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REPORT

Contrasting Patterns of Urban Expansion in Colombia, Ecuador, Peru, and Bolivia Between 1992 and 2009

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Abstract The global urban population is increasing rapidly, but patterns of urban expansion differ greatly among countries. Urban transition theory predicts that the shift from low to high urbanization depends on a country's history and level of economic development. This study describes urban expansion in Colombia, Ecuador, Peru, and Bolivia between 1992 and 2009. Urban dynamics were analyzed by combining nighttime lights and census data from 4032 municipalities. High-lit areas (>52–63 pixel values) were correlated with urban populations across municipalities and years ($R^2 > 0.90$). Analyses showed that between 1992 and 2009 Bolivia and Ecuador had rapid population growth and rapidly increasing high-lit areas, while Peru and Colombia had lower rates of population growth and urbanization (i.e., expansion of high-lit areas). We demonstrate how nighttime lights can be a useful tool, providing a homogeneous platform for multi-scale analyses of urban growth.

Keywords Andean countries · Nighttime lights · Population growth · Urban expansion · Urban transition

INTRODUCTION

The global urban population (3.42×10^9) surpassed the rural population (3.41×10^9) in 2009 for the first time in history (UN 2010). Current projections suggest that most future population growth will occur in urban areas, with urban populations estimated to reach 5.26×10^9 by 2050 (Montgomery 2008). In 2000, urban areas covered less than 0.2 % (~300 000 km^2) of the world's terrestrial area (Angel et al. 2011) despite substantial urban population growth occurring since the 1950s (UN 2010). Urban areas are estimated to expand 2.6 times by 2030 and cover 770 000 km^2 (Angel et al. 2011), which translates to 60 % of the total population living in 0.6 % of the world's terrestrial area. This high concentration of people will have global impacts. Urban expansion is considered one of the greatest contributors to global climate change and biogeochemical fluctuations (Grimm et al. 2008), and a primary driver of forest loss and species extinction (Grimm et al. 2008; DeFries et al. 2010). On the other hand, the concentration of humans in urban areas can alleviate many social problems by centralizing infrastructure, services, technological innovation, and economic activities (Bloom et al. 2008). An ongoing debate is whether urban population growth should be encouraged or limited, and how urban expansion can accommodate the needs of the growing urban populations (Bloom et al. 2008; DeFries et al. 2010).

While the global urban population is growing quickly, rates of urban growth vary greatly among countries (Angel et al. 2011; Seto et al. 2011). This variation in urban growth can be explained by the theory of urban transition, which is defined as the shift from low to high urbanization, and is influenced by a country's history and level of economic development (Bocquier 2005). Urban transition occurs in four stages: (1) low proportion of urban population and low urban growth, (2) low proportion of urban population and high urban growth, (3) high proportion of urban population and high urban growth, and (4) high proportion of urban population and low urban population growth (Zelinsky 1983). Urban transition in stages (3) and (4) is best illustrated in developed countries, where significant urban growth started in the eighteenth century and by 1950 more than 55 % of the population was urban. By 1995 the urban population increased to >75 % (Bocquier 2005). In contrast, urban transition in early stages is best exemplified in developing countries, where the urban population consisted of approximately 10 % in 1900, and had only reached 38 % by 1995 (Bocquier 2005). These demographic changes are also reflected in urban expansion (i.e., increases in built-up areas). For example, between 2000 and 2010 the rate of urban expansion was much greater in developing countries (~2.5 % year^{-1}) than more developed countries (0.8 % year^{-1}) (Angel et al. 2011).

In Latin America, projections indicate that 85 % of the population will live in cities by 2025, highlighting the importance of examining urban expansion in this region (UN 2010). Ensuring that these urban areas become ecologically, economically, and socially more sustainable cities in the future, will require detailed current information on the patterns of urban dynamics (e.g., population growth, urban expansion, migration) (Martine et al. 2008). In this study we examine different forms of urban expansion by contrasting the distribution and growth of urban areas in the Latin American countries of Colombia, Ecuador, Peru, and Bolivia in 1992, 2000, and 2009. The populations of these countries have experienced a marked transition from rural to urban, as total urban population has increased from 37 to 74 % between 1950 and 2010 (UN 2010) (Fig. 1). We combined urban population data with nighttime light (NTL) images, an indirect measure of urban area, to examine: (1) the relationship between urban population growth and urban expansion as interpreted by remotely sensed data, and (2) patterns of urban population growth and urban expansion among Colombia, Ecuador, Peru, and Bolivia. Although some studies have addressed these questions (Sutton et al. 2001; Seto and Kaufmann 2003), few studies have analyzed both the demographic and land-change aspects of urbanization at multiple spatial scales (e.g., municipality, country, region).

STUDY AREA

The countries of Colombia, Ecuador, Peru, and Bolivia include 19 % of the total population of South America (UN 2010), representing more than 190 different ethnic groups, and covering a total land area of 3.8 million km^2. These countries have similar climate and terrain, including lowlands, plains, and mountain ranges, with the Andes Mountains present in all four countries. Peru is the largest country, with a total land area of 1.28 million km^2 and an estimated population of 29 million in 2009. Colombia is slightly smaller than Peru, with an area of 1.14 million km^2, but has a much larger population of 46 million. Peru and Colombia are similar in that they have had large rural–urban migrations due to armed conflict (Fjeldså et al. 2005). In Colombia alone, more than 3.5 million people moved from

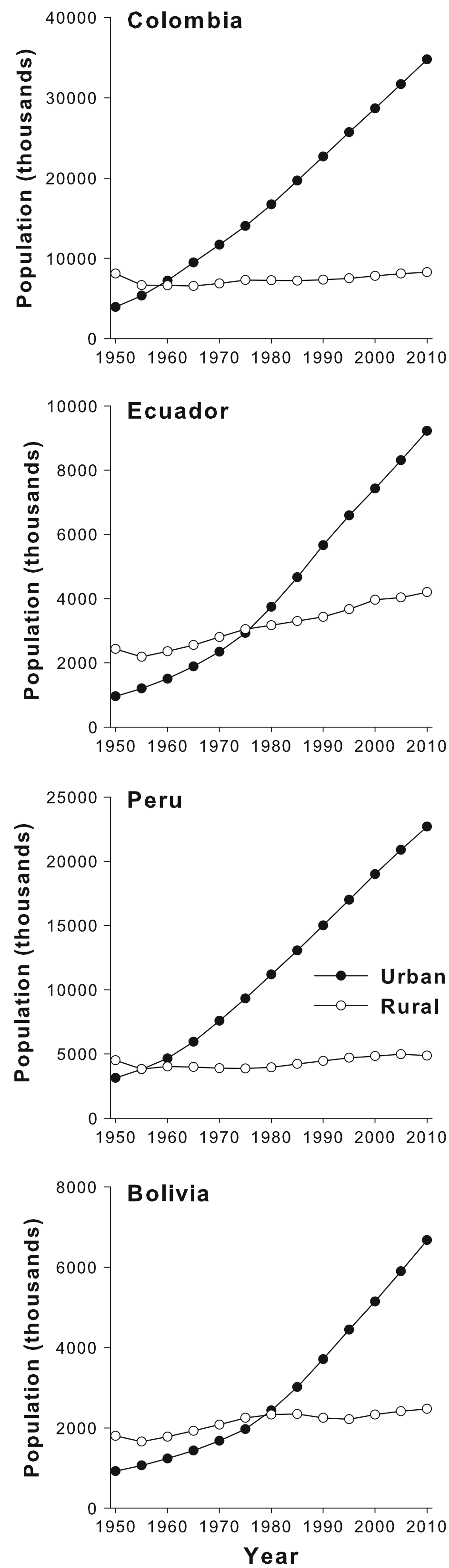


Fig. 1 Urban and rural population in Colombia, Ecuador, Peru, and Bolivia from 1950 to 2010 (from UN 2010)

rural to urban regions between 1985 and 2006 to evade guerrilla and paramilitary violence (CODHES 2006). Ecuador is the smallest country of the region with a land area of 276 840 km^2, but it has a population of 14.3 million. Bolivia has the smallest population (10.3 million), and is similar in size (1.1 million km^2) to Peru and Colombia. Bolivia is also the poorest country of the region with an estimated GDP per capita in 2010 of USD1758, compared to that of Ecuador (USD4205), Peru (USD4403), and Colombia (USD5030) (UN Statistics Division 2010).

MATERIALS AND METHODS

To study urban expansion in relation to urban population growth and contrast the relative importance of both processes, we combined census population data (DANE 2011; INE 2011; INEC 2011; INEI 2011) with urban area estimates derived from NTL data from 1992 to 2009. Our analyses consisted of five steps. In step 1, we created a GIS (Geographic Information Systems) database of population for the 4032 municipalities in the four countries, and examined urban population trends at the municipality, country and regional scale for 1992 and 2009. In step 2, we classified NTL data into four light intensity classes that were statistically related to four distinct urban classes (Figs. 2, 3). With these data we created a transition matrix of the different light classes of NTL between 1992 and 2009. In step 3, we used linear regression analysis to determine the relationship between NTL and urban population for the 4032 municipalities. In step 4, we compared the change in lit area with the change in urban population at the country level.

Census Data

Demographic data were obtained from national censuses for the following years: (1) 1993, 2005, and 2010 for Colombia (DANE 2011), (2) 1990 and 2001 for Ecuador (INEC 2011), (3) 1993 and 2005 for Peru (INEI 2011), and (4) 1992 and 2010 for Bolivia (INE 2011). Urban and rural populations for the second administrative level, usually referred to as the municipality, were extrapolated to 1992 and 2009 (the dates of our NTL images).

Nighttime Lights Data

Monitoring and measuring urban growth using conventional remote sensing data and techniques over large scales can be challenging (Herold and Roberts 2010). This is because urbanized areas have many land-cover types that can be interpreted as non-urban in spectral classification methods. For example, it is difficult to differentiate between impervious zones of urban areas with barren terrains and deserts because of their spectral similarity (Herold and Roberts 2010). The NTL images provided by the Defense Meteorological Satellite Program's Operational Linescan System (DMSP/OLS), which records urban extent and growth by tracking NTL areas over time, can be an alternative to more conventional images. NTL images can overcome the spatial limitations of commonly used satellite images (e.g., Landsat) when examining land-cover changes at global scales.

NTL have been widely used for urban mapping at national, continental, and global scales by relating lit areas to census data (e.g., population size and growth) (Sutton et al. 2010). NTL have also been related to economic activity (Ghosh et al. 2010), electrical power consumption, CO_2 emission (Oda and Maksyutov 2011), and fires associated with slash and burn agriculture (Elvidge et al. 2001). Time series of NTL have also been used to study temporal trajectories of urbanization (Zhang and Seto 2011; Liu et al. 2012). These studies showed that NTL can characterize urbanization dynamics through time, but there are limitations. First, changes in a time series of NTL can be due to shifts in the signals of the different DMSP/OLS sensors (Zhang and Seto 2011; Liu et al. 2012). Second, light emission from gas flare in oil installations can be confused with the illumination coming from urban areas, thus influencing the calculation of urban expansion (NOAA 2011). Third, it can be difficult to detect the densification of highly urbanized areas because of oversaturation of NTL data in areas of high lights (Letu et al. 2012). Fourth, NTL studies may not detect the large proportion of the urban population that lives in near the urban fringe in informal housing settlements (i.e., shantytowns) without lighting infrastructure (Sutton et al. 2010).

We addressed these limitations by: (1) validating the use of NTL data from different sensors by conducting linear model analyses that related NTL with urban population obtained from census data ("Validation of NTL" section) similar to the methodology of Zhang and Seto (2011); (2) documenting the contribution of gas-flares to our estimates of urban growth. We found that gas-flaring activity decreased during our study period in the four countries (NOAA 2011). As we were concerned with urban expansion, we only included municipalities where lit areas expanded and excluded those that showed negative growth; (3) acknowledging the oversaturation problem in the interpretation of our findings; and (4) justifying the use of NTL data to monitor and measure urban growth in this region given the high electrification rates in Colombia (94 %), Ecuador (92 %), Peru (86 %), and Bolivia (78 %), particularly in urban areas (IEA 2011).

We used NTL images from 1992 to 2009 available from the National Geophysical Data Center (http://www.ngdc.noaa.gov/dmsp/download.html). Each image is a composition of

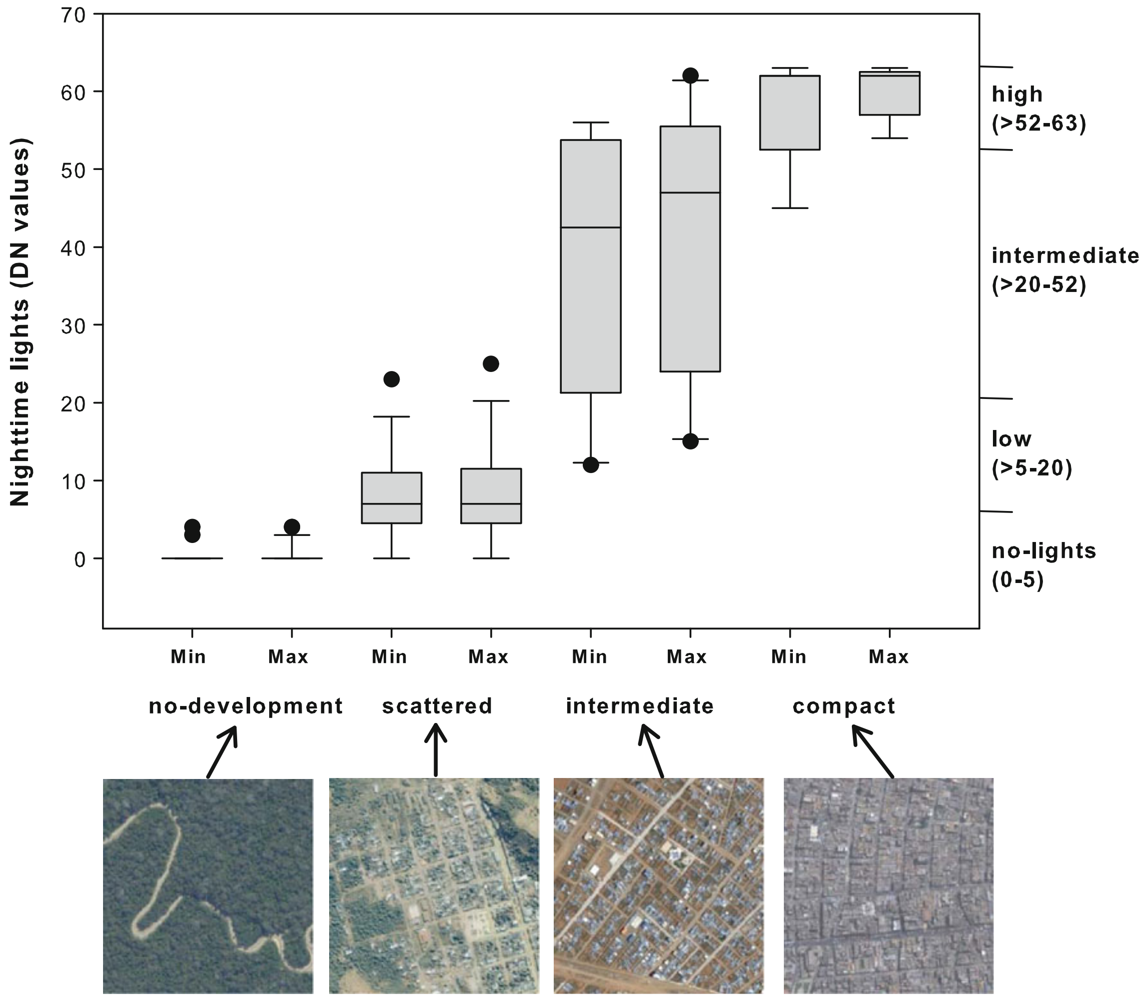


Fig. 2 Box-plots showing the minimum and maximum nighttime lights DN values for four urban land-use classes: no-development, scattered, intermediate, and compact. The box includes values between the 25th and 75th percentiles, the *line* within the box represents the median, and the *circles* indicate outliers

cloud-free DMSP-OLS scenes. Specifically, we used NTL images that only contain permanent light sources (i.e., stable-nighttime lights) from cities, towns, and other continuous lighting, such as gas flare and mining and oil exploration sites. The resolution of these images is 0.008333 degrees square or approximately 1 km^2. Each pixel is assigned a value (i.e., digital number DN) that represents the level of brightness, which varies from 0 (no-lights) to 63 (bright lights).

Threshold Selection and NTL Classification

One of the main challenges in using NTL images for mapping urban areas is dividing the DN values into separate classes of urban and non-urban land-use types. To define our thresholds, we first defined four types of urban land-use classes using indices of compactness following Galster et al. (2001): no-development, scattered development, intermediate development, and compact development (Fig. 2). We then used Google Earth's Quick Bird and IKONOS images (available circa 2000 and 2009) to find examples of the four urban land-use types across the four countries. We delineated 68 urban polygons representing no-development, scattered, intermediate, and compact urban developments. For each polygon, we also recorded the year of the Quick Bird or IKONOS image, and the name of the urban area. We then imported our Google Earth polygons (kml format) into a shape file format (using GIS) and then superimposed each urban polygon to the corresponding NTL image for each year. We recorded the

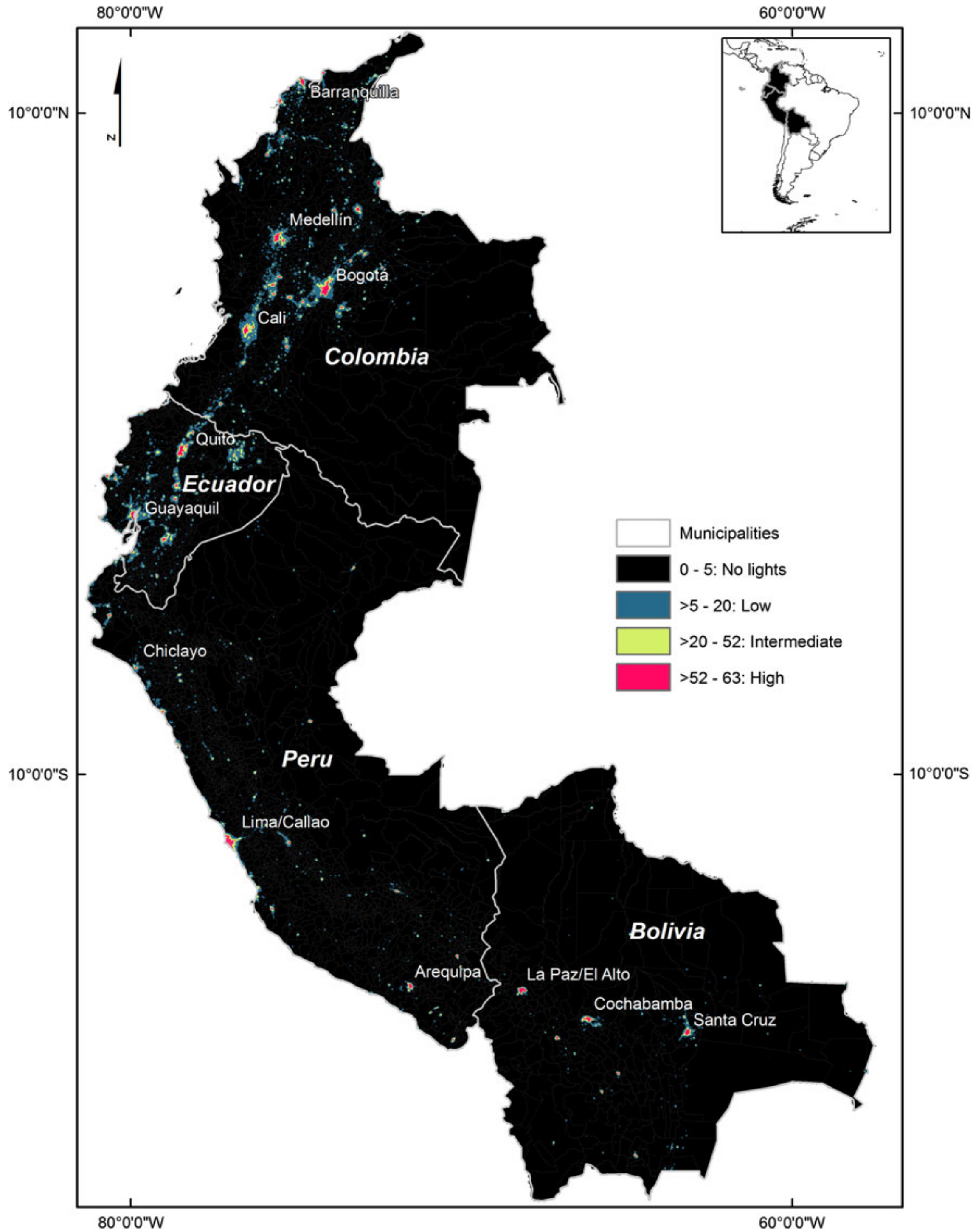


Fig. 3 Classified nighttime lights for 2009 in Colombia, Ecuador, Peru, and Bolivia according to four DN value ranges: 0–5 no-light, >5–20 low, >20–52 intermediate, and >52–63 high-lit areas

minimum and maximum digital number (DN) value of NTL within each polygon.

There were significant differences in the minimum and maximum DN values of NTL for each of the four urban land-use classes (ANOVA: minimum $f = 501.52$, $p < 0.001$; maximum $f = 311.74$, $p < 0.001$). The value range for the urban classes was: (1) 0–5 for no-development; (2) >5–20 for scattered urban; (3) >20–52 for intermediate urban; and (4) >52–63 for compact urban. These classes were used to classify the NTL images in different groups of light "intensity", as a proxy for the urban land-use types (Fig. 2). The NTL images for 1992 and 2009 were classified into the four classes: no-light, low, intermediate, and high-lit areas (Fig. 3). We then combined the 1992 and 2009 images to create a transition matrix between the different classes (e.g., from low-lit in 1992 to high-lit in 2009).

Using GIS we calculated the areas that were classified as no-lights, low, intermediate, and high-lit areas in 1992 and 2009 for the 4032 municipalities across the four countries. We then joined the lit area with the population data for 1992 and 2009. We also calculated the change in urban population, rural population, and total population, for 1992–2009, for each municipality. We eliminated 170 municipalities because they did not report urban or rural population data in one of the two census years. In total, we analyzed 288 municipalities in Bolivia (92 % of total municipalities), 1112 in Colombia (99 %), 842 in Ecuador (88 %), and 1789 in Peru (98 %), for a total of 4032 municipalities in the four countries.

RESULTS

Urban Population Change

The population of the region increased from 69.7 to 97.6 million between 1992 and 2009 (Table 1). The gain of approximately 28 million people over a period of 17 years represents a 40 % increase in population for the region as a whole, at an average annual growth rate of 2.0 %. About 88 % of this population growth occurred in urban areas; urban population increased by 24.5 million (from 47.4 million in 1992 to 71.9 million in 2009) and the rural population only increased by 3.5 million (from 22.2 million in 1992 to 25.7 million in 2009) (Fig. 1). As a result, the percentage of population living in urban areas increased from 68 to 74 %, at an average annual growth rate of 2.5 %, while the percentage of population living in rural areas decreased from 32 to 26 %, at an average annual rate of 0.9 % (Table 1).

At the country level, Bolivia had the highest average annual growth rate (3.2 %), which represents a 70 % increase in population (from 6 million in 1992 to 10.3 million in 2009). Ecuador (2.3 %) and Colombia (1.9 %) had intermediate rates of population growth while Peru had the lowest average annual growth rate (1.7 %) (Table 1). Population size in the four countries increased at a faster rate in urban than in rural areas (Fig. 1). Urban population in Bolivia almost doubled between 1992 and 2009, increasing from 3.7 to 7.1 million people at an average annual rate of 3.9 %, a faster rate than any of the other countries. This represents a 90 % increase in urban population for Bolivia, almost twice the increase in urban population when compared to Ecuador (52 %), Peru (48 %), and Colombia (46 %).

Table 1 Population growth and percentage of urban and rural population for 1992–2009 in Colombia, Ecuador, Peru, and Bolivia

Country	Net population estimates				Annual population growth rate 1992–2009
	1992	%	2009	%	
Colombia					
Urban	22 965 471	71	33 425 797	75	2.2
Rural	9 499 621	29	11 016 263	25	0.9
Total	32 465 091	–	44 442 060	–	1.9
Ecuador					
Urban	5 614 855	60	8 939 333	65	2.8
Rural	3 724 085	40	4 891 383	35	1.6
Total	9 338 940	–	13 830 716	–	2.3
Peru					
Urban	15 175 139	70	22 470 372	77	2.3
Rural	6 653 257	30	6 551 934	23	−0.1
Total	21 828 396	–	29 022 305	–	1.7
Bolivia					
Urban	3 682 753	61	7 054 310	69	3.9
Rural	2 330 806	39	3 222 249	31	1.9
Total	6 013 559	–	10 276 559	–	3.2
Region					
Urban	47 438 218	68	71 889 811	74	2.5
Rural	22 207 768	32	25 681 829	26	0.9
Total	69 645 986	–	97 571 640	–	2.0

The average annual percentage rates of population growth (ARPG) were calculated using the following equation: $ARPG = 100*((PE_{end}/PE_{start})^{(1/d)} - 1)$, where PE_{start} is the population at the initial time period, PE_{end} the population at the final time period, and d the time span in years

Urban Dynamics and Expansion

Validation of NTL

We compared the area of NTL classes (i.e., no-light, low, intermediate, and high-lit areas) with the urban population for each of the 4032 municipalities (Table 2). All lit classes were linearly correlated with urban population in 1992 and 2009 (Table 2). The high-lit class was the best predictor of urban population (2009: $R^2 = 0.90$, $p < 0.001$) (Fig. 4), followed by the combined area of high-lit and intermediate-lit classes (2009: $R^2 = 0.61$, $p < 0.001$), and by the combined area of high-lit, intermediate-lit, and low-lit (2009: $R^2 = 0.42$, $p < 0.001$). Municipalities with a population of approximately 10 000 people had between 1 and 10 km^2 of high-lit areas. At the other extreme, the municipality of Bogota had a population of approximately 8 million people and approximately 600 km^2 of high-lit

Table 2 R^2 values of the linear regressions between nighttime lights area and urban population values for low, intermediate, and high-lit areas

Class	1992	2009
Low	0.07	0.05
Intermediate	0.26	0.20
High	0.94	0.90
Int + high	0.67	0.61
Low + int + high	0.68	0.42
n	3159	3153

n Number of municipalities. All *p* values <0.001

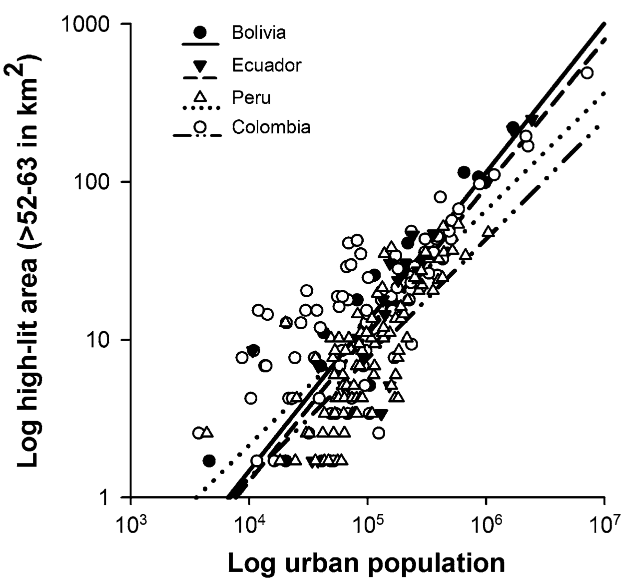


Fig. 4 Relationship between high-lit (>52–63 DN) urban areas and urban population (Colombia $n = 93$, Ecuador $n = 21$, Peru $n = 105$, and Bolivia $n = 19$)

area (Fig. 4). While the high-lit area (threshold of >52–63 DN) was the best predictor of urban population size, intermediate and low-lit values (>5–52 DN) detected smaller towns and lower-density urban areas. We did not analyze the expansion of low-lit areas given that these areas also captured the glare of the cities. Yet we incorporated the low-lit areas into the analysis of change, as these low-lit areas provide a proxy for early urbanization.

Given the strong correlation between the high-lit NTL class and population, we compared the net change in high-lit area with the net change in urban population between 1992 and 2009 (see Zhang and Seto 2011 for a similar approach). The linear model showed that the change in urban population explained nearly half of the variation in the difference in high-lit area at the municipality scale ($R^2 = 0.48, p < 0.001$). The strong relationship between NTL and urban population in 1992 and 2009, and the relatively high predictive power of area change between periods, show that NTL data can be used to estimate urbanization dynamics at the municipality scale in our study region.

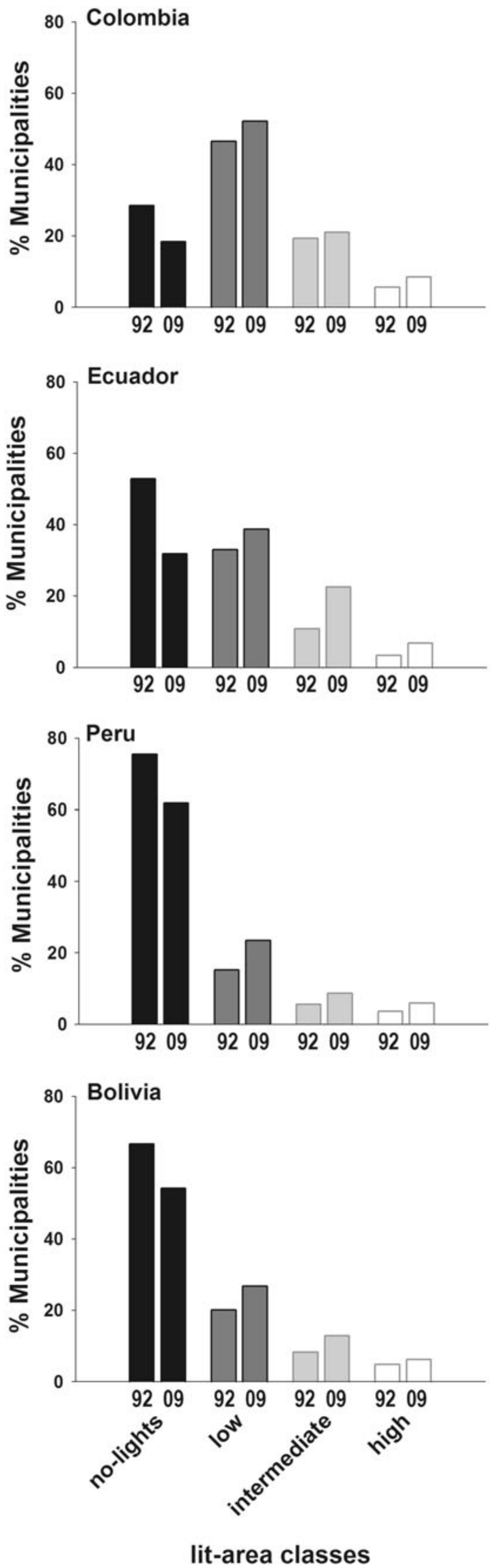
NTL Patterns: Municipality Scale

The NTL data indicated that the percentage of municipalities with lit areas increased from 43 to 57 % between 1992 and 2009 in the four countries (Fig. 5). This increase represents a total of ~570 municipalities that gained a source of light during these 17 years. Between 1992 and 2009, the percentage of municipalities in the high-lit class increased from 4 to 6 %. This increase represents the transition of 106 municipalities to the high-lit class. During the same time, municipalities in the intermediate-lit class increased from 11 to 15 % indicating that 186 municipalities transitioned to this light class. In addition, 378 municipalities transitioned from the no-light class to the low-lit class, increasing the percent of municipalities in the low-lit class from 28 to 35 % (Fig. 5).

Ecuador showed the highest increase in the percentage of municipalities that transitioned to the high-lit class, followed by Colombia, Peru, and Bolivia (Fig. 5). Ecuador also had the highest increase in the percentage of municipalities transitioning to the intermediate-lit class, followed by Bolivia, Peru, and Colombia (Fig. 5).

Changes in Urban Areas

The results illustrate that there were considerable differences among the four countries' urban cover and rates in the expansion of high-lit urban areas. Both in 1992 and 2009, Colombia had the largest area of high-lit, followed by Peru, Ecuador and Bolivia (Table 3). In terms of urban expansion, between 1992 and 2009, Ecuador had the largest high-lit increase (2.5-fold) and highest annual high-lit expansion rate (5.6 %), followed by Bolivia (2.4-fold; 5.3 %), Peru (2-fold; 4.2 %), and Colombia (1.6-fold; 2.8 %) (Table 3). In all countries, the main source of the increase in high-lit areas corresponded to an intensification of the intermediate-lit areas (Table 3). The increase in high-lit area coming from intermediate-lit areas surpassed the area classified as high-lit in Bolivia and Ecuador in 1992, whereas in Colombia and Peru the majority of the high-lit area in 2009 already existed in 1992. Bolivia showed the highest percentage of low-lit areas that intensified in light into the high-lit class (Table 3). The area of intermediate-lit area more than doubled in Ecuador and Peru (Table 3). The majority of the increase in intermediate-lit areas corresponded to an intensification of low-lit areas. In Bolivia, 81 % of the new areas of intermediate-lit class in 2009 came from areas that had no-light or low-lit areas in 1992 (Table 3).



◀ **Fig. 5** Percentage of municipalities in each of the four lit area classes in 1992 and 2009. Classification of municipalities is based according to the higher DN value range existing within the municipalities' boundaries. For instance, a municipality that had both high-lit and intermediate-lit areas within its boundaries was assigned to the high-lit class, regardless of the area covered by the high-lit class

In the region as a whole, there was an increase of 2940 km^2 in high-lit area and an increase of 6528 km^2 in intermediate-lit area between 1992 and 2009 corresponding to annual expansion rates of 3.9 and 2.9 %, respectively (Table 3).

DISCUSSION

Despite the ability of multi-temporal NTL data to analyze variations in urban dynamics, there are still challenges in their use and interpretation. Therefore, our calculations of urban extent are approximate and should be used as such. However, we consider that the trends observed are strong and consistent throughout the analyses. The results from the NTL analyses revealed substantial differences in the spatial and temporal urban dynamics of Colombia, Ecuador, Peru, and Bolivia between 1992 and 2009.

Urban Transition and Drivers of Urban Growth

The patterns of urban population growth in Colombia, Ecuador, Peru, and Bolivia reflect two distinct stages of urbanization and development. Bolivia and Ecuador have entered the intermediate stage of the urban transition, corresponding to a high proportion of urban population and a high urban growth rate, whereas Colombia and Peru are in the advanced stage, corresponding to a high proportion of urban population and a low urban population growth rate (Zelinsky 1983).

Peru and Colombia: Advance Urban Transition

The advanced stage of the urban transition is usually reached when urban population surpasses 70 % of the total population (Cerrutti and Bertoncello 2003). By 2009, approximately 77 % of the population in Peru and 75 % of the population in Colombia lived in urban areas. Both countries started their urbanization process in the late 1950s (Fig. 1), but are now experiencing slow demographic growth. During the 1950s and 1960s, migration was the main driver of urbanization in Peru and Colombia, caused by several factors including economic growth, armed conflicts, and the impoverishment of rural areas (Fjeldså et al. 2005; Etter et al. 2008). The economic growth during

Table 3 High-lit urban and intermediate-lit annual expansion rates from 1992 to 2009

	Colombia	Ecuador	Peru	Bolivia	Region
High-lit area (km^2)					
In 1992	1605	444	612	279	2940
In 2009	2583	1120	1239	676	5618
Trajectory of change to high-lit (1992–2009)					
% High-lit to high-lit	54.2	37.2	46.9	34.3	46.8
% Int-lit to high-lit	43.7	54.9	43.6	43.3	45.9
% Low-lit to high-lit	2.0	7.7	9.1	21.2	7.0
% No-lights to high-lit	0.2	0.2	0.3	1.2	0.3
High-lit annual expansion rate 1992–2009	2.8 %	5.6 %	4.2 %	5.3 %	3.9 %
Intermediate-lit area (km^2)					
In 1992	5812	1860	1646	1107	10425
In 2009	8365	3892	3320	1337	16953
Trajectory of change to intermediate-lit (1992–2009)					
% High-lit to high-lit	41.6	25.8	23.8	19.7	32.7
% Low-lit to int-lit	46.8	68.4	57.0	57.1	54.5
% No-lights to int-lit	9.2	5.1	18.3	24.2	11.2
Int-lit annual expansion rate 1992–2009	2.2 %	4.4 %	4.2 %	1.3 %	2.9 %

The average annual percentage rates of urban expansion (ARUE) were calculated as ARUE $= 100*((UE_{end}/UE_{start})^{(1/d)} - 1)$, where UE_{start} is the extent of the urban area at the initial time period, UE_{end} the extend of the study at the final time period, and d the time span in years. The trajectory of change is the distribution (in percentages) of the class transitions from 1992 to 2009. For example, 0.3 % of the high-lit area in 2009 was low-lit in 1992 in the region category

this time along with the migratory waves increased the demand for labor in cities, and motivated the improvement of infrastructure and services in urban areas.

Between 1956 and 1968, the historic period called *Formalidad Democrática*, Peru had a remarkable economic expansion and the development of infrastructure and state services, which stimulated urbanization (Palacios 2005). People migrated to Lima and to the main cities of the country attracted by new economic opportunities. This caused a rapid increase in the country's proportion of urban population, from 35 % in the 1940s to 60 % in the 1970s. Migration to urban centers increased during the 1980s and continued in the early 1990s in response to security concerns in the countryside caused by armed conflicts (Coral 1994). This large influx of migrants concentrated on low density settlements on the edges of the cities (Coral 1994). Based on NTL, by 1992, the urban cover in Peru consisted of compact urban areas of 612 km^2 and intermediate urban areas that doubled the urban compact areas in size (1239 km^2) (Table 3). Similar rates of expansion of compact and intermediate areas between 1992 and 2009 indicate that a dual model of urban dynamics occurred in Peru's main cities: densification of the city centers and an increase in lower-density development in the peripheries due to squatter and informal settlements (Table 3) (Pereyra 2009). The latter is particularly evident in Lima, where 20–30 % of the city population lives in informal settlements in the cities' marginal lands (Riofrío 2003).

Similarly, rural to urban migration has been a major driver of urban population growth since the 1950s in Colombia. During the decade of the 1950s, political and social armed conflicts were the main cause of the migratory trends towards the cities (Etter et al. 2008). The political violence and struggles over land during the period called *La Violencia* (1946–1965) resulted in 3 million peasants migrating from the countryside to urban areas (Sánchez 2007). In the 1970s, the urbanization trend was further fueled by the increasing industrialization around the larger economic centers such as Bogota, Medellin, Cali, and Barranquilla. As a result, urban population reached 75 % of the total population (Etter et al. 2008). Forced displacement of peasants due to rural violence continued during the 1980s, 1990s, and 2000s, contributing to more than 3.5 million migrants to urban areas between 1985 and 2006 (CODHES 2006). This increase in urban population was related to a twofold increase in Colombia's compact urban cover, and ~1.5-fold in the intermediate urban cover between 1992 and 2009 (Table 3). Recent urban initiatives in Colombia are promoting the densification of its main cities (e.g., Bogota, Medellin, Cali, Barranquilla), to accommodate urban population growth (Sarmiento 1999); however, densification of the urban core may be difficult to detect by NTL given problems of oversaturation (Letu et al. 2012).

Colombia and Peru urbanized very rapidly, but recent trends of lower fertility rates are contributing to slower urban population growth (Cerrutti and Bertoncello 2003; Cotlear 2006; Miller 2010). According to The World's Bank estimates (2012), fertility rate in Colombia declined from 3.0 to 2.4 between 1992 and 2009, and in Peru, from 3.6 to 2.5 (total births per women). The contribution of rural–urban migration to urban growth has also declined in Peru and Colombia. Rural–urban contributed 56.8 and 50.5 % of urban growth in the 1960–1970 in Peru and Colombia, but in the period 1990–2000 these rates decreased to 14.9 and 30.8 %, respectively (Cerrutti and Bertoncello 2003).

The comparison of urban population size and high-lit urban areas between Peru and Colombia suggest that more compact urban development is occurring in Peru. This is because urban populations of similar sizes (10 000 to >100 000 inhabitants) corresponded to smaller high-lit areas in Peru than in Colombia (Fig. 4). These results corroborate other NTL studies examining GDP and population size, where countries with lower GDP had greater aggregated population densities than countries with higher GDP (Sutton et al. 2010). But the oversaturation of NTL may be hindering the detection of important patterns in these highly urbanized cities. These preliminary observations call for a more detailed study of urban densities in the highly populated cities of these countries.

Ecuador and Bolivia: Intermediate Urban Transition

Ecuador and Bolivia, which are at an intermediate stage of the urban transition, started their urbanization process in the late 1970s and early 1980s (Fig. 1), and by 2009 approximately 65 % of the population in Ecuador, and 69 % of the population in Bolivia lived in urban areas.

In Ecuador, urban growth was associated with unprecedented economic growth due to the beginning of oil exports in 1972 (Carrión and Vazconez 2003). The production and export of oil stimulated government spending on infrastructure in urban areas (roads, electricity, telecommunications, and water services) as a means to promote industrial expansion and manufacturing. This economic growth also stimulated the migration of people to work in construction and services industry (Peek 1980). Rural to urban migration continued to fuel urban growth in the 1990s (Martine et al. 2008). Urbanization occurred simultaneously in the two major cities of Quito and Guayaquil, but there was also substantial urban growth in medium-sized cities (e.g., Manta, Cuenca, Esmeraldas) (Carrión and Vazconez 2003). By 1992, Ecuador had $\sim 444\ km^2$ of compact urban cover, and $\sim 1860\ km^2$ in intermediate urban cover, and these areas more than doubled in 17 years. Ecuador had the highest expansion rate of compact and intermediate urban areas between 1992 and 2009 when compared to Peru, Colombia, and Bolivia (Table 3). The dynamics of urban expansion at the municipality scale also showed that many municipalities in Ecuador have transitioned from our no-light and low-lit classes to intermediate and high-lit classes (Fig. 5). Projections of urban expansion for Ecuador indicate that most of the large to medium-size cities that are growing rapidly are expected to double their populations and triple their built-up areas in the next 25 years (Martine et al. 2008).

In Bolivia, between 1981 and 1990, two main events triggered waves of migration to urban areas (Balderrama et al. 2011): (1) a drought from 1983 to 1985, which impoverished rural people in the valleys and the highlands, and (2) an economic crisis from 1985 to 1990, which caused the closing of tin mines. These events caused migration in different directions: to the largest cities (La Paz, Cochabamba, and Santa Cruz), to rural areas in the lowlands, mainly El Chapare (Cochabamba), San Julian (Santa Cruz) and Yucumo-Rurrenabaque (Beni), and abroad (the United States and Argentina). Since these events, rural–urban migration has continued to fuel population growth and to populate new urban settlements (Balderrama et al. 2011). The expansion of compact urban land occurred to a large extent over sparsely developed urban areas (i.e., low-lit to high-lit) (Table 3). A major area of urban expansion in Bolivia has been the conurbation formed by the municipalities of La Paz and El Alto (Arbona and Kohl 2004). Since 1950, population growth has been dramatic in this urban area doubling in size by 1970, and then doubling again by 2000 (INE 2011). Santa Cruz, considered the economic capital of Bolivia, has also experienced rapid urban growth in part due to the hydrocarbon industry and agricultural exports (Balderrama et al. 2011), and is one of the fastest growing urban areas in South America (UN 2010).

The urban populations of Ecuador and Bolivia have continued to increase at rapid rates. The urban population in Bolivia is increasing at an annual growth rate of 3.9 %, followed by Ecuador with an annual growth rate of 2.8 % (Table 1). Both in 1992 and 2009, Bolivia had the highest fertility rates in the region (4.8 and 3.4). Although the fertility in Ecuador (3.5 in 1992 and 2.5 in 2009), was similar to the levels of Peru, its urban populations continues to increase rapidly due to high rates of rural–urban migration. Rural–urban migration continues to be a major driver of urban growth in Ecuador and Bolivia; rural–urban migration contributed 46.7 and 34.7 % of urban growth in the 1970–1980, but in the period 1990–2000 these rates increased to 50.5 and 36.3 %, respectively (Cerrutti and Bertoncello 2003). In general, between 1992 and 2009 Ecuador and Bolivia underwent a very dynamic urbanization process as suggested by the changes in the compact urban class (Table 3). Ecuador's and Bolivia's compact urban areas expanded at a faster rate than those in Peru and Colombia, and most of this change occurred due to the intensification of intermediate urbanized regions (i.e., transition from intermediate-lit to high-lit).

CONCLUSION

Latin America has seen the fastest urban growth in history (Angel et al. 2011). As urban areas continue to grow faster than rural areas, the need for housing, infrastructure, and urban services will require increased resources and attention to mitigate problems of concentration and congestion in urban areas (Grimm et al. 2008). Despite rapid population growth in Latin America, urban expansion is taking place in substantially different patterns across countries. Countries with longer urban growth histories are undergoing lower urban population growth and reduced rates of urban expansion, whereas countries in early stages of urban growth are expanding faster in response to urban population growth. Our study illustrates the effectiveness of nighttime lights to monitor urbanization dynamics at different scales. As worldwide data sets are readily available from the National Geophysical Data Center website, nighttime lights are a feasible alternative for mapping urban growth. This is especially the case for areas that lack reliable or up-to-date demographic and socioeconomic data and require a homogeneous platform for multi-scale analysis across different countries.

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