Built-up expansion between 2001 and 2011 in South America continues well beyond the cities

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Abstract

The expansion of built environment is a major driver of land change which can have irreversible consequences on the environment, ecosystem services, and biodiversity. While most studies have focused on urban areas, particularly large cities, the built environment includes much more. This is exemplified by the complex interconnection among cities of all sizes and rural areas through trade, people, policies, and infrastructure, which ultimately shapes the patterns of land use. However, a comprehensive spatial analysis of built-up areas is lacking. Here, we used nighttime data to evaluate the extent and spatial distribution of the built environment across the South American continent between 2001 and 2011, with the objectives of determining where built-up expansion is occurring and the relative contribution of the 30 major cities with populations greater than 1 million people. Our results reveal that built-up expansion occurs well beyond the 30 major cities, with the majority of expansion occurring in small and medium cities and rural areas. This detailed and spatially explicit description of development patterns across South America provides a valuable baseline for land use policies, which hopefully will balance future built expansion with the need for agriculture lands and the protection of large uninterrupted natural areas.

1. Introduction

The built environment comprises all human-made infrastructures located in urban areas (e.g. cities, towns, suburbs, and conurbations), rural areas (e.g. villages and farms), and transport networks (e.g. roads, railways, and canals). In general, studies addressing some aspect of the built environment have focused on urban areas, particularly large cities, the built environment includes much more. This is exemplified by the complex interconnection among cities of all sizes and rural areas through trade, people, policies, and infrastructure, which ultimately shapes the patterns of land use. Therefore, a thorough evaluation of the built environment should include all infrastructure associated with humans and their activities, regardless of where it occurs.
producer of agricultural products, and between 2001 and 2013 the area in pastures and croplands expanded considerably (Graesser et al. 2015). South America is also a major global exporter of raw materials (e.g. petroleum, minerals, gas, and agricultural) (Belloni and Wainer 2014). All of these activities require infrastructure and energy, and part of the increasing demand for energy will be provided by >300 hydroelectric dams in construction or in the planning stage in the Andes (Finer and Jenkins 2012) and the Brazilian Amazon (Lees et al. 2016). The increase in population, agriculture, and energy production all point to a large and extensive expansion of the built environment in a continent with five of the 25 biodiversity hotspots (Myers et al. 2000), 39 of the 137 most irreplaceable areas for biodiversity conservation on Earth (Le Saout et al. 2013), and the largest area of relatively undisturbed tropical forest (Eva et al. 2004).

In this paper, we assess the patterns of built-up expansion across the South American continent between 2001 and 2011. We determine the extent and spatial distribution of built-up areas and evaluate the relative contribution of the major 30 cities (urban areas with >1 million people) to built-up expansion. Our analyses showcase the diverse dynamics of built-up expansion, particularly its rapid expansion outside of the major urban centers.

2. Methods

We use nighttime light (NTL) data to evaluate the patterns of built-up expansion in South America between 2001 and 2011. We selected the 2001–2011 timeframe because it included the most recent and high-quality DMSP-OLS NTL images (Zhang et al. 2016). In addition, this timeframe included the most recent population censuses in most South American countries. Instead of using the common urban/non-urban classification method, we classified NTL data into three built-up classes across a gradient of compactness: no-development (no compactness), scattered (low to medium compactness), and aggregated (medium to high compactness) following the methodology used in smaller-scale studies in South America (Parés-Ramos et al. 2013) (figure S1 available at stacks.iop.org/ERL/13/084006/mmedia). With these data, we first estimated the extent, spatial distribution, and transitions among the three built-up classes for all of South America, and for the 11 573 municipalities (i.e. second or third administrative units) within the 13 countries of the continent. Second, we generated a spatial population dataset at the municipality-level using national census data. Following this, we classified municipalities based on built-up and population net changes between 2001 and 2011, and then assigned each municipality to one of four built-up/population categories: (1) shrinkage, (2) densification, (3) rural expansion, and (4) urban expansion. Finally, we evaluated the relative contribution of the 30 major cities (i.e. urban areas with >1 million people) to built-up expansion by extracting the extent of scattered and aggregated expansion area between 2001 and 2011, as well as the total, urban and rural population in 2011 for these municipalities within a buffer of 50 km radius from the center of each city (figures S2 and S3) and compared these data with built-up expansion, and population data in the rest of the continent. The scales of the analyses in this study are South America, municipality, and the 50 km buffer around the 30 largest cities. In addition, population data was obtained at the municipality scale and NTL data was collected at the 1 km² pixel scale.

In this study, we used the term ‘urban area’ for a human settlement with large population and high population density which is dominated by the built environment in a contiguous area (table S1). To clarify the urban definition and other key terms used throughout this manuscript, we provide a brief definition of each term in table S1. Methods are described in more detail in the supplementary information.

3. Results and discussion

The spatial distribution and changes in the built-up classes varied greatly across South America (figure 1). Between 2001 and 2011 the aggregated built-up class increased from 94 606 km² (0.54%) to 123 766 km² (0.7%) (figure 2). Our aggregated built-up class corresponds well with the urban class commonly used in other studies, and our estimate of the extent of this class is similar to previous estimates (Schneider et al. 2009, Zhou et al. 2015). During the 10 year study period, the area of aggregated (i.e. urban) expansion was 29 160 km², equivalent to the area of Belgium (30 528 km²). Although other studies have suggested that urban expansion will slow in highly urbanized South America (Angel et al. 2011b, Seto et al. 2011), we documented a ~30% increase in the aggregated built-up class over 10 years. The scattered built-up class increased at an even faster pace (3.7% yr⁻¹), from 938 235 km² (5.3% of South America) in 2001 to 1 286 434 km² (7.27%) in 2011 (figure 2). The sum of the scattered and aggregated built-up classes (i.e. built-up area) increased by 377 359 km², an area equivalent to the size of Suriname and Guyana combined, increasing from 5.84% (2001) to 7.97% (2011) of the South American continent (figure 2). As a result of built-up expansion, the area of the no-development class decreased 377 360 km² (~2% of South America) between 2001 and 2011 (figure 2).

Given that recent studies on urban expansion in South America have highlighted a sprawling growth pattern around the fringes of major cities (Inostroza et al. 2013, Parés-Ramos et al. 2013) and nearby cities being absorbed by larger metropolises (ONU-HABITAT 2012, Pulido 2014), we expected that the majority
of built-up expansion would be located around the major cities (30 urban areas with > 1 million people). Nevertheless, our findings showed a different pattern; built-up expansion occurred well beyond the proximity of the 30 major cities. Furthermore, only 3.6% of the scattered expansion and 21% of the aggregated expansion area in South America occurred within 50 km of the 30 major cities despite the fact that 44% of South American urban dwellers live in these areas (figure 3(a)).

We found that 56.5% (n = 6542) of municipalities had a net increase in built-up areas coupled with an increase in total population (table 1). Specifically, we found that built-up expansion occurred predominantly in municipalities with a maximum urban population of 50,000 inhabitants (figure 4). In addition, our results showed that rural expansion (i.e. a net increase in built-up area associated with a decrease in total population) occurred in 20.5% of municipalities (table 1). This result suggests that built-up expansion is occurring outside urban agglomerations across the continent. The third most common pattern was densification (table 1), which occurred in 15.1% of the municipalities. Of the 1738 municipalities that had an increase in population, but no increase in built-up area, 23.5% occurred in Colombia (table S2). Finally, 7.9% of the municipalities lost population and built-up area (table 1), and while these municipalities occurred across South America, 65% occurred in mountainous areas (>1000 m) (e.g. Andes).

These results clearly demonstrate that built-up expansion in South America continues well beyond the cities, supporting the argument that growth in many countries is shifting to small and medium cities (OUNHABITAT 2012) (figure 4). These cities play a central role in rural-urban interactions as they are tightly linked with activities (e.g. agriculture, mining) occurring in the surrounding rural areas (Bolay and Rabinovich...
Figure 2. Built-up class transition between 2001 and 2011 in South America. The extent (km$^2$) of each built-up class transition is reported. ND = no-development, SC = scattered, and AG = aggregated. The extents for ND-AG and AG-ND are showed above the asterisks.

Figure 3. Comparison of built-up expansion and population between the 30 major cities in South America and the rest of the continent. (a) Area of scattered and aggregated built-up classes expansion between 2001 and 2011. (b) Total, urban, and rural population in 2011 in the 30 cities and in South America. Built-up expansion and population data for each city were obtained by extracting data using a 50 km buffer from the city center.

Table 1. Built-up and population dynamics of the 11,573 municipalities in South America between 2001 and 2011. The changes in built-up area and population represent four general patterns: urban expansion, rural expansion, densification, and shrinkage.

| Pattern | Pattern name | Number of municipalities | Percent |
|---------|--------------|--------------------------|---------|
| Built-up >0 and Total pop. >0 | Urban expansion | 6542 | 56.5 |
| Built-up >0 and Total pop. ≤0 | Rural expansion | 2381 | 20.5 |
| Built-up ≤0 and Total pop. >0 | Densification | 1738 | 15.1 |
| Built-up ≤0 and Total pop. ≤0 | Shrinkage | 912 | 7.9 |

Therefore, in an era of political and administrative decentralization (Bolay and Rabinovich 2004), we expect that the expansion of the built environment will continue in small and medium cities across South America.

Furthermore, much of the scattered expansion in rural areas could be associated with large development projects (e.g. gas and oil extraction, hydroelectric power plants, and tourism) and the rapid urbanization of small towns on the agriculture frontier (da Gama Torres 2004).
Figure 4. Built-up class expansion between 2001 and 2011 by municipality urban population classes. Built-up class expansion includes: ND-SC = no-development to scattered, ND-AG = no-development to aggregated, and SC-AG = scattered to aggregated.

2011, Chen et al 2015). For example, in Peru, infrastructure was an important driver of forest loss (5.6%), mostly due to illegal mining activities, and in Venezuela dam construction contributes to 37.8% of deforestation (De Sy et al 2015). In Brazil, anthropogenic activities related to human settlement and resettlement such as road expansion, building construction, agriculture conversion, and logging were identified as the major drivers of deforestation around the Tucuruí Dam (Chen et al 2015).

In addition, another driver of the large increase in the scattered built-up class could be the ‘parcelization’ of continuous agricultural lands and natural areas. For example, in Ecuador both peri-urban and rural areas are being converted into primary or vacation residences (Reyes-Bueno et al 2016).

4. Conclusion

These analyses highlight two major points. First, while South America has a very urbanized population, the expansion of the built environment was not concentrated around the largest cities. On the contrary, the majority of change occurred around municipalities with ≤50,000 urban inhabitants and in rural areas. Our results, specifically the built-up change map, the recognition of four built-up/population patterns, and the identification of major areas of built-up expansion provide valuable baseline information for major organizations (e.g. the World Bank, United Nations Human Settlements Programme) and the international research community (e.g. Future Earth Global Land Programme) to better understand the implications of globalization, to promote sustainable development approaches and developed land policies that mitigate the undesired effects of the built environment.

Second, the rapid expansion and dispersed spatial distribution of the built environment beyond major cities have enormous implications for biodiversity conservation. Although approximately ~50% of South America is classified as forest (Eva et al 2004) and 24% of the continent has some level of protection (https://protectedplanet.net/), our analyses showed a significant reduction on areas free of development (i.e. no-development).

Expanding agriculture frontiers (Graesser et al 2015), hydroelectric dams (Finer and Jenkins 2012, Lees et al 2016), petroleum exploration (Baynard et al 2013) and mines (Alvarez-Berrios and Aide 2015) are important components of the built environment even though they often occur far from urban areas. They all require infrastructure, in particular roads, which provide access to new areas for further development (Baynard et al 2013, Lees et al 2016) causing deforestation and forest degradation (Chen et al 2015). In South America, the rapid expansion of the built environment beyond cities is contributing to the reduction and fragmentation of the largest tracts of tropical forest on the planet.

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