.4	12,985.5	10,474.4	3,791.5	135.9	20,669.2
	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
Circuity index	1996	1.019	1.028	1.046	1.037	0.034	1.002	1.419
	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
Sprawl index	1996	0.479	0.595	0.721	0.598	0.177	0.108	1.00
	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
Fullness index	1996	0.494	0.630	0.763	0.618	0.192	0.014	0.996
	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

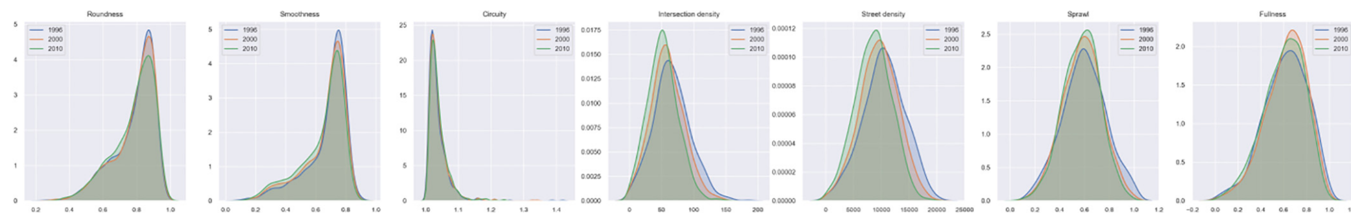

Fig. 5. Kernel density distributions of urban form variables.

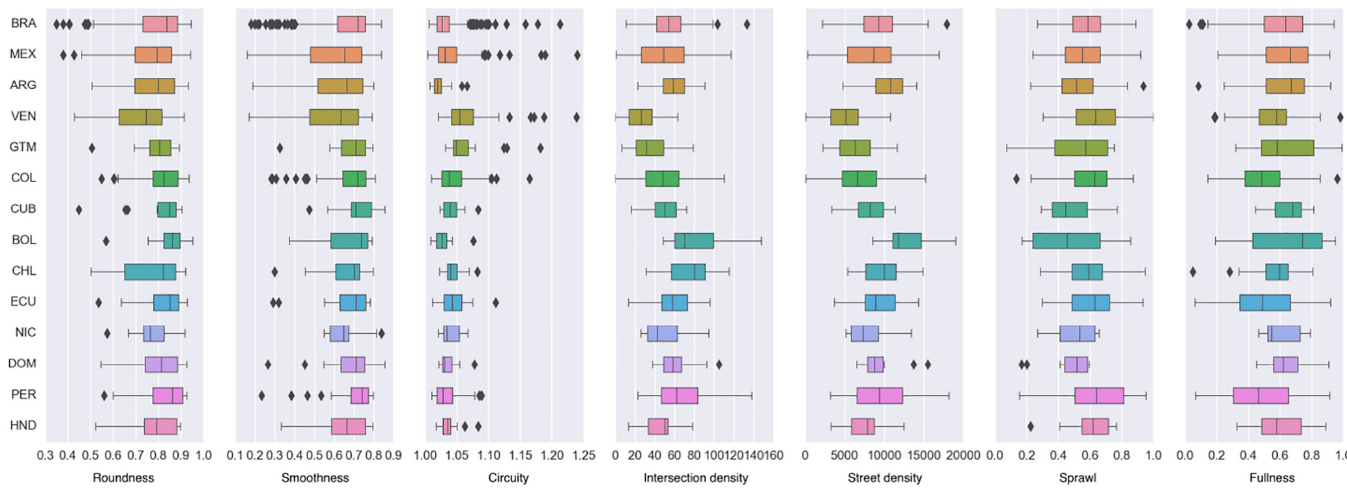

Fig. 6. Box plots of urban form variables for 2010 by country (ISO3 code). Only countries with more than 9 detected urban extents based on NTL are shown.

open spaces within their urban extents. We look at the 2010 data to highlight country level differences in urban areas (Fig. 6). The roundness index boxplots from Fig. 6 show that Venezuelan cities tend to be more elongated than most of the other cities in the region, whereas Bolivian cities tend to be more rounded. This could be the effect of physical geographic constrains, as many Venezuelan cities are located along the Caribbean coast (e.g., Maracaibo, Barcelona), along the Orinoco river (e.g., Ciudad Guayana), or in the mountains in elongated valleys (e.g., Mérida, Barquisimeto, Caracas). The situation in Bolivia is rather different, with most of their cities located in a plateau or high plain, as well as in the low lands towards the Amazon river watershed, with less geomorphologic constrains. Bolivian cities also tend to have smoother perimeters (high values of smoothness index), and the cities with less-smooth perimeters are in México, Brazil, Argentina and Venezuela. Santa Cruz (Bolivia) and Puebla (Mexico), which are located in relatively flat areas with few constraints for growth have high smoothness values; while Medellin (Colombia) and Sao Paulo (Brazil) – both located in areas with growth constraints such as the presence of protected areas and mountains – have low smoothness values. The urban texture plots show that more-regular networks are often denser than organic ones: in general, Venezuela and Guatemala have the cities with the most-organic street networks in the region (higher values of circuity index), and they have also the lowest street and intersection densities. Regarding land occupation, Venezuela and Peru exhibit higher values of sprawl index, which indicates less uniform distributions of population in their urban areas and more intraurban differences, whereas Bolivia and Cuba exhibit lower values, evidencing more uniform distributions of the population within their cities. The fullness index 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.

4.2. *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. Fig. 7 shows the distributions of urban form variables (rows) grouped by factors (columns). The factor *slope* was grouped into two classes to differentiate between cities located on flat terrain and cities located in mountains or on rugged terrain: below 10% and above 10%. The factors *size of the city* and *economic performance* were grouped into quartiles to inspect differences between quartile groups. The factor *colony* was assigned according to the colony that the area was part of in 1700: Portugal, Spain, England, the Netherlands, or France (Gascoigne, 2001).

4.2.1. *Topography*

We analyze the topography using the mean slope (%) within the urban extent (Fig. 7, first column), calculated from the SRTM Digital Elevation Data at 90 m of spatial resolution (Jarvis, Reuter, & Nelson, 2008) with the slope function in ArcGIS. The roundness and smoothness indexes do not exhibit important differences between the two classes. The urban texture graphs corroborate that cities with steepest slopes have lower values of street and intersection densities, in addition to more-organic urban layouts, with higher values of circuity index. This is an expected behavior because the street network in rugged terrain should adjust to the topography with curvy roads. Additionally, according to Batty and Longley (1994), organic cities, which are associated with high levels of circuity index, fit their natural landscapes. This observation explains the high and positive correlation between circuity index and slope (0.52). The relation with sprawl index indicates that cities with steeper slopes have a less uniform distribution of their population within the urban areas than cities located on flat terrain. Fullness index exhibits a small difference: urban extents with slopes above 10% tend to have lower values than those with slopes below 10%. This result indicates that cities located on rugged terrain have more empty spaces than cities located on flat terrain.

4.2.2. *Size of the city*

We classified the urban extent area in square kilometers into

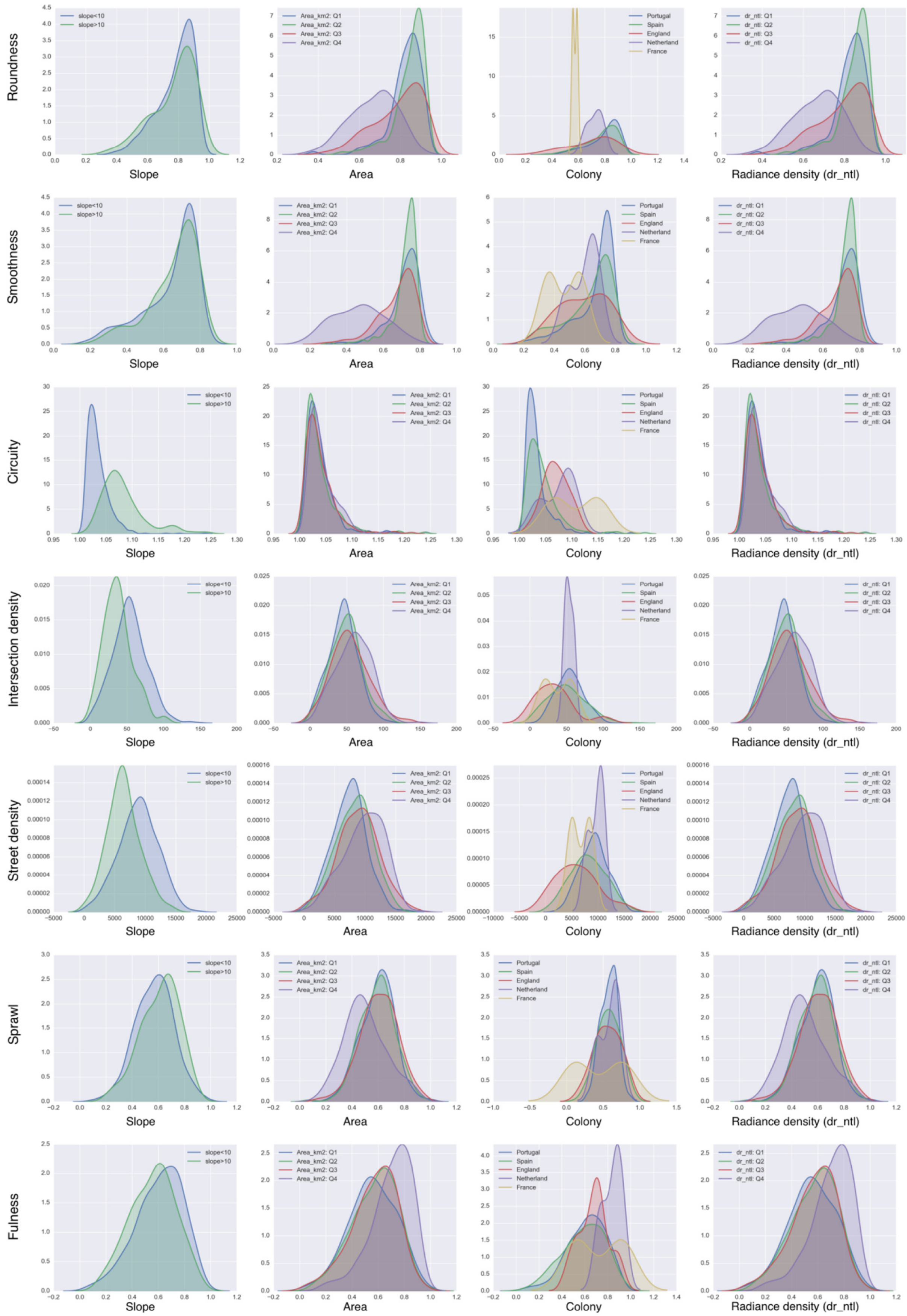

Fig. 7. Distribution of urban form metrics from 2010 data, according to the factors that influence the urban form.

quartiles and built kernel density plots of the distribution of urban form variables for each group (Fig. 7, second column). Roundness index and smoothness index 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 indicates that larger urban areas deviate more from the circular shape. The moderate negative correlation between smoothness index and Area_km^2 (-0.6) also indicates that larger urban areas in the LAC region have less smoothed perimeters. Urban texture doesn't seem to be affected by city size. Circuity index 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 index distributions. Sprawl index distributions show an interesting trend: larger cities have lower values than the rest and a low negative correlation (-0.22), indicating that the population in those cities tend to be more uniformly distributed than in the smaller urban areas. The trend in fullness is quite the opposite: larger cities show higher values, meaning a more efficient use of urban space, with a low positive correlation (0.3).

4.2.3. 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 to in 1700 (Gascoigne, 2001), and built the kernel density plots of urban form variables for each class (colony). Portugal, Spain, England, Netherland and France had colonies in Latin America and the Caribbean by 1700. The third column of Fig. 7 shows the distribution plots of urban form variables for the colony groups. English and Iberian (Spanish and Portuguese) colonies exhibit a similar trend in shape variables, whereas French and Dutch colonies exhibit smaller values in both cases, indicating more-elongated cities and less-smooth perimeters than their English and Iberian counterparts. The urban texture distributions show an interesting trend: after sorting the urban extents by the circuity index values, the Portuguese colonies show the lower values, followed by Spanish colonies, then English, then Dutch, and then the French ones. This result 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 lower densities than the rest, and the highest densities correspond to the Iberian colonies. The 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. The fullness distributions also exhibit some differences, with French and Dutch colonies having higher values than the rest. These results show that most Latin American cities reflect much of their planning legacy, following the planning traditions of their respective conquerors, specially the Spanish and Portuguese (Bigon & Hart, 2018; Sandholz, 2016). It is known that the kings of Spain issued guidelines for planning new towns and settlements, like the 1573 law issued by king Felipe II: *Ordenanzas de Descrubrimiento, Nueva Población y Pacificación de las Indias*, recommending, among other strategies, the use of a square grid to allocate urban plots and to guide the development of the urban fabric (Gomez Tagle Morales, 2007).

4.2.4. Economic performance (proxy: density of radiance in NTL imagery, dr_ntl)

We used the density of radiance from the nighttime imagery as a proxy for economic performance (*dr_ntl*, Fig. 7 column). We classified the LAC cities in quartiles according their registered radiance density in 2010. The roundness and smoothness indexes do not reveal noticeable differences across quartiles. The distributions of urban texture variables show that street and intersection densities both increase with radiance density, and the group with higher values of radiance density has more-regular urban layouts (circuity index 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. The distributions of fullness show that the group of cities with lower-density radiance values also has lower values of fullness. These results are in line with the finding of Duque, Lozano-Gracia, Patino, and Restrepo (2019) that compact and well-connected cities exhibit higher levels of productivity. Good mobility reduces transportation costs, and compactness reduces the cost-per-household of public service infrastructure.

5. Spatiotemporal analysis of urban growth in 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 determine whether there is a trend of growing in steeper terrain, how fragmented the growth is, if the new urban areas occupy protected lands, and the relationship among urban growth, the initial size of the city, and the population density of the urban extent in the prior date.

5.1. Slope

Fig. 8 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 on 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%, whereas urban extents in rugged terrain grow most of

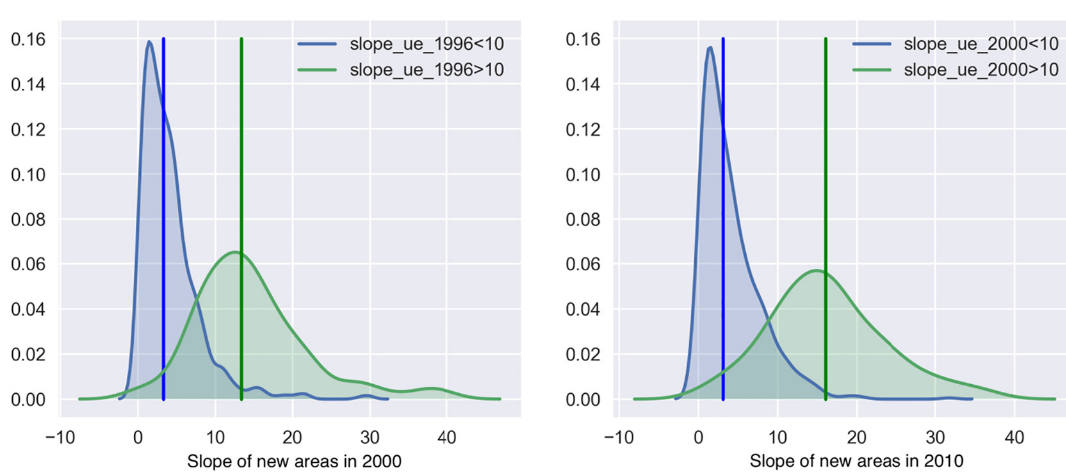

Fig. 8. Kernel density distribution of slope (percent rise) of new areas. The vertical lines show the mean of each distribution.

the times 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 on rugged terrain. Urban growth in high slope areas can increase a cities exposure to natural disasters as these areas are more prone to landslides and flash floods. It can also constraint the use of certain public transportation systems, as the options to cope with slopes greater than 15% are reduced to a few, such as cables and shuttle buses, and the energy consumption is higher than for transportation systems operating in flat terrain.

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 towards more- or less-fragmented urban growth. For each urban extent, the new urban areas in 2000 (2010) were obtained by subtracting the urban extent in 1996 (2000) from the urban extent in 2000 (2010). Higher values of fragmentation indicate that the cities are growing in multiple directions over the prior urban extent boundary. Fig. 9 shows 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 towards a less-fragmented urban growth between 2000 and 2010 than between 1996 and 2000, except for Central America, which exhibits a small increase. Considering the different groups' boxplots, it is clear that some Mexican cities, in addition to some South American ones, have the highest values of fragmentation within the region. High fragmentation can have negative environmental impacts as it may limit the connectivity of natural corridors within and around cities and thus reduce biodiversity (Angel et al., 2010a; Goddard, Dougill, & Benton, 2010).

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 in protected areas implies the loss of ecosystem services and cultural values, and it jeopardizes urban sustainability in the long term. We quantified urban growth in protected areas using the World Database on Protected Areas (WDPA) produced by the United Nations Environment Programme (UNEP-WCMC, 2016), 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. Fig. 10 shows the percent of urban growth in protected areas. Most cities in the LAC region exhibit relatively low values, and 72% of the urban extents in the sample did not grow over protected areas from 1996 to 2010. But the rest 28% of the urban extents have growth over protected areas, with the highest values (greater than 85% in both periods) located in Argentina, Bolivia, Brazil, Guatemala, Mexico, Peru, and Venezuela. According to the United Nations, (2014), it is expected that Bolivian cities will increase the urban population by 79% between 2014 and 2050, representing the second-largest annual rate of change in South America: 0.6% per year. This rapid growth makes the detected trend an important issue to address in the near future.

5.4. Growth vs. initial spatial size

The initial spatial size of the urban extent does not seem to play an important role in the magnitude of urban growth. As shown in Fig. 11, the initial area of the urban extent does not exhibit 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.

5.5. Growth vs. population density

Regarding the relationship between urban growth and population density, we analyzed the distributions of the initial population density (for year 1996 in the period from 1996 to 2000 and year 2000 for the period from 2000 to 2010) divided into quartiles (Fig. 12). The 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 approximately 0.1 to 0.2% more than the rest of urban extents. This result was expected, as less-dense urban areas can accommodate new people up to a saturation point without growing spatially. When the population density is close to reaching its physical limit or saturation point, spatial growth to new areas is required to accommodate the new population.

6. Discussion and conclusions

This work demonstrates that the use of open spatial data, remote sensing imagery, and automatic data retrieval systems (such as OSMnx)

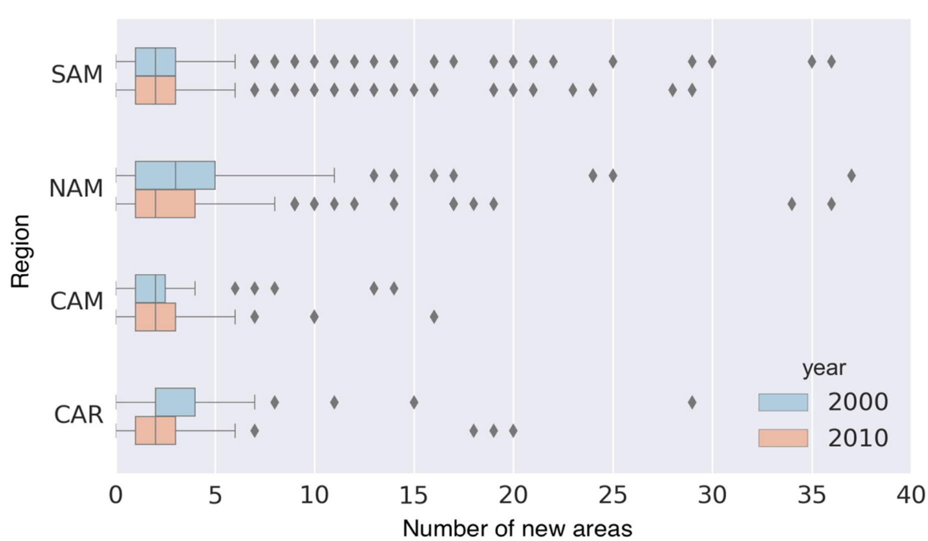

Fig. 9. Boxplots of growth fragmentation (number of new areas) in 2000 and 2010, grouped by region.

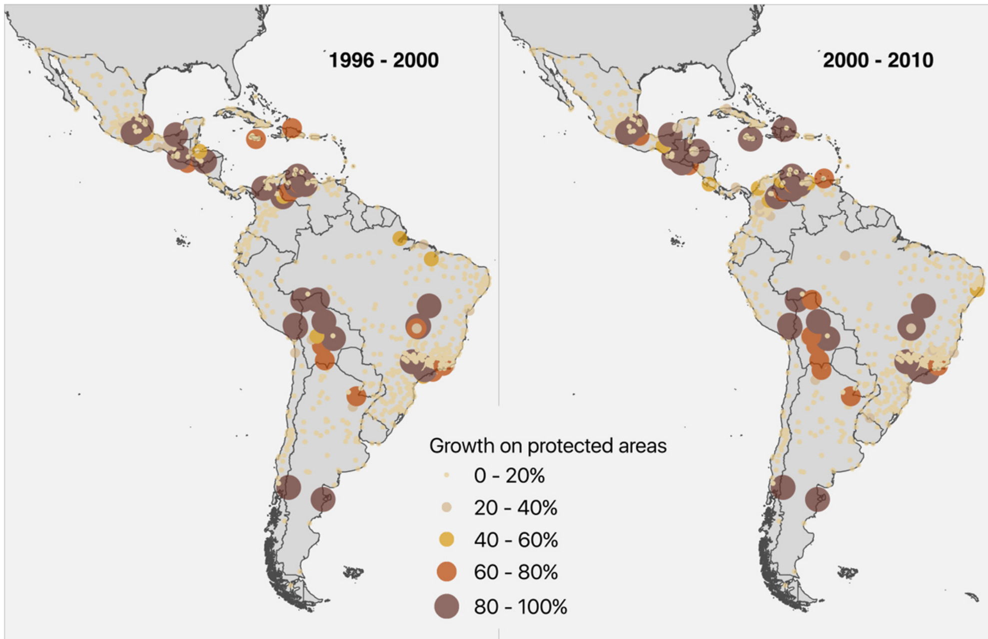

Fig. 10. Percentage of urban growth on protected areas in LAC. Left: 1996 – 2000, right: 2000 – 2010.

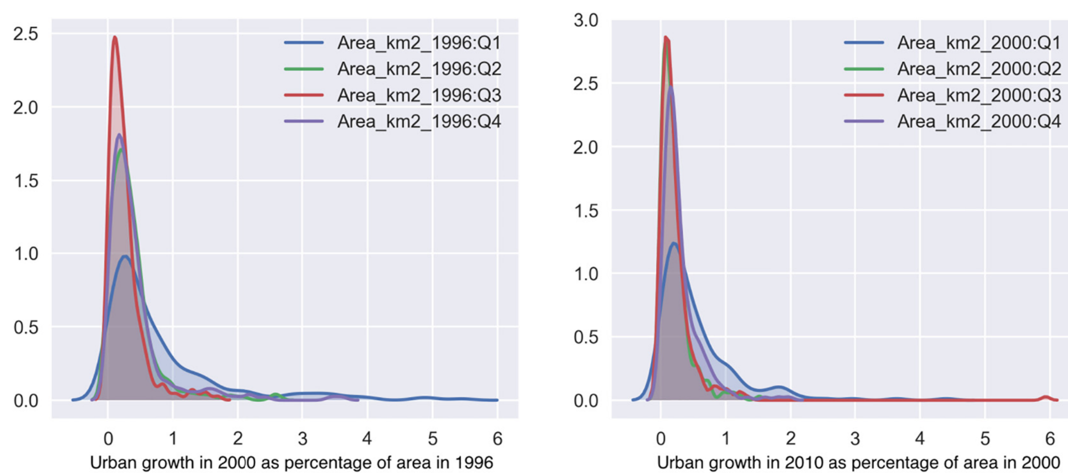

Fig. 11. Initial urban extent size (area in km2, classified into quartile groups) and urban growth (as a percentage of initial size).

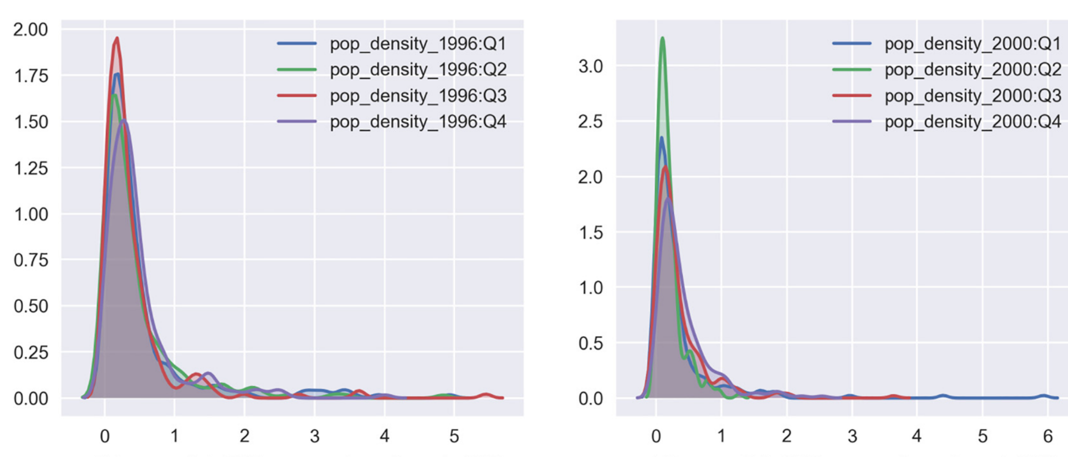

Fig. 12. Initial population density (people/km2, classified into quartile groups) and urban growth (as a percentage of initial size).

open a new horizon of possibilities for 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 about the manner in which urban extents are evolving. This work contributed with empirical data and descriptive analysis to the literature about urban form in Latin America and the Caribbean. Based on the integral definition of the concept of urban form from the urban planning literature, this paper approached urban form as a combination of three dimensions: shape of the perimeter, urban texture and land occupation patterns. Several indicators for each dimension were calculated using freely available data and highly automatized libraries for geometry and network analysis. Those indicators show that LAC cities are very diverse and that the average LAC city is more rounded than elongated, with a smooth rather than complex urban perimeter and little open space. The street networks in LAC cities tend to be regular and dense.

Regarding the factors that can be correlated with urban form, we found that factors such as topography and historical legacies linked to urban design (colony history) are highly correlated with urban form indicators. Organic/natural urban structures are usually located on rugged topographies, and LAC cities that were Iberian colonies have more-regular urban layouts and denser street networks. As found in the 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. The cases of Bolivia and Venezuela emerged as critical cases of urban growth in protected areas, which can jeopardize sustainable urban growth in those countries.

Urban planners and policy makers should be aware that compactness alone is not enough to ensure better economic performance if it does not come with appropriate connectivity. Besides that, a more uniform distribution of population within the urban extent is associated with better economic performance. Those findings indicate that cities should be planned to have less segregated land uses, allowing a smooth (as opposed to patchy) distribution of their population across the urban extent, in hand with high levels of connectedness that allow for better interaction between individuals and across people and firms. Regarding the growth over steep terrain and protected areas, there are three main points that authorities and policy makers should take into account. The first is about knowledge and information. There is a general lack of information and understanding of the natural risks in urban areas in many countries of Latin America and the Caribbean. It is important to reduce information asymmetries and ensure that policy makers, urban planners, and the general public have access to and a good understanding of information that is often used by researchers. Natural hazards maps and protected areas maps should be made open to the public via Internet, newspapers and public libraries. In this way property developers and other agents of the housing market can make better-informed decisions about the places they choose to develop and live. Second, urban land-use master planning should be used to better shape LAC cities into higher-performing forms and avoid growing in risk or protected areas. Some countries in the region score better than others in this aspect, but they are all relatively new to urban planning ruling and legislation (e.g., Paraguay just started to implement urban master plans in 2018). Third, in places where there is information and understanding of natural hazards and there is urban planning legislation, like Colombia, we have seen that the obstacle is the lack of law enforcement or local government capacity to define and implement plans and direct urban growth away from risk-prone and protected areas. The information-planning-enforcement triad should help to make cities more livable, secure and sustainable. Future research should explore the possibility of using these input data and indicators to forecast the evolution of urban extents. This can help prepare policymakers to avoid unnecessary pressures, build incentives for urban expansion in desired areas, and protect the population for unnecessary exposure to natural hazard, as well as testing the potential outcomes of different type of urban growth patterns.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.landurbplan.2019.103640.

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