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Land development, land use, and urban sprawl in Puerto Rico integrating remote sensing and population census data

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Abstract

The island of Puerto Rico has both a high population density and a long history of ineffective land use planning. This study integrates geospatial technology and population census data to understand how people use and develop the lands. We define three new regions for Puerto Rico: Urban (16%), Densely Populated Rural (36%), and Sparsely Populated Rural (48%). Eleven percent of the island is composed of urban/built-up surfaces. A large part of these developments occur in both low-density patterns of construction and sparsely populated neighborhoods. Half of the urban development occurs outside of urban centers. This analysis helps differentiate zones in the landscape with different uses and conditions, identifying not only urban and rural settings, but also the interface where development occurs in a territory dominated by forests and pastures, analogous to a wildland urban interface. The ineffective plan of land development has left a high degree of urban sprawl in 40% of island, where cities and towns appear typically surrounded by sprawl. The San Juan Metropolitan Area is one of the most expanded urbanized areas with a population of 2–2.5 million, comparable with the most sprawled cities of the U.S. mainland. This study reinforces the need for an efficient land use planning, and provides information to support research and planning efforts related to land development and conservation. It represents the first approach integrating satellite imagery with population census data for studying the human environment in the Caribbean.
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Keywords: Land development; Urban cover; Urban sprawl; Population census; Land use; Remote sensing; Puerto Rico

1. Introduction

Urbanization is a significant problem in many parts of the world, particularly in densely populated territories such as Puerto Rico. Island-wide analyses of urban development and population distribution provide an opportunity to visualize and understand the human use of the landscape. They are useful for projecting trends in urbanization, assessing "smart growth" and conservation efforts, and for evaluating ecosystem impacts of human activities. In this study we combined satellite information with population census data to study three main aspects of the Puerto Rican landscape: development, land use, and urban sprawl. We first map the most recent urban/built-up cover. Then we analyze patterns of land development, identify areas of urban and rural use, and address land consumption. We ultimately combined this information to identify different tendencies in urban sprawl. Finally, we used population density to compare the San Juan Metropolitan Area (SJMA) with other urbanized areas in different countries.

1.1. Urbanization and planning in Puerto Rico

Puerto Rico is an attractive region for urban studies: first, it is a densely populated island where urbanization has occurred under an ineffectual plan of land development that has resulted in uncontrolled urban sprawl (Puerto Rico Vision 2025[1]); sec-

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[1] Puerto Rico Vision 2025 is a governmental long-term vision for the island, encompassing all aspects of economic, social, environmental, and infrastructure development.

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ond, the landscape is in rapid transformation due to urban expansion and forest recovery (Lopez et al., 2001; Helmer, 2004); and finally, the island could be considered as a "window into the future" of many tropical landscapes that are undergoing a transformation from agriculture to industrial economies, change that happened in Puerto Rico 60 years ago (Dietz, 1986).

Nearly 3.9 million people live in the 9000 km^2 (160 km × 60 km) of Puerto Rico. As a result, it is one of the most densely populated regions in the U.S. and territories, with 438 persons/km^2 (similar to the State of New Jersey) (U.S. Census Bureau, 2000a). Politically, the island is subdivided in 78 municipalities, the equivalent of counties in the U.S. Each municipality contains one urban center, either a city or a smaller town. The San Juan Metropolitan Area encompasses 41 from 78 municipalities (U.S. Office of Management and Budget, 2000). Recent past estimates of urban/built-up cover using satellite imagery such us Landsat ETM+ or Spot range from 11% (Helmer and Ruefenacht, 2005) to 14% of the island (Lopez et al., 2001). As in many mountainous islands, urban centers are concentrated on the coastal plains or restricted to valleys. Urban developments have grown 7% between 1991 and 2000. They expand at lower elevations, over flat topography, and close to roads and urbanized areas (Thomlinson et al., 1996; Helmer, 2004; Lopez et al., 2001; Thomlinson and Rivera, 2000), facilitated by an extensive rural-road network developed during the agricultural era. Residential constructions are typically horizontal. The small size of the Puerto Rico and the extensive road network make it possible to commute from one region of the island to any other.

Urban sprawl has been part of the Puerto Rican environment for the last 40 years (Santiago, 2004). It is defined as "peripheral growth that expands in an unlimited and non-contiguous way outward from the solid built-up core of a metropolitan area" (Transportation Research Board, 2002). It is characterized by low-density development (Edwin, 1997), significant per capita land consumption of exurban lands, and almost total reliance on the automobile for transportation. Principal consequences include traffic congestion, increase in energy consumption and costs for community services, reduction of open spaces and fragmentation of habitats, and pollution of waterways and air. Today, Puerto Ricans are suffering the consequences and paying the costs of sprawl. In the island, traffic jams are habitual, enhanced by a high proportion of cars per person equal to 0.54 (U.S. Department of Transportation, 2002), industrial electricity costs are 73% higher than for developed economies and are dependent on imported oil, and 40% of water bodies are impacted and do not meet quality standards (Puerto Rico Vision 2025). Productive agricultural lands have been transformed into urban areas (Helmer, 2004; Lopez et al., 2001), and even forest reserves like the Caribbean National Forest come under human pressure (Lugo et al., 2004). An illustration of the importance of sprawl to the government is the US$ 2 billion investment in a light-rail "Urban Train" system to provide for an alternative and more effective type of transportation in the SJMA.

Urban planning is not a new issue in Puerto Rico. Several laws and institutions do exist,[2] but the problem is that planning and environmental assessment is done using a lengthy and unpredictable evaluation process, and the current permitting system is seen as widely inefficient, where the exceptions are the rule (Puerto Rico Vision 2025). As part of the local efforts to revert this situation, the government recently created the Office for Land Use Planning (http://www.gobierno.pr/OPUT), where the major objective is the development and implementation of a plan of land use for the island.

Notably, there is a lack of scientific studies analyzing the Puerto Rican landscape integrating both land development and population. We have addressed the following questions: What is the extent of developed lands? How are these lands distributed across the island? How are people distributed in the lands they occupy? Which areas of the island suffer from urban sprawl, and how does urbanization spread out from the core of urban centers?

1.2. Remote sensing of urban areas

Remote sensing technologies provide a powerful tool for studying urban problems, including those related to urban/built-up land cover mapping (Helmer and Ruefenacht, 2005; Seto and Liu, 2003; Yang et al., 2003; Lopez et al., 2001), urban growth modeling (Herold et al., 2003; Wilson et al., 2003a), urban sprawl (Clapman, 2003; Sutton, 2003), zoning (Wilson et al., 2003b), population density (Pozzi and Small, 2002), urban density (Faure et al., 2003), and environmental effects of urban development (Gillies et al., 2003; Milesi et al., 2003). Additional information comes from integrating remotely sensed data and ancillary sources such as population maps (Hutchinson, 1982; Mesev, 1998; Radelhoff et al., 2000; Sutton, 2003).

The major problem for mapping urban areas using satellite imagery resides in the diversity and heterogeneity of its spectral response (Herold et al., 2002; Green and Boardman, 2000; Small, 2002), which results in a preponderance of spectrally mixed pixels observed in Landsat imagery of urban areas (Small, 2003). Mixed pixels are problematic for mapping using conventional classification methods because most algorithms are predicated on the assumption of spectral homogeneity within a particular type or land cover; therefore, the urban mosaic can result in high rates of misclassification between urban and other land cover classes. Previous studies for Puerto Rico mapped the urban cover by two different methods: simple photo interpretation of aerial photography and Spot imagery (Lopez et al., 2001; Thomlinson et al., 1996; Thomlinson and Rivera, 2000), or using automated classification algorithms (supervised, unsupervised, or both) in Landsat TM or ETM+ data (Helmer and Ruefenacht, 2005; Helmer et al., 2002; Ramos Gonzales, 2001). In these studies, stratification of the imagery by pre- or post-clustering,

[2] A list of near 40 regulations, zoning and land management plans for different areas of Puerto Rico are listed in http://www.gobierno.pr/OPUT/LeyesReglamentos.

or both, improves the classification by reducing heterogeneity within strata. Additionally, aerial photos have been used to manually discriminate, misclassified pixels corresponding to pastures, agricultural lands, and natural barrens.

Studies for Puerto Rico analyzed urban areas in terms of extent and growth, considering the developed lands as a single and uniform category. Differentiation in high and low-density developments has been made for only 1 of the 78 municipalities (Luquillo) and by visual interpretation (Thomlinson and Rivera, 2000). Our distinctive contribution for understanding the human landscape resides in mapping and analyzing different classes of development and land uses for the entire island using automated methods.

An additional problem for the Caribbean, as well as for other humid and mountainous regions, is related to persistent cloud cover in the satellite imagery. Applications may require cloud and cloud-shadow-free parts from many scenes for each specific map.

1.3. From urban cover to urban use—rationale and terminology

"Urban" pixels that form the basis of many remote sensing analyses consist typically of developed and non-vegetated surfaces (pixels) that result from human activity, including built structures, concrete, asphalt, and buildings. We refer to them as "urban/built-up cover" or "developed lands". However, from a land-use perspective, these areas may or may not be within what we think as, and refer to, "urban use" setting. Urban use settings may also include a number of non-developed and vegetated pixels such as parklands and urban forests, and may exclude developments that are components of other land uses.

The U.S. Census Bureau provides a different view for the urban component of the landscape. According to the 2000 Urban and Rural Classification (U.S. Census Bureau, 2000b), all territory, population, and housing units located within census block that have a population density of at least 1000 people/mi^2 (or 390 people/km^2), plus surrounding census block that have an overall density of at least 500 people/mi^2 (or 195 people/km^2), are considered urban areas. All territory, population, and housing units located outside urban areas are rural areas. From the census perspective, 50% of the island is urban and 50% is rural. Although the idea (and extent) of what is "urban" varies from census and remote sensing environment, they are not mutually exclusive. Linking remotely sensed data with population census data has shown its value as auxiliary information for image classification (Hutchinson, 1982; Mesev, 1998), in an examination of housing density (Radelhoff et al., 2000), and in analysis of urban sprawl (Sutton, 2003).

Finally, "land consumption" is used to refer to the amount of urban/built-up lands that people use (persons per developed km^2).

2. Data and methods

The resources for this study consisted of Landsat ETM+ images, aerial photos, and information from the U.S. Census 2000, including population for the 900 neighborhoods, and the Urban and Rural Classification. The set of images included cloud-free parts from 18 individual Landsat ETM+ scenes acquired between 1999 and 2003, with 15 m pixel resolution. We used NOAA aerial photos from 1999 at the scale of 1:48,000 as auxiliary data for image interpretation. We used ERDAS IMAGINE 8.7 (ERDAS, 2003) software.

The complete process of our study can be envisioned as six major steps: (1) image preparation, (2) mapping of developed lands, (3) analysis of patterns of land development, (4) analysis of land use, (5) analysis of land consumption, and (6) analysis of urban sprawl (Fig. 1).

2.1. Image preparation

The first step was to create a composite image for Puerto Rico. We constructed a mosaic of the imagery, attempting to minimize the spectral differences among individual images, using the least number of scenes, and maintaining the same season when possible. The best solution was to create two complementary mosaics. The first mosaic was made from six images covering 80% of the island. For the remaining area we made a second mosaic, using 12 images, which cover another 17% of the island. The second mosaic includes more spectral variability due to multi-date acquisition, which represents a disadvantage for image classification, but this variability was confined to a small area. As a result, the two mosaics combined cover 97% of Puerto Rico. Only 3% of the island was persistently covered by clouds, principally in forested areas at high elevations.

2.2. Mapping of developed lands

We mapped the urban/built-up cover separately in each of the two mosaics using the Iterative Self-Organizing Data Analysis Technique (ISODATA) unsupervised classification algorithm (ERDAS, 2003), with a large number of clusters per scene: 300 in the first mosaic and 60 in the second, taking into consideration the spectral variability related to the complexity of the landscape and the multiple dates. NOAA aerial photos, previous land cover from 1991 to 1992 (Helmer et al., 2002), field knowledge, and expert opinion were used for image interpretation and for the identification of misclassified pixels. The two partial urban/built-up coverages were ultimately joined together and areas with persistent clouds (3%) were replaced with previous land cover data. The accuracy assessment consisted of a random sample of 100 ground control points for each category, urban and non-urban, that were evaluated using NOAA aerial photos.

2.3. Analysis of patterns of land development

We identified two patterns of urban developments: high and low-density. We used a textural filter that evaluates, for a certain developed pixel, the proportion of developed versus non-developed pixels in a surrounding area. High-density refers to those urban pixels that are surrounded by more than 50% of developed pixels in a 300 m × 300 m window, while low-density

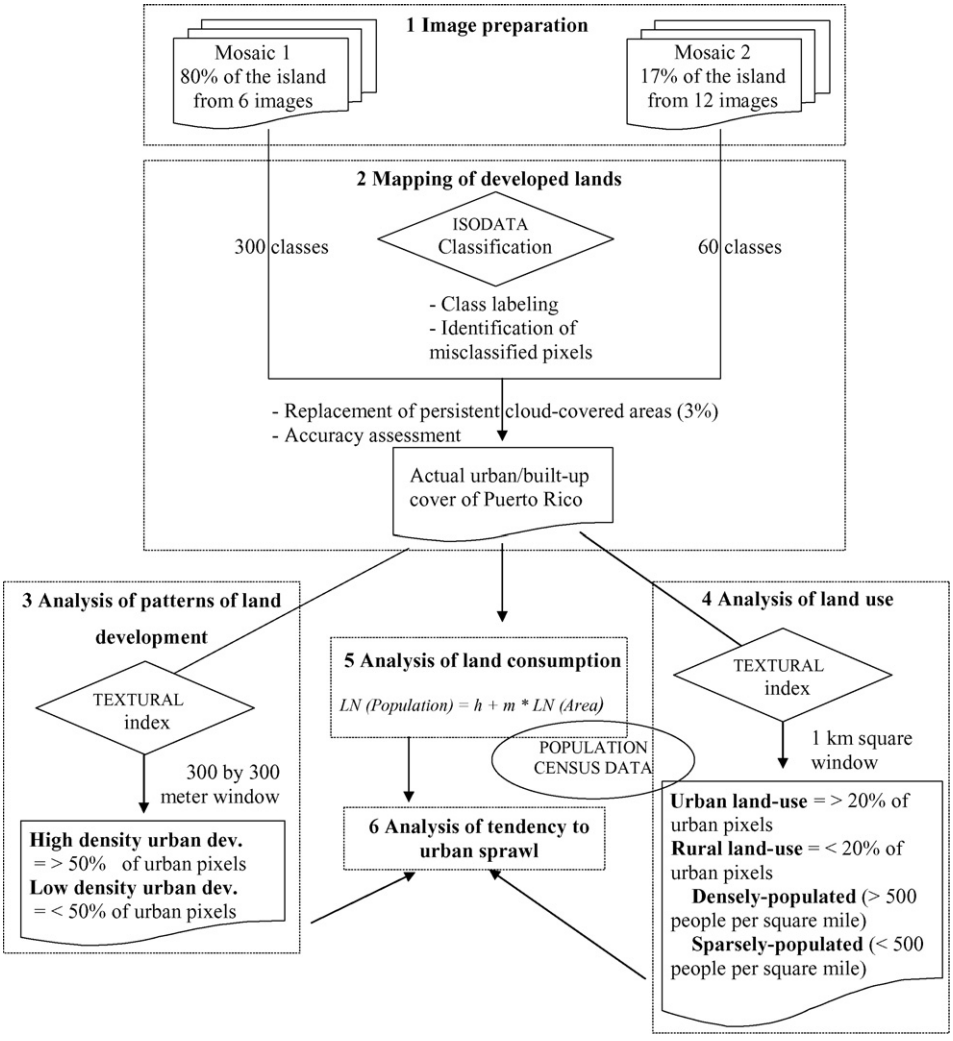

Fig. 1. Six steps involved in the methodology: image preparation, urban mapping, analysis of urban density, analysis of land use, analysis of urban-land consumption, and analysis of urban sprawl.

refers to those urban pixels that are surrounded by less than 50% of developed pixels. The dimension of the filter and the proportion of developed versus non-developed pixels for separate low and high-density were selected after testing with various dimensions and break points. We studied the distribution of high and low-density developments in relation to different topographic units and changes in slope.

2.4. Analysis of land use

We integrated the patterns of development in the landscape with census data and identified three types of land uses: (I) Urban, (II) Densely Populated Rural, and (3) Sparsely Populated Rural. We applied a similar texture approach for separating the urban-use from the rural-use areas. In this case the value for each pixel in the landscape is the proportion of developed versus non-developed pixels in a surrounding 1 km^2 window. Urban-use refers to those areas where the presence of developed pixels is greater than 20% within the window, while rural-use refers to those regions where developed pixels represent less than 20%. These parameters were set by visual interpretation of the limits of the urban centers and by comparison with aerial photos. We subdivided the rural areas, based on the Census Urban and Rural Classification for densely and non-densely settled/populated territories, into two additional classes: Densely Populated Rural (with core census block groups or blocks that have a population density of at least 1000 people/mi^2 plus surrounding census blocks that have an overall density of at least 500 people/mi^2), and Sparsely Populated Rural (with lower population density). Urban-use clusters smaller than 30 ha were considered as components of the rural class. Additionally, in the San Juan Metropolitan Area some major interior forests, parklands, and water bodies were incorporated manually.

2.5. Analysis of land consumption

We categorized each neighborhood based on the number of people per developed km^2 compared with the average reported for the island. We estimated for each one of the 900 neighborhoods from the U.S. Census, the difference between the real population (from the census) and the expected population (from the average of the island). This approach was originally applied

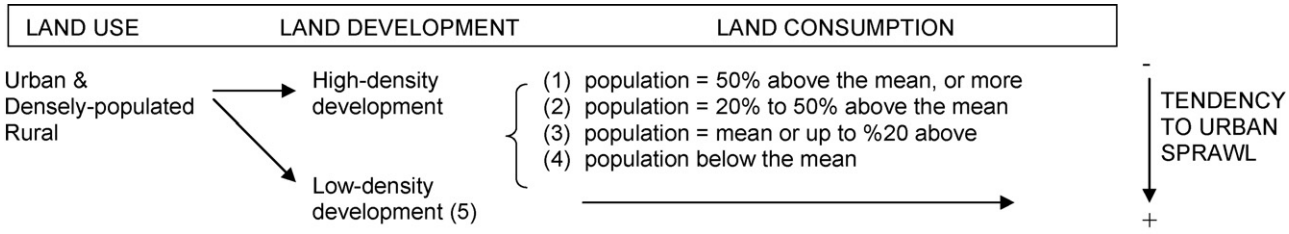

Fig. 2. Decision rules for identifying five classes of increasing tendency to urban sprawl based on parameters of land use, land development, and land consumption.

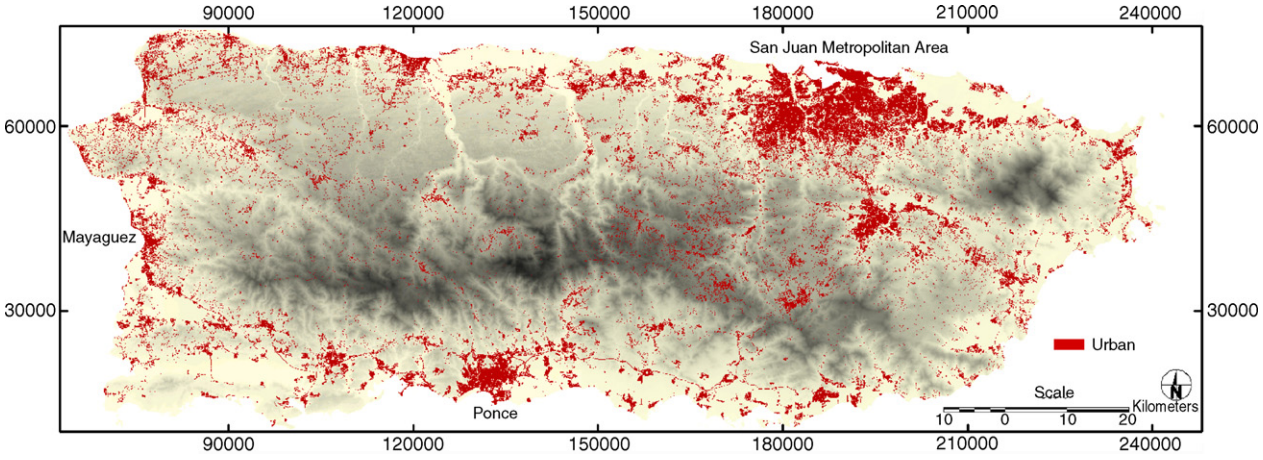

Fig. 3. Urban/built-up land cover of Puerto Rico in red, equal to 95,342 ha or 11% of the total area. The islands of Vieques and Culebra are not included in the map. Gray colors correspond to higher elevations, including the central mountains, and the Caribbean National Forest in the east. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

for study per capita land consumption and urban sprawl among different urban areas for the conterminous U.S. (Sutton, 2003). The assumption is that areas with higher than expected population will have lower land consumption than areas with lower than expected population.

2.6. Analysis of urban sprawl

We developed a classification schema to categorize the relative tendency to sprawl of urban developments by integrating previous steps (Fig. 2). We first identified the boundaries of urban expansion, territory where sprawl might take place. This corresponds to our Urban and Densely Populated Rural uses, region where urban areas growth maintains a high connectivity with urban centers. Outside this territory, in the Sparsely Populated Rural use, development can occur but less well connected with urban centers. Within Urban and Densely Populated Rural lands, we analyzed the patterns of construction and population distribution. Five classes of increasing tendency to sprawl were identified, ranging from 1 (lowest tendency) to 5 (highest tendency). Low-density developments were considered due to their natural non-compact spatial arrangement to have the greatest tendency to sprawl, even higher than any solid high-density development. Thus, low-density developments were included in category 5. High-density developments, on the other hand, were classified based on the population they are supporting: the higher the land consumption the higher the tendency to sprawl (Sutton, 2003). High-density developments with population above the expected were separated in categories 1–3, while high-density developments with population below the expected were included in category 4.

3. Results

3.1. Urban/built-up cover

Our study reported 95,342 ha of developed lands in Puerto Rico for 2000–2003, equivalent to 11% of the island. The Kappa coefficient (Landis and Koch, 1997) measured accuracy equal to 94%. Our estimation is consistent with those from Helmer and Ruefenacht (2005), which was calculated at a coarser scale (30 m pixel). Visual interpretation of the urban/built-up cover indicates that developed pixels are distributed throughout the island, including large urban clusters in coastal plains and valleys, and linear developments along highways and routes. A few open regions appear without this human impact: regions that are protected, have steep slopes, are dedicated to agriculture, or are affected by wetlands (Fig. 3). In relationship with the major physiographic units of the island, plains, hills, and mountains (Gould et al., 2005),[3] we found that 60% of the total develop-

[3] Physiographic units were identified using landforms (originally derived from parameters of slope and land position), and elevation ranges (Gould et al., 2005). The plains correspond to the original "plains" landform, while hills and mountains correspond to arrangements of non-plain formations with elevation below or above 400 m, respectively.

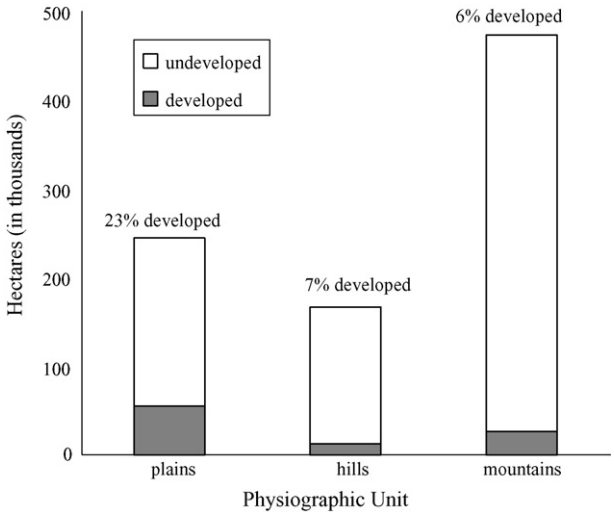

Fig. 4. Distribution of urban developments in plains, hills, and mountains. Plains account for 55,822 ha of urban developments, hills 12,284 ha, and mountains 27,236 ha.

ments occur in the plains, where the most productive lands for agriculture are also located. As a result, one-quarter of these rich soils have been transformed into built-up areas. In hills and mountains the presence of developed areas represents less than 7% of their total extension (Fig. 4).

3.2. High and low-density urban developments

From a total of 95,342 ha of urban/built-up lands, 54,899 ha (nearly 60%) corresponds to high-density developments, and 40,443 ha (nearly 40%) corresponds to low-density developments. High-density development reflects the compact pattern of construction within urban centers, including cities and towns, along important connections between major cities, and within exurban agglomerations that are non-contiguous with the urban centers; conversely, low-density reflects the non-contiguous pattern of development that expands outward from urban centers in linear features following the road network

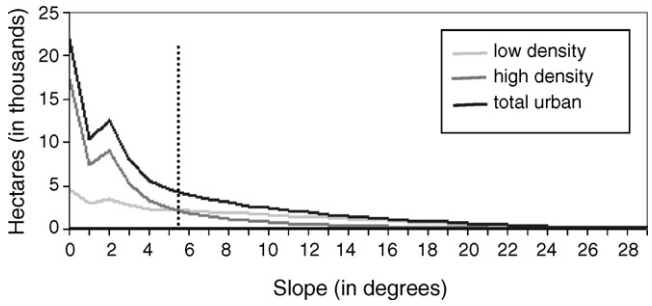

Fig. 6. Distribution of urban development in relation to the slope. The dash line between 5° and 6° represents the break point for the proportion of low and high-density developments. The peak at 2° is an artifact from the DEM (similar peak is found in the DEM).

and isolated constructions. Some of the biggest highways and routes are also included within the low-density developments (Fig. 5).

Development decreases rapidly as slope increases. This tendency is applicable to the total built-up areas as well as the high-density developments, but for low-density development the decrease with the slope is much slower (Fig. 6). Between 5° and 6° the relationship between the two types of development inverts. From 0° to 5–6° the amount of high-density development is greater than the corresponding low-density development, while the contrary if found at higher slopes. The 6° slope represents also the variable for separating plains from hills and mountains in the physiographic map of the island (Gould et al., 2005). Consequently, high-density development predominates in the plains, while low-density development predominates in hills and mountains (Fig. 7).

3.3. Urban and rural land uses

Urban use covers 16% of Puerto Rico (142,562 ha). It is home to 2.7 million people, and includes not only the major developments (urban centers, exurban agglomerations, industrial areas, large isolated residential complexes, ports, and airports), but also non-developed lands that are part of the urban landscape,

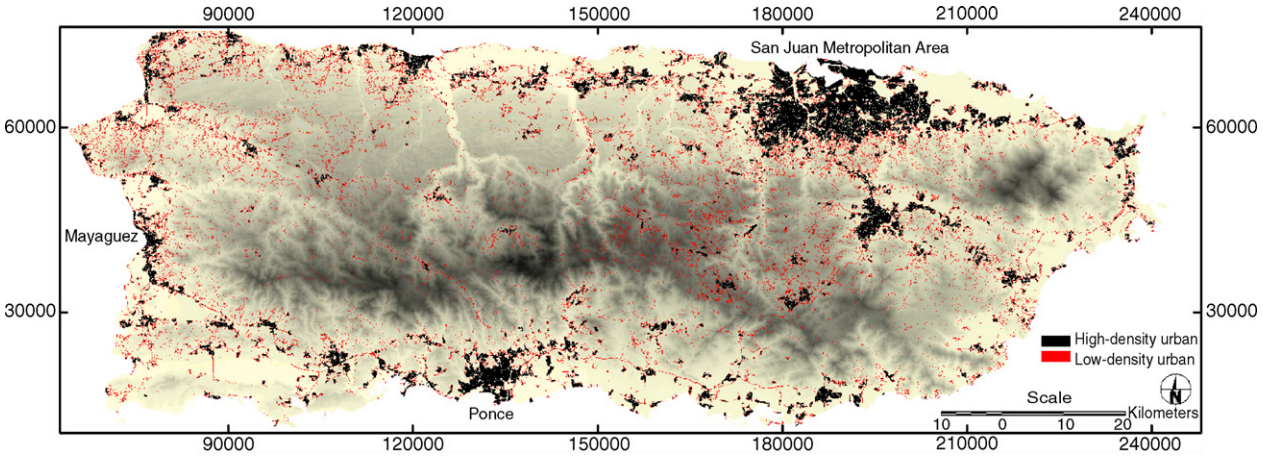

Fig. 5. Patterns of urban development of Puerto Rico: high-density developments (in black) and low-density developments (in red). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

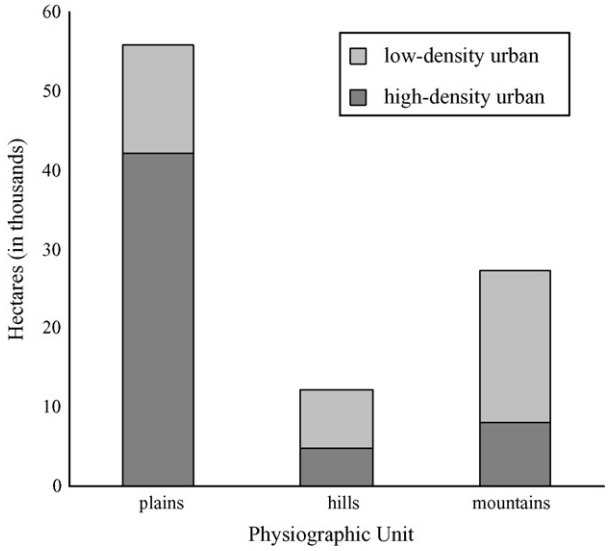

Fig. 7. Distribution of high and low-density urban areas in plains, hills, and mountains.

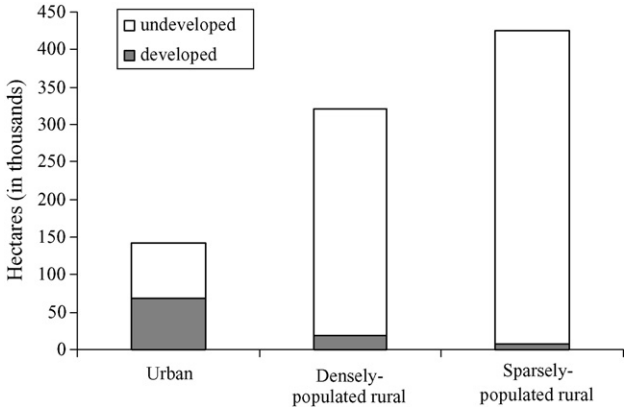

Fig. 9. Proportion of land-use types including the relationship between developed and undeveloped pixels.

such as forests, parklands, and other vegetated areas (Fig. 8). The urban-use class enhances the contiguity between the compact urban areas across the island, and gives an accurate view of the urban situation: it is easy to distinguish a major coastal "urban ring" that surrounds the island and minor rings that encircle interior mountainous and protected areas like the Caribbean National Forest. Within this coastal ring the areas of developed and non-developed land are about equal (Fig. 9).

In the rural lands, Densely Populated Rural use covers 36% of the island (320,219 ha) and supports a population of 0.8 million people. It surrounds the urban-use areas and represents most of the territory where human developments expand out from the urban centers following secondary routes. The landscape within these still high-populated areas is dominated by pastures and secondary forests, and developments represent a minimum fraction (Fig. 9). Finally, Sparsely Populated Rural encompasses the remaining 48% of the island (425,146 ha). This large area, with low population (less than 0.3 million people) and minimal urban development, corresponds to agriculture fields, higher elevations, protected lands, or rugged topography.

3.4. Land consumption

In Puerto Rico there is an average of 3996 persons/developed km^2. The reported difference between real population (from the census) and expected population (from the average of the island) for each one of the 900 neighborhoods demonstrates how heterogeneously the population is distributed in the landscape, and thus, the different patterns of land consumption. The lowest land consumption was reported in some neighborhoods of the San Juan Metropolitan Area, with 7000–8000 persons/developed km^2 (in cities such as Paris or New York, the population density can reach 22,000 and 44,000 persons/km^2, respectively). Within the SJMA there are also areas with population below the expected, which are considered relatively high land-consumption areas. The highest land consumption rates were reported in neighborhoods dominated by non-residential developments like airports, ports, commercial centers, and industries.

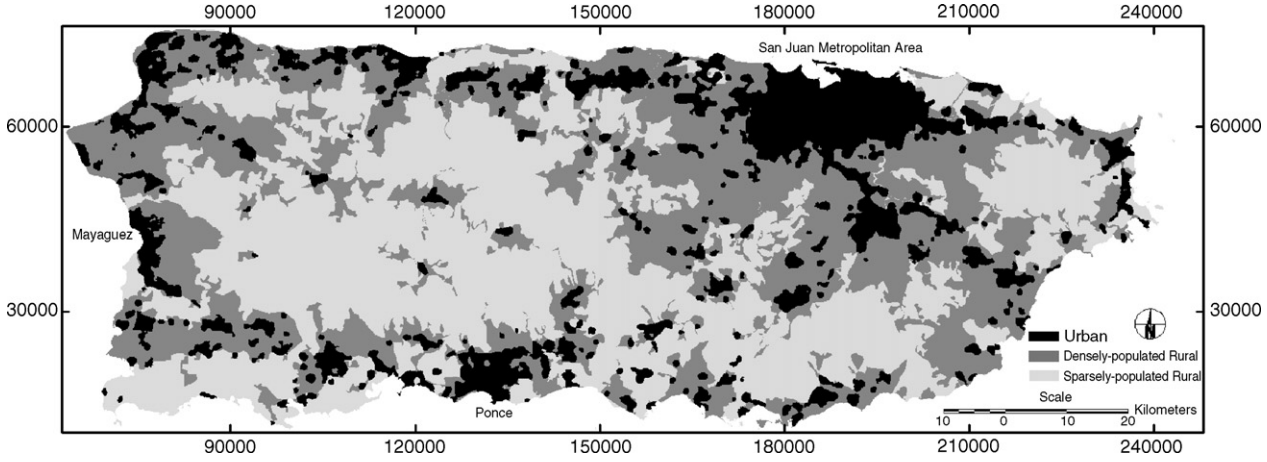

Fig. 8. Land uses of Puerto Rico, including Urban, Densely Populated Rural, and Sparsely Populated Rural.

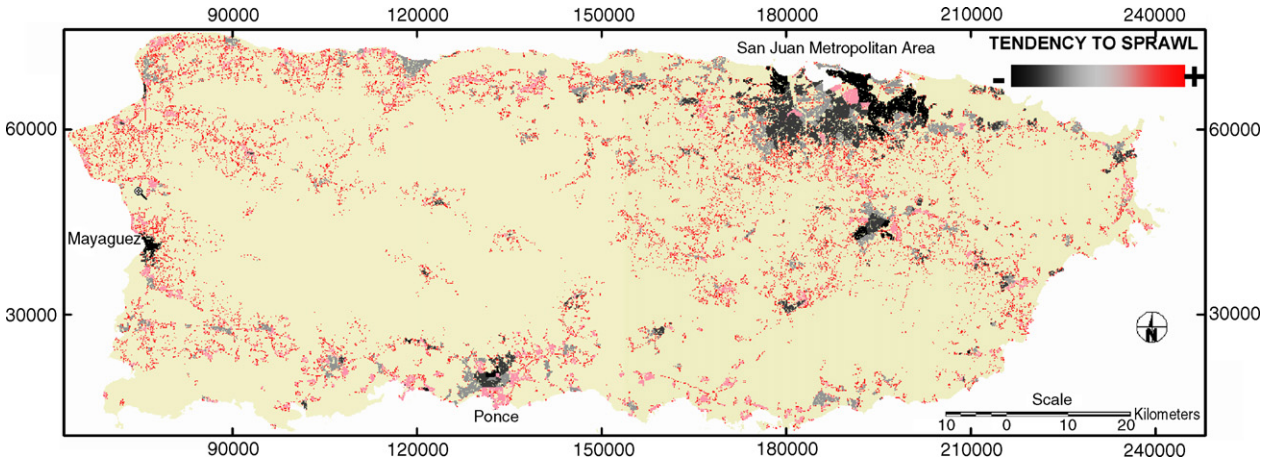

Fig. 10. Map of the developed lands showing different tendencies towards urban sprawl.

3.5. Urban sprawl

Most of the 78 urban centers appear surrounded by sprawl developments. The results from the classification show a clear increase in tendency to urban sprawl when going from the core of urban centers, periphery, exurban agglomerations, developments along rural roads, particularly visible in the major cities like the SJMA (Fig. 10). In the periphery of the urban centers as well as in the exurban agglomerations the population supported is typically below the expected, and so, the land consumption and the tendency to sprawl are high. Certain neighborhoods which are high-density developed, like the banking and commercial areas, ports, and airports, have lower values of land consumption and thus, they appear with high tendencies of sprawl, but would not be considered as sprawl; these zones are highly developed for non-residential purposes.

Sprawled developments, previously characterized by low-density constructions and by areas with significant land consumption, can be comprised of classes 4 and 5 of the classification schema. They represent 35–50% of the total development (Fig. 11). Nevertheless, when considering the way they are distributed across the landscape, the territory affected by sprawl is far larger than the extent of the developments alone. This region might include Densely Populated Rural lands (territory of expansion of urban centers), and part of the urban-use areas (including exurban agglomerations and low density developments). Consequently, 40% of the island could be considered as experiencing a high degree of sprawl relative to the rest.

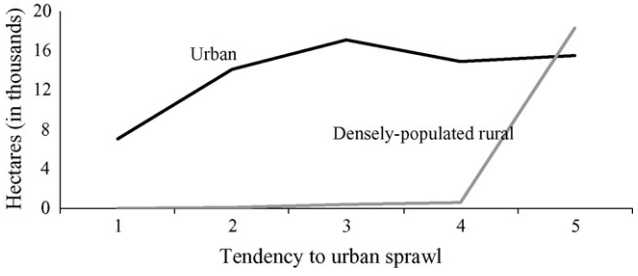

Fig. 11. Distribution of urban sprawl in urban developments with different land uses.

3.6. Population densities in San Juan Metropolitan Area compared to other countries

The comparison of the San Juan Metropolitan Area with urbanized areas of similar population (2.2 million) in different countries reveals that SJMA is one of the most extensive, and thus, one with the lowest population densities, with 960 persons/km^2 (Table 1a). For urbanized areas with similar extent (2300 km^2), SJMA is one of the least populated, and as such one of the least densely populated (Table 1b). Although other cities in the USA, Canada, and Australia have similar population densities to SJMA, those cities are typically smaller (Table 1c).

4. Discussion

Urban developments are major component of the landscape and as such must be carefully considered in any regional analysis for research or planning purposes related to land development and conservation. Understanding how humans use and develop the land is far more complex than a simple mapping of the urban cover, independent of the spatial resolution and detail obtained. Improvement depends on our ability to analyze both the extent and changes in developed land surfaces, qualify the types of development, analyze how urban developments are distributed across the landscape, and how they associate with population distribution. The combined application of remote sensing, spatial analysis, and census data represents an innovative approach for studying land development, with humans as central component.

The present methodology for mapping built-up areas is particularly practical for small regions like Puerto Rico or other Caribbean islands. The procedures for analyzing patterns of land development and for integrating population census data into the study (including analysis of land use and sprawl) are based on simple GIS operations such as filters and overlaying functions, and, contrarily to the mapping method, are not restrictive to a certain scale. Advances can be made with the development of standardized methods for categorizing high and low-density developments and land consumption

Table 1
Comparison of the San Juan Metropolitan Area with worldwide cities with similar population (a), extent (b), or population density (c)

Urbanized area	Population (million)	Area (km^2)	Population/ km^2
(a) Population			
Surabaya (Indonesia)	2.5	140	17664
Nanjing (China)	2.1	124	17258
Tel Aviv (Israel)	2.5	339	7227
Bucharest (Romania)	2.0	285	7018
Napoles (Italy)	2.4	583	4117
Manchester (UK)	2.2	558	4023
Vienna (Austria)	2.0	557	3591
Cape Town (South Africa)	2.4	673	3566
Curitiba (Brazil)	2.3	803	2802
Frankfurt (Germany)	2.3	984	2297
San Diego (USA)	2.7	2025	1320
Minneapolis–St. Paul (USA)	2.4	2315	1032
St. Louis (USA)	2.1	2147	968
San Juan (USA-PR)	**2.2**	**2310**	**960**
(b) Extent			
Sao Paulo (Brazil)	16.6	1981	8378
Manila (Philippines)	14.5	1943	7465
Jakarta (Indonesia)	17.0	2590	6564
Osaka, Kobe, Kyoto (Japan)	15.5	2760	5681
Buenos Aires (Argentina)	11.2	2771	4041
Paris (France)	9.6	2721	3545
San Diego (USA)	2.7	2025	1320
Minneapolis–St. Paul (USA)	2.4	2315	1032
San Juan (USA-PR)	**2.2**	**2310**	**960**
(c) Population density			
St. John's (Canada)	123000	124	990
Canberra (Australia)	278000	287	967
Toledo (USA)	503000	524	960
Quebec (Canada)	635000	668	950
Tucson (USA)	720000	755	954
Memphis (USA)	972000	1036	939
Orlando (USA)	1157000	1173	986
St. Louis (USA)	2078000	2147	968
San Juan (USA-PR)	**2217000**	**2310**	**960**

Source: http://www.demographia.com/. Data for SJMA in bold.

patterns, enabling the comparison between different countries or regions.

We found that 11% of Puerto Rico is covered by urban/built-up surfaces. Compact construction of urban centers encompasses 60% of the total development and is restricted to flat areas, while the other 40% occur in low-density forms and is widespread across much of the island facilitated by the extensive rural-road network. Uncontrolled development has led to a high degree of sprawl in 40% of Puerto Rico, with cities and towns poorly populated and surrounded by large sprawl areas. Nearly half of the total development is occurring outside of the solid urban centers, covering one-quarter of the best lands for agriculture, impacting watersheds and reducing open spaces.

Notably, the SJMA is one of the most extended urbanized areas in the world when compared with cities of similar population from different countries. It is comparable to St. Louis and Minneapolis–St. Paul, which have been identified within the most sprawled cities in the U.S. (Sutton, 2003). The importance of SJMA is enhanced by its particular environmental situation: while urbanized areas comparable to SJMA are in relatively flat continental landscapes with vast sources of land for agriculture, expansion, and conservation, SJMA is located on a small and essentially mountainous island with limited sources of land.

We define for Puerto Rico three main regions related to population distribution and development: Urban (16%), Sparsely Populated Rural (36%), and Densely Populated Rural (48%). The Densely Populated Rural is equivalent to the Wildland–Urban Interface, which is recognized as a focal area for a variety of human–environmental conflicts, and is receiving major attention in the U.S. mainland (USDA and USDI, 2001; Radeloff et al., 2005). Evaluating the local significance of this urban–rural interface, territory that covers 36% of the Puerto Rico, represents an exciting subject for future research. The identification of regions in the landscape with distinct human impacts is also useful from biodiversity analysis efforts, such as the Puerto Rico Gap Analysis Project (USGS, 2004), allowing to incorporate the human component in the modeling and mapping of animal species distribution.

In rapidly transforming landscapes such as Puerto Rico, proper plans of land development and conservation efforts should have the capacity to visualize and model future landscapes resulting from human activities, and to model ecosystem responses. This includes the development of Land Cover and Land Use Change (LCLUC) models that define and monitor urban growth (including the progress of high and low-density developments and changes in the extent of urban and rural-use areas), and forest loss or recovery, coupled with continuously updated efforts at monitoring animal species and habitat distribution.

This study not only reinforces the necessity of an effective plan of land use for Puerto Rico, but also provides operational information for planning purposes, including maps and GIS layers of the actual extent of the built-up areas, patterns of constructions, location of sprawled areas, and land use classification. Revitalize urban centers, re-attracting people and development to urban centers, as well as promote vertical constructions might reverse and/or improve the situation. The existence of more densely populated cities can serve as model for more efficient use of the land, reducing development pressure on rural areas and open spaces. This improvement can be maintained with the relatively stable population of Puerto Rico. The creation of the Office for Land Use Planning as part of the local government represents a unique opportunity for a radical change and progress in local planning. We expect this effort to generate a proper atmosphere where planners, governmental agencies, scientists, local communities, and NGO's can communicate directly with each other to support and develop efficient land use management strategies under the political will for its implementation.

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