Urban Growth in the Metropolitan Region of San José, Costa Rica: A Spatial and Temporal Exploration of the Determinants of Land Use Change, 1986–2010

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Lincoln Institute of Land Policy
Working Paper

Lincoln Institute Product Code: WP13RP1

Abstract

This paper analyzes the pattern of growth of the Metropolitian Region of San José, Costa Rica, and how it has changed over time. The analysis is based on maps of the build-up area of the region for three points in time—1986, 1997, and 2010. These maps were developed using both supervised and unsupervised Landsat satellite images classified using land cover metrics following Angel et al. (2005) and Burchfield (2006). The results show that the region is more dispersed and less dense than other Latin American cities. However, over time, the build-up area has become more compact than in the initial observation period. To explain the possible determinants of growth and sprawl of the metropolitan build-up area, we use econometric analysis that shows statistically significant associations, consistent with theory, among sprawl and accessibility, hydrogeological resources and population, and prevalent agricultural crops.

Keywords: patterns of urban growth, determinants of urban growth, land cover metrics, satellite images, urban sprawl and compactness, Metropolitan Region of San José, Costa Rica

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Acknowledgements

The authors wish to recognize the work performed by Roger Mesén, Railly Solano, Leyla Hoppe, and Natalia Zúñiga in data processing, specifically for the generation of the maps of urban land use. They also wish to thank the participants of the Research Seminar on Land Policy and Urban Development in Latin America (Montevideo, October 2011), and in particular Diego Erba, Ciro Biderman, Cynthia Goytia, Gregory Ingram, Luis Inostroza, Anna Sant'Anna, Paulo Sandroni, and Martim Smolka. We assume sole responsibility for all errors.

Table of Contents

Introduction 1
Background 1
Determining Changes in Land Use 4
Urban Use, Built-up Areas, and Urban Growth 4
Methodology to Determine Urban Growth 6
Image Preprocessing 10
Extensions of the Analysis 13
Spatial Patterns of Structures and Urban Growth in San José 14
Measures of Built-up Area, Urban Growth, and Sprawl Levels 15
Evolution of Urban Growth in the San José Metropolitan Region, 1986–2010 19
Determinants of the Urban Structure and Growth of San José 21
Determinants of the Urban Growth Process and the Monocentric City Model 22
Econometric Strategy, Limitations, and Extensions 26
Estimates of the Models that Describe the Built-up Area and its Structure 26
Estimates of Models Describing Urban Growth and Its Structure 29
Discussion of Selected Results 32
From Coffee Cultivation to Development: A Historical Perspective 32
Agricultural Returns and Urban Growth 33
Infrastructure, Regulation, and Urban Growth 36
Agglomeration Economies and Public Transportation 40
Monocentricity vs Polycentricity 41
Conclusions 42
Appendix 47

**Urban Growth in the Metropolitan Region of San José, Costa Rica:
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Introduction

The San José Metropolitan Region is an urban system formed by four cities (San José, Alajuela, Heredia, and Cartago), with different levels of functional and physical relationships with each other. It is located in a tectonic depression and its physical context is characterized by large variations in topography and other variables, such as climate, vegetation, and soil fertility. The topography of the region comprises rivers of deep canyons and mountains that act as accessibility barriers between the population centers, and in particular, as hurdles for the transportation system. Due to these multiple restrictions, plus its origin as a series of rural towns and small cities, the structural form of the region has always been relatively dispersed (see Pujol, 1988, 2005).

During the past three decades, the national and regional economic and social dynamics fostered the expansion of the city. The population has increased significantly, from 1.35 million in 1984 to 2.08 million in 2000 (INEC: Population Census 1984, 2000). By 2011, the regional population had reached 2.27 million. Household income has also increased, as per capita GDP grew by 85 percent in real terms between 1985 and 2010. The growing use of automobiles and the creation of a relatively high capacity national/regional network of highways have probably reduced the private costs of transportation. On the other hand, due to non-existing or ill-defined local regulations, and weak regional regulations, the city growth has produced significant negative environmental impacts. The growth of the metropolitan built-up area encroached on the rural spaces that formerly separated cities and towns in the region, with a resulting loss of environmental quality (see Perez et al., 2011, for a recent discussion). The peripheral urban expansion, particularly in the north and northwest (high areas of Alajuela and Heredia), poses risks to the water table that supplies drinking water to most of the region (Reynolds, 1996).

In this context, this study seeks to make an initial general assessment of patterns of urban land use by interpreting satellite images. The urban footprints derived from these images, were analyzed in terms of the size of the built-up area and its changes over time, the city's overall growth rate, the total built-up area level of sprawl, as well as the level of sprawl of the growth area—understood as new built-up areas. The built-up area maps consolidated by municipality were analyzed to identify the main determinants of urban growth and structural patterns. In this analysis we used a general modeling technique, based on a traditional probabilistic causation structure, thereby the independent variables that produce the modeled effect are on "the right side" of the equation. We consider our fndings as a significant contribution to the understanding of the dynamics of urban growth and levels of sprawl.

Background

A city is the result of complex interactions between human groups and their natural environment, organized around transportation systems, and performing various economic activities. Urban theories that explore the interaction and local manifestation of these factors have been around for quite some time, at least since the 1920s (Bessusi et al., 2010). The most successful model that describes the behavior of a city was formulated originally by William Alonso, and later on further developed by Mills and Muth for a monocentric city. These authors base their theory on a fundamental intuition: that the value of land is defined by its distance from the city center, the further away the lower is the return to land. The changes in land value reflect the need to compensate for the increase in transportation costs to the city center—where presumably all the city jobs are—as one moves away from it. Brueckner (1987) presents a synthesis of the Alonso-Mills-Muth model and derives many of its characteristics (see also Glaeser, 2008). Glaeser and Kahn (2004) derive the determinants of sprawl within the framework of the Alonso-Mills-Muth model. In their formulation, the key variable is the reduction in transportation costs. Given a monocentric city, lower transportation costs permit the expansion of the city limits and lower densities. Similarly, when the model is extended to a polycentric city, a change in the mode of transportation (from public to private) significantly reduces the cost of new employment centers, promoting decentralization.

The analysis of dispersed and low density development has triggered much recent reflection on the magnitude, determinants and impact of sprawl. In general, we can classify urban studies in terms of the scale of the unit of analysis, from the microscale, or the neighborhood level, to a mesoscale, when the focus is a single city, and the macroscale when several cities are compared. Two studies in particular have led research in the area of urban spraw: the pioneering work by Burchfield et al. (2006) and the studies in the framework of global urban development by Angel et al. (2005) for the World Bank, later expanded in Angel et al., 2010a, 2010b, and 2010c.

Both Burchfield and Angel share the same general analytical approach and that allows considerable flexibility to generate databases for urban development modeling. Starting with land cover maps, these authors create matrix cells representing urban land uses. "Focal" statistics are thus estimated. Each cell is described in relation to its neighbors (Burchfield et al., 2006, define a sprawl index; Angel et al., 2005, define compactness and contiguity indices, among others). Next, the resulting land cover metrics are estimated as average values for the entire city, which permits redily comparisions among cities. Regression analysis can then be used to explore the correlation between the average value of various land cover metrics and the possible factors that may determine the city structure. Determinant factors may be represented by specific variables. For example, in the Alonso-Mills-Muth model, an increase in the size of the city or a reduction in density may be explained by a reduction in transportation cost. Similarly, a variable measuring land slope may be used to qualify the assumption of isotropic space inherent in the monocentric city model.

This methodological framework is very flexible because the process of developing maps of built-up areas from the interpretation of land covers metrics derived from remote sensors is relatively easy (see Bessusi et al., 2010). From the basic study of Burchfield et al. (2006), a number of other studies followed. For example, Deng et al. (2008) focusing on China, linked the size of the main urban footprint and its growth to economic development, population growth, the value of rural land, and transportation costs using panel data of Chinese municipalities (where each municipality represented a city) during a three year period. Schneider and Woodcock (2008) made global comparisons using urban land cover metrics including build-up area and its growth, patch density, and population density. Based on these data, these authors created a classification of cities as a function of their growth rate. Angel et al. (2005), introduced new land cover metrics but also used a measure of sprawl defined by Burchfield et al. (2006) in a comparative analyzis of 90 cities, assessing urban growth patterns in the 1990s.

Burchfield et al. (2006) have been criticized methodologically by Irwin and Bockstael (2008), among others, for two reasons. First, from a technical point of view, Burchfield et al. (2006) use two inconsistent maps to measure the change in land use, thus imposing a technical limitation. In addition, the maps used were generated from a medium scale sensor, with cells measuring 30 m x 30 m. Irwin and Bockstael (2008) argue that, given that developments in low density areas have an average construction size of 200 m^2, the maps employed by Burchfield et al. (2006) are systematically biased toward underestimating lower density developments.[1] A second, though less relevant critique refers to the association between impervious land cover and urban use. Irwin and Bockstael suggest that, given a parcel with buildings and a large yard—a typical suburban development that causes sprawl in the United States—the entire parcel should be considered urban. They suggest that the unit of analysis ought to be the parcel, not an arbitrary subdivision of space. It follows that most studies of urban land use based on medium scale remote sensors only take into account the impervious land cover as urban use, ignoring open space in low density parcels.

In the tradition of rural and environmental economics, we know that the cost of opportunity is the most relevant factor, from an urban perspective (as argued by Glaeser and Khan, 2004), and the most important explanatory variable is *location* and the *determinants of said location*. And given that the biggest externalities are generated by human concentrations, it is highly probable that rejecting such a promising method for the only reason that it is based on land cover metrics derived from medium scale sensors is an overreaction.

The present study follows Burchfield et al. (2006) and Angel et al. (2005), applying this framework to a single city (the San José Metropolitan Region.), and expands the time period of analysis from two to three points in time. As in prior studies, we approach the analysis of the determinants of land use changes based on the monocentric city model to examine the basic relationships between accessibility, physical spatial differentials and built-up area patterns. Thus, we expect to produce analytical results that are consistent with the findings from macro- and mesoscale studies that compare land cover metrics across cities because these studies are based on the same hypothesis derived from the monocentric model of urban activity location.

As for the underestimation of the built-up area, and particularly, underestimation of lower-density developments, it is difficult to judge how relevant this would be in the case of San José. In Costa Rica there are high-resolution aerial and satellite photography surveys but no comparative studies of urban land use combining several sources of information. Judging by the experience of previous analyses with high resolution satellite images (Pérez et al., 2011), urban land use in the San José Metropolitan Region seems to be much more clustered than the densities cited by Irwin and Bockstael (2008), probably due to the restrictions imposed by the topography. Fortunately,

[1] The main point of contention is the categorical statement by Burchfield et al. (2006) that the levels of sprawl have not grown significantly in the United States between 1976 and 1992, in open contradiction to many studies that use different methodologies to conclude the opposite (e.g. the work by Glaeser and Kahn (2004), which uses densities of population and jobs).

high levels of humidity in the region tend to generate a better contrast between cells that are partially impervious and those that are completely dominated by vegetation canopy. Therefore, we expect that the underestimation of built-up areas will be minimal.

Determining Changes in Land Use

The use of satellite imaging to detect changes in land cover has a long history that goes back to when the first satellites were used by the United States government to monitor agricultural crops in the Soviet Union (Williamson, 1997). Since then, remote sensor technology and the processing of information acquired from remote sensors have improved to an extraordinary degree. As remote sensors detect land coverage—more specifically, the reflection of energy impinging on different objects which can be interpreted as the energy of those objects which, in turn, is taken as the land cover. But the interpretation of the data in terms of land use is not necessarily an automatic operation. For example, as pointed out by Seto et al. (2002), if we accept that land cover corresponding to construction materials in infrastructure projects (concrete, steel, cement) is equivalent to the set of human activities performed there, we can interpret land covered with these materials as urban land. If that is the case, the infrastructure for agricultural activities, as for example a barn, would also be interpreted as urban use, as indicated in the previous section.

Urban Use, Built-up Areas, and Urban Growth

A city is the product of the clustering of urban agents, and therefore in order to decide if a particular space belongs to the city, its location with regard to all the other urban agents (residential, commercial, and other uses) needs to be analyzed. From this point of view, a city is a social phenomenon with physical manifestations in a particular spatial context. The analysis of the location of activities within a city, in fact, the analysis of the city as a whole, requires a prior definition of the environment occupied by the city, and in particular its spatial limits. In other words, one must identify what is included as part of the city.

In the most simplistic version of a solution to this problem, demographic analyses classify the territory as urban or nonurban using geostatistical units and even, in some cases, entire municipalities (Cohen, 2004). This approach, however, is of limited use when we want to explore spatially explicit structures, given the inherent diversity in the areas covered by these administrative units.

Geographic sciences provide an alternative in the form of land use maps that describe the territory as a function of the activities performed in it. In the context of these maps, the analytical problem is how to describe the patterns of urban use, which means that first we must decide which area to include in the analysis.

The broader version of the city limits would include all locations that participate in the urban real estate market, independently of the use given to those locations. In that sense, all rural land subject to real estate speculation by their owners would belong to the city. In fact, in the territory covered by this study there is strong evidence that in certain areas (particularly in Heredia) land prices in the rural-urban interface reflect an expectation of urban development, rather than the present value of agricultural returns (see Pujol and Pérez, 2012). From this perspective, the entire metropolitan region, as defined by its regulatory borders (Institute of Housing and Urban Development, or INVU, 1983), could be considered urban, with the possible exception of the municipality of Alvarado, located in the northeast corner of the Cartago Metropolitan Area.

Although one might assume that any location within the metropolitan regional boundaries is potentially urban, not all the land is occupied by people performing urban activities. An urban space differs from other forms of occupation by human beings in the number and density of the population in that area. This, in turn, creates work specialization, freeing many people from the need to produce their own food. What specifically distinguishes urban areas is, therefore, the prevalence in space of activities not related to cultivation or animal breeding but instead, productive activities such as manufacturing, services and commerce, but also nonproductive activities such as residential and recreational activities. These activities require a certain infrastructure. This feature allows us to link physical spatial measurements (via remote sensing) with the use (activities) that take place in that space. In sum, we can assume that the land surfaces that exhibit the physical characteristics of construction are probably used for urban endeavors.

The matching of built-up areas with urban use is imperfect for three reasons, two of which are not important in the context of Costa Rica and the San José Metropolitan Region. First, not all the built-up areas are occupied by urban activities; some correspond to the infrastructure needed for agricultural production or the scattered occupation of natural spaces, such as isolated houses, maintenance areas in national parks, and the like. But this is a minor problem, as the vast majority of construction is for urban use. Moreover, even in building clusters associated with agricultural production, such as some population centers in the north of Cartago, Heredia or Alajuela, these clusters maintain strong daily links with the city. For example, the head of a household may work in agriculture, and his children may go to the local rural school, but his spouse probably works in the city and the older children may attend school in the center of town. This is particularly the case when an agricultural production cluster is linked to the city by a relatively high frequency bus service. For example, the Alvarado county has the highest number of people employed in the primary sector (agriculture, fishing, mines and quarries), but nevertheless it has 47 percent of its labor force working in nonagricultural activities. Similarly, the county of Poas is the second highest in proportion of primary sector workers in the region, but only 32 percent of its labor force is dedicated to primary sector activities (INEC: Population Census 2000).

Second, it is possible that some construction may not be detected by the sensors or, because a construction is very isolated, it might be interpreted incorrectly as an error. But this source of error is unimportant, by definition. If the built-up area is small, the undetected urban activities are also small.

The third source of imperfection, and potentially the most significant, occurs when spaces used for urban activities exhibit physical characteristics that do not match the characteristics of built-up areas. Instead, they present nonurban characteristics. For example, a park or a vacant lot resembles more a rural area with grass and scattered trees than a building in the center of the city.[2] These urban areas have not been included in the present analysis. In the case of vacant lots,

[2] There is also the opposite problem (a quarry looks more like a urban place than an agricultural area); but, because of its geographic location, this type of confusion is easier to detect and correct.

one can argue that eventually they are going to be developed as something will be built on them, although it is interesting to examine *per se* the pattern of vacant lots in a city. Another particularly problematic use is the very low density residential developments in the periphery of the city, although the impact of these on urban growth is possibly limited.

A final aspect of the location of urban use areas that needs to be discussed is the type of urban development that takes place. In general, because private construction needs access to public networks, and the cost of these networks is greater when development is land-intensive, it is of common interest to promote new urban developments immediately adjacent to preexisting built-up areas. This type of growth is considered organic.[3] Growth can also be dispersed (sprawl) if it is physically separated from the denser built-up areas. In general, dispersed growth causes greater environmental impact, some of which are internalized as higher cost of living in dispersed developments, e.g. when higher transportation costs are counterbalanced by better quality of life. There are also market failures. For example, when the opportunity cost of using the land for new urban development leads to degradation of hydrogeological resources with dire consequences for the region as a whole in the medium term, as in northern Heredia and Alajuela.

In sum, the analysis presented here covers the majority of urban activities, represented by built-up areas. It has limitations with regard to vacant lots, especially when they have to be considered as urban instead of underutilized agricultural land, and with regard to urban uses that do not required buildings, such as recreational activities in large regional parks. Even so, we consider that using the change in built-up areas as an indicator of urban use is, in general, representative of the underlying phenomena, and in particular of lower transportation associated with the structure and density of urban activities. However, one must remember throughout this work that we are analyzing an indicator of the degree of land occupation (the built-up area) of a potentially total urban space (the region).

Methodology to Determine Urban Growth

Given the scale of the available data and the dynamics of growth in the San José Metropolitan Region, land cover corresponding to building clusters and highways has been interpreted as spaces dedicated to urban activities. In order to generate the maps of built-up areas, we followed this general procedure:

1. A group of Landsat images was selected from 1986 (one image), 1997 (one image), and 2009–2010 (five images) (see table 1). These images were downloaded from the US Geological Services Website, free of charge (in Glovis: http://glovis.usgs.gov and EarthExplorer: http://earthexplorer.usgs.gov).

2. We estimated the value of the satellite reflectance (i.e., atmospheric distortion) for all the images. The areas with mist were interpreted as clouds.

[3] In addition to lower infrastructure costs, organic growth tends to be denser, because these locations adjacent to urban centers are more accessible (have a higher land value), and thus promote higher density of urban activities. This, in turn, creates other benefits, such as protection of services provision and natural resources.

3. All the images were preprocessed to identify areas with cloud cover. These areas were excluded from the analysis because the use of the land below the clouds cannot be identified, and because they reflect energy so intensely as to distort the results of the classification algorithms. Areas with no data due to a sensor failure were also excluded from the analysis (such as the 2009–2011 images). These areas were ignored in the classification process.

4. The 2009–2010 images (3 images for the 2009–2010 dry season, one image taken during the 2008–2009 dry season and the last image during the 2010–2011 dry season) were averaged to supply the missing data due to the faulty sensor.

5. The 2010 composite image was classified with a supervised sample obtained by visually inspecting different combinations of the visible bands of the images. We paid especial attention to the combinations of the following bands: 3-2-1 (true color), 4-3-2 (false color), 7-5-4 (highlighting the forests). We applied a maximum likelihood estimator, generating a map that includes the following categories: urban, green grasses, yellow grasses, coffee, nonpermanent crops and bare soil, water, tree cover, tree cover with cloud shadow and nurseries. We extracted the urban cover and reviewed the result against the aforementioned combination of bands to identify and eliminate misclassified cells.

6. The urban land use for 2010 was extracted and this map was used as a mask to classify land use in 1997. Only the cells of the 1997 images that were urban in 2010 were used. The classification was done using a maximum likelihood estimator and unsupervised classification algorithms, specified to generate between 20 and 30 categories. The categories were interpreted as land cover that was urban in 1997 (built-up area in 1997) or that was used for other activities, especially for coffee (land use change 1997–2010).

7. The urban land use in 1997 was extracted and this map was used as a mask to classify the land use in 1986; as in the previous year, the cells of the 1986 image were classified (using an unsupervised classification) and reinterpreted for land use change in 1986–1997 and built-up areas in 1986.

Table 1. Images Selected to Analyze Land Use

Date	*Path*	*Row*	Sensor
February 6, 1986	15	53	TM
December 21, 1997	15	53	TM
March 1, 2009	15	53	ETM+
December 30, 2009	15	53	ETM+
January 15, 2010	15	53	ETM+
April 5, 2010	15	53	ETM+
November 15, 2010	15	53	ETM+

GIS software programs have two main ways of representing information: vector elements and raster data. This last representation consists of square cells, where each cell represents a position in space (its corners represent physically existing locations, with known latitude and longitude), size (the side of the square has a length dimension, called resolution of the raster data) and value.

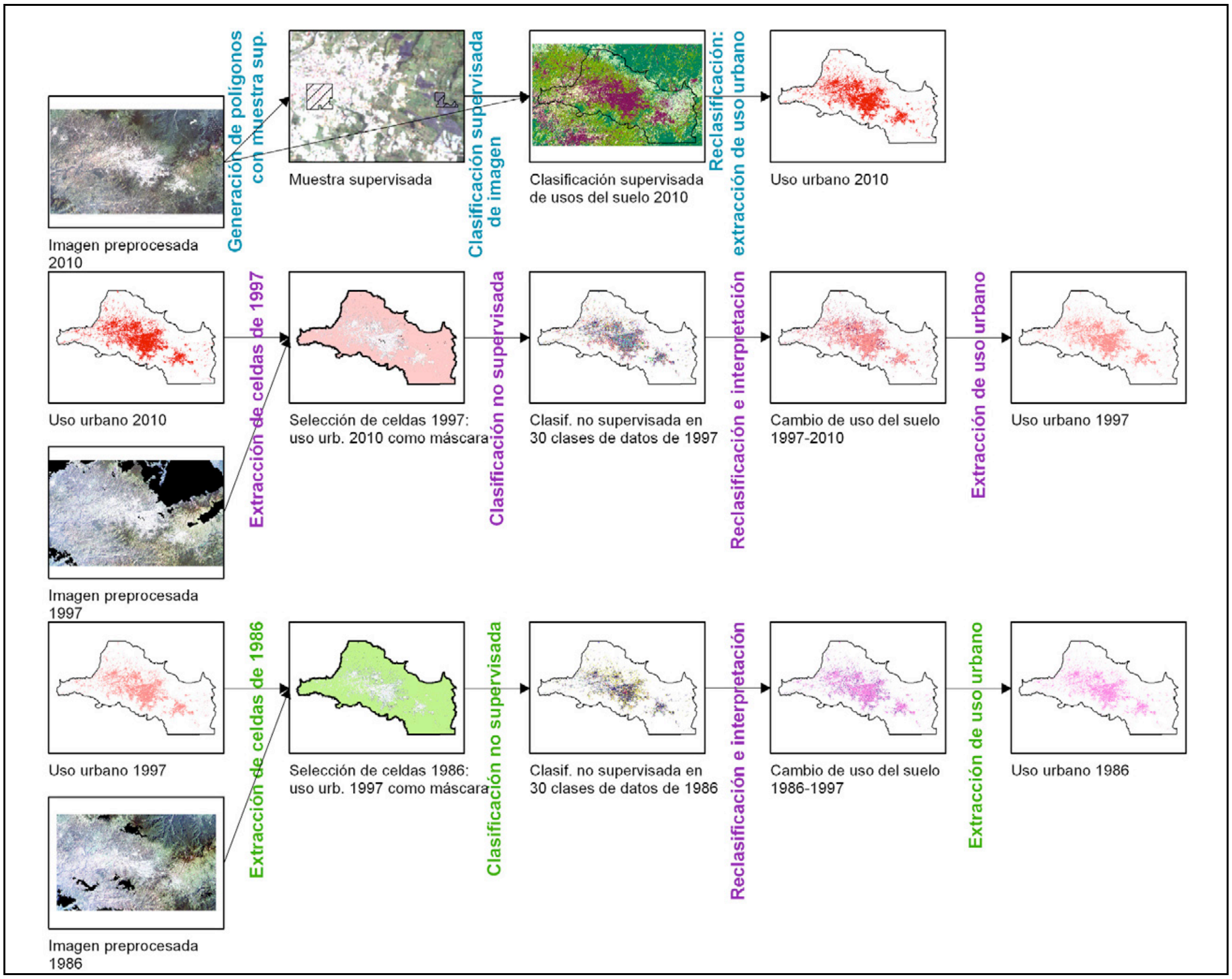
The value of the cell can store a combination of numbers that represent its color, a substantive value (e.g. density) or a discrete value that represents categories (e.g., 1 for built-up area, 2 for grasses, etc.)

Each Landsat image is composed of seven raster layers; six of them have a resolution of 30 m. The sixth, known as the thermal layer because it measures the degree of heat in the soil, has a resolution of 60 m. Each one of these bands stores a DN (digital number) value, which is a linear transformation of the reflectance value—the energy reflected by the land cover—in a specific bandwidth (see Lillesand and Kieffer, 1994, for a theory and analysis of remote sensors). The present analysis uses all six layers[4] of the Landsat satellite image, with a resolution of 30 m.

The images of 1986 and 1997 are fully compatible. Both were acquired by the Thematic Mapper (TM) sensor, and they have the same resolution (cell size of 30 m). The images circa 2010 were taken with the Enhanced Thematic Mapper (ETM+) sensor, which is an improved version of the TM sensor (Goward et al., 2001, describe these differences in greater detail). From the point of view of change in land cover, this difference in the sensors means that the generation of maps using information from different sensors and later comparison between them (an approach called post-classification comparison) may be inappropriate, because although the methods to generate the maps (i.e. to analyze the images) were identical, it is still possible that the differences in built-up areas are not due to a change in land use but to the form in which the sensors perceive the energy emitted by the land cover. This does not mean that it is impossible to generate consistent maps with information from different sources (in this case, from different sensors), but the creation of these maps needs to account for the difference in consistency between the various maps in order to make valid comparisons.

[4] We pointed out that certain specific combinations of bands—especially the combination of the green (2), red (3) and near infrared (4) band, called false color—have been very useful historically to distinguish built-up areas with remote sensors. The use of the six bands is tied to the original objective of the maps. We tried to create the masps to distinguish between nonurban covers (trees, grasses, permanent crops—per type—and nonpermanent crops, etc.). The confusion between some of these uses led to the decision to concentrate, at this stage, on the built-up areas.

Figure 1. Method Use to Generate Maps of Urban Growth



In general, and even under the best conditions, post-classification comparisons tend to be inefficient. Several approaches have been developed to overcome this difficulty. One of the most interesting consists in jointly classifying the bands of satellite images for several years (e.g. Seto et al., 2002).

The approach adopted in this study is based on a simpler assumption, also made by Burchfield et al. (2006), that there is no "deurbanization." In other words, the built-up areas are considered irreversible. If an area is occupied by construction at a given time, we assume that thereafter it will remain a built-up area. Therefore, when we classify for a period t only the area that was urban in the period t+1 (creating a mask with the built-up area at t+1), we are implicitly asserting that all the area constructed in period t is already included in the mask. Therefore, the analytical problem is reduced to identifying which cells in this mask were urban and which were not, in period t. The change in land cover, which is the urban growth between t and t+1, is given by the cells of the mask that were not urban in t. And the stable built-up area is that which corresponds to the land covers interpreted as urban in both periods (t and t+1). Figure 1 shows the process of generating land cover maps from the preprocessed images.

In principle, this process can be repeated as many times as desired, and the resulting land uses are consistent between them in terms of construction (due to the nonexistent “deurbanization”). In practice, every time an iteration is performed, there is always a small percentage of misclassified cells that can cause considerable errors as iterations (periods) are added. Therefore, it is necessary to review the results of the classification against the combinations of bands for each period.

However, despite this limitation, the classification method adopted here has two clear advantages: First, it is consistent over time, which is something we want to ensure. But also, the most recent period, which defines the first mask (i.e. the set of cells that includes the possible universe of built-up cells at the same resolution), is the year 2010. The 2010 satellite images produce results that are more precise for two reasons. First, the ETM+ sensor can distinguish better between land covers, minimizing confusion between built-up areas and other uses; and second, it reduces the possible errors associated with particularly extreme conditions (e.g. that the soil is abnormally dry, confusing built-up areas with degraded grasses) because it is the average of several images.

Image Preprocessing

The preprocessing of the selected satellite images seeks to concentrate the quantitative analysis (supervised and unsupervised classification algorithms) on the variations of land cover in the areas of interest. For that purpose, we proceeded as follows: (a) only a rectangular area defined by the extreme coordinates (latitude and longitude) of the region is considered; (b) values of reflectance for clouds and cloud shadows, which tend to be extreme, are excluded to avoid biasing the classification, and also because cloudy images do not contribute useful information for classifying land cover underneath;[5] and (c) we performed the classification based on the reflectance values—which are a physical dimension—and not on the abstraction of the digital number.[6]

As mentioned above, the remote sensors (and, in particular, the TM and ETM+ sensors) record the reflectance values (i.e. the energy reflected on a determined wavelength) corresponding to different points in space. However, the digital file storage of magnitudes that have many decimal points needed to appropriately represent the physical dimension of the reflectance value is not very practical. Consider that in order to store a number in the hundreds without decimals three digits are required and the same number with four decimals needs 7 digits, which doubles the size of the digital file. As a reference, the downloadable compressed file of an image of the ETM+ sensor (Landsat 7 satellite) using digital numbers has a size of 200 to 300 MB.

The conversion process of a digital number into a reflectance value is relatively straight forward: the digital number is simply a discrete value that rescales the radiance value. The reflectance values received by the sensor, in turn, are a function of that radiance value and the latitude at which the satellite image is recorded, the way the solar light is reflected on Earth and the position

[5] This is true for the TM and ETM+ optical sensors. Other sensors (e.g. SAR sensors) measure frequencies and use measurement methods that can interpret the soil independently of the existence of clouds or solar illumination.

[6] This last adaptation is quantitatively irrelevant, because it is a linear transformation of the original data; it is done for conceptual reasons (reflectance is a physical dimension, which can be interpreted as land cover, whereas the digital number is a mere abstraction).

of the satellite with respect to the Earth and the Sun. The conversion between a digital number and the reflectance value is performed using equations [1] and [2]:[7]

$$L_\lambda = \frac{(LMAX_\lambda - LMIN_\lambda)\cdot(QCAL - QCALMIN)}{QCALMAX - QCALMIN} + LMIN_\lambda \qquad [1]$$

where L_λ is the spectral radiance of the cell, $LMIN_\lambda$ and $LMAX_\lambda$ are the minimum and maximum values, respectively, of radiance in the band, QCAL is the value of the digital number, QCALMIN is 1 (the minimum possible value of the digital number) and QCALMAX, 255 (the maximum possible value of the digital number). In turn, the relation between reflectance and radiance is given by:

$$\rho_P = \frac{\pi \cdot L_\lambda \cdot d^2}{ESUN_\lambda \cdot \cos(\vartheta)} \qquad [2]$$

where ρ_P is the reflectance value, $ESUN_\lambda$ is the solar irradiation beyond the atmosphere, $\cos(\vartheta)$ is the cosine of the solar zenith, and *d* is the distance between the Earth and the Sun.

The classified images from 1986 and 1997 were selected to include the least amount of land covered by clouds as possible. In general, all the images were taken during the region's dry season (approximately from December to April) to avoid clouds. Even so, after cutting the complete image to cover only the area of interest, the second task was to identify the area of clouds and invalidate the data in that region. For that purpose, non-supervised classifications using the six bands of each region were performed. The results were reclassified in two categories: the area under cloud cover, which was assigned a value of –1[8], and the area for all the remaining cells for which the value of the digital number was maintained, later converted to reflectance following the procedure described above.

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[7] Specialized analysis programs (e.g. GRASS, ERDAS, ENVI) perform this transformation directly from the metadata file that comes with the downloadable data of the USGS Websites. These equations were taken from Irish (2008).

[8] It would have been convenient to assign the value of 0 to these cells, but this reflectance value is theoretically valid (a certain land cover could not absorb all the energy at a given wavelength); therefore, we used –1. In practice, this means that in other classification exercises, all the cells with value –1 (i.e., with invalid data) are grouped in a single category.

Figure 2. Preprocessing of the Images Selected

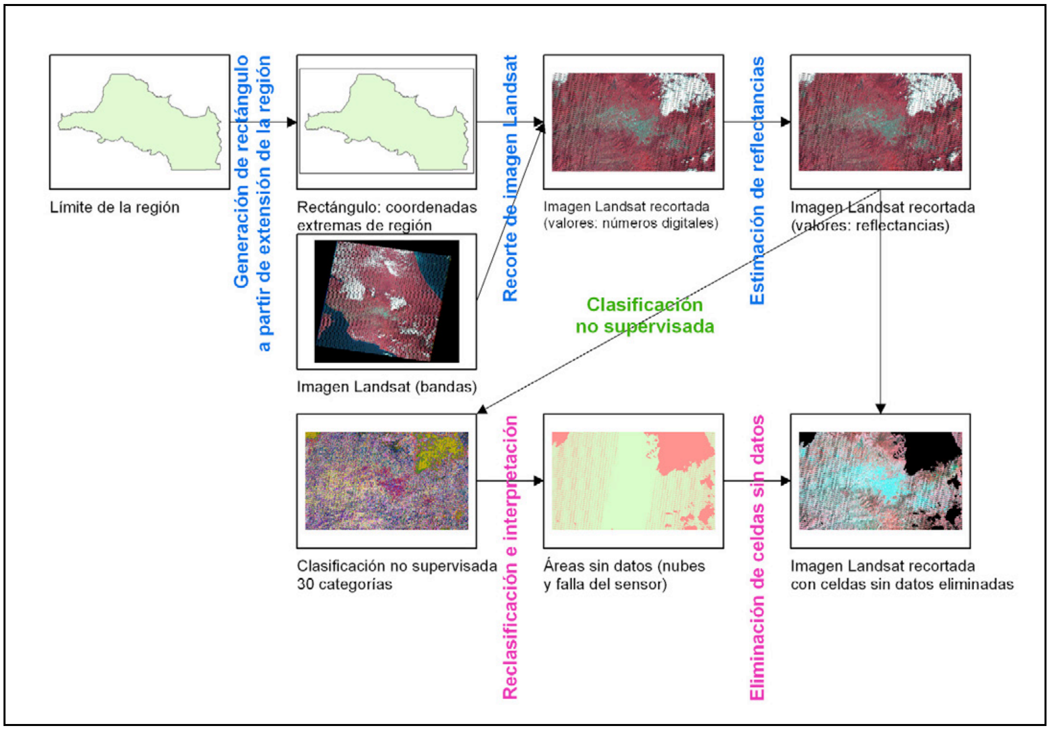
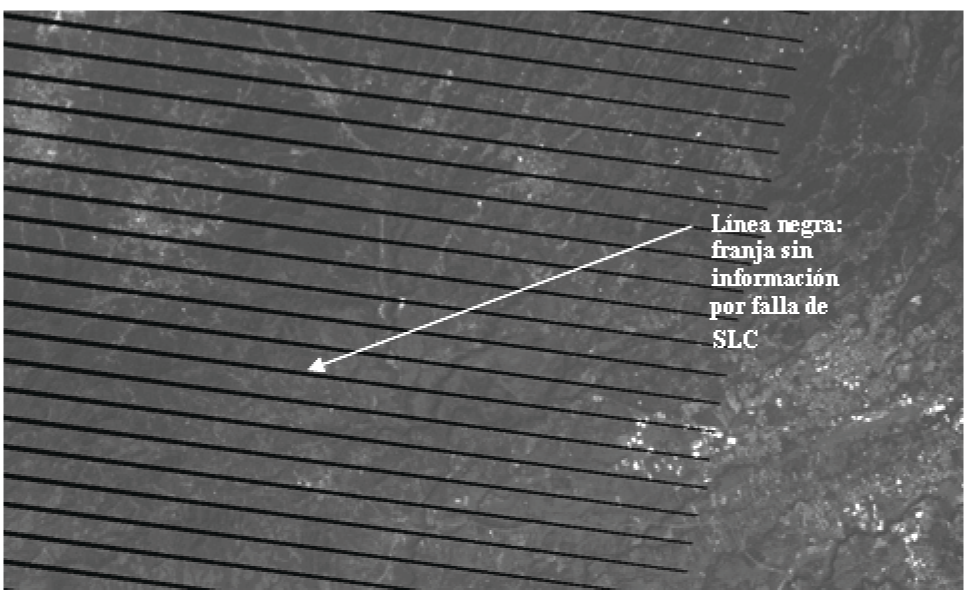


Figure 3. Close-up of Band 1 Image Processing Acquired by the ETM+ Sensor, January 15, 2010

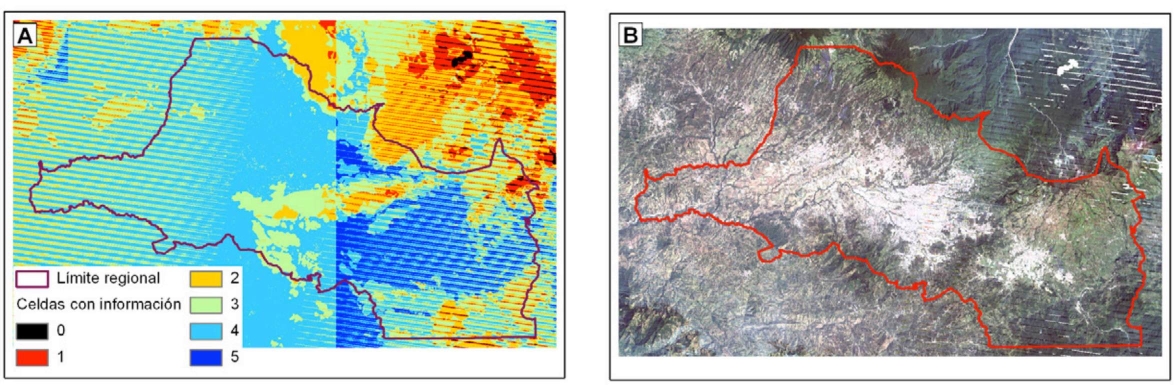


On May 31, 2003, the scan line corrector of the ETM+ sensor failed. This component compensated the forward movement of the satellite. Consequently, starting on that date, the Landsat 7 satellite images present a systematic lack of information: a line is thicker at the border of the image, but tends to disappear at the center (see figure 3).

In order to evaluate land use in these bands, we developed a method to estimate reflectance in the cells without information. When the satellite acquires an image centered approximately in the region, it does not always do that at the same latitude. There is a small offset. This means that a cell with the same position (same coordinates) may not have information in one image but have it on another image taken at another time. Therefore, five images were processed for the year 2010: three for the dry season in 2009–2010, one for the dry season in 2008–2009, and another for the dry season in 2010–2011.

Ignoring the changes in land cover given the short period of time, we estimated the reflectance value of each cell as the *average of all the cells that have a value.* Therefore, if a hypothetic cell is covered by clouds in the first image, does not have any data in the second image due to sensor failure, and has information in the third image, the value of reflectance is assigned in this third image. Also, if a cell has land cover information in all three images, it is assigned the average of the reflectance value of each of the three images. We essentially completed the land reflectance information for practically the entire region and noticed that the areas with missing information are located far from the center of the cities in the region. Figure 4 shows the cells classified by the number of images that contain information, and the resulting composite image.

Figure 4. Cells by Number of Images with Information [A] and Resulting Composite Image for the Year 2010 in True Color (Combination of Bands 3-2-1) [B]



Source: Images taken by the ETM+ sensor of the Landsat 7 satellite, path 15, row 53, on: March 1st, 2009, December 30, 2009, January 15, 2010, April 5, 2010, and November 15, 2010.

Extensions of the Analysis

The development of methodologies to detect urban growth that are consistent over time allows us to extend the data series to include more periods. In our study, it would have been desirable to perform at least two further assessments of the built-up area and the urban growth circa 2004, and circa 1991. The selection of the year aims to reduce the loss of information due to cloud cover and to account for the availability of Landsat images in the USGS files. When we analyze Landsat images in future studies, we will explore the possibility of using the method developed to solve the data loss problem by SLC, and apply it to the loss of data due to cloud cover.

In the interim, it would be valuable to explore additional ways of summarizing the information of satellite images by enhancing the variations between land covers (e.g., principal component analysis or the Kauth-Thomas transformation). The systematic use of multiple supervised classifications for several periods should have a great potential for additional estimates. This can be done by incorporating different land use categories, rather than only the change in built-up area.

Spatial Patterns of Structures and Urban Growth in San José

The maps of built-up areas were developed following the methodology described above. The map, "Urban Growth in the Greater San José Metropolitan Region, Costa Rica, 1986–2010" (figure 7), shows the results. Before discussing the metrics for built-up areas and levels of sprawl, it is necessary to explain the impact that scale has on the results. Irwin et al. (2006), in their original evaluation of Burchfield et al. (2006) and their analysis of sprawl in the State of Maryland, United States, distinguish three scales. One, the resolution of the baseline information, i.e. the maps of urban land use were generated using satellite images with a resolution of 30 m, the same used for the land use maps. A second scale corresponds to the unit used to define the indicator. Meaning, if the data is presented on uniform squares of size L, and L is very small, some squares will have results that do not represent the land use data, but rather errors in the classification process. If L is too large, the heterogeneity of the phenomenon can be lost in the average value assigned. Finally, a third scale is that on which the indicator is summarized.

In the present analysis we use the following indicators: built-up area, growth of built-up area and sprawl, contiguity and compactness indices, as well as the equivalent year-to-year rate of urban growth. In general, we calculate the indicators at the level of a municipality. The only exception is the sprawl index, which is calculated for each cell using a 1 km x 1 km window (approximately 990 m x 990 m, defined by a square of 33 x 33 cells. This index was also summarized by municipality.

Originally, we thought of making the estimates of the various indicators at a smaller scale, the district level. The San José Metropolitan Region has 31 municipalities, divided into 167 districts. The area of the municipalities ranges from 675 ha in the Municipality of Flores, to 26,146 ha in the Municipality of Alajuela. Districts vary in area from 55 ha in San Francisco de Goicoechea, to 6,319 ha in Colón, Mora.[9] However, the limitations in the generation of urban land use maps forced us to use larger spatial units, and therefore the analysis was performed at municipal level. Specifically, the built-up areas in the rural and peripheral districts of the region are much dispersed, and the buildings are relatively small. Therefore, they were not picked up by the satellite, or generate much confusion with other uses with similar spectral characteristics (e.g., bare soil and nonpermanent crops, or degraded grasses). As a result, the values of the indices—including

[9] Using the administrative territorial division of 2005; since then, three districts were created in the region. We only consider the area of the districts within the region.

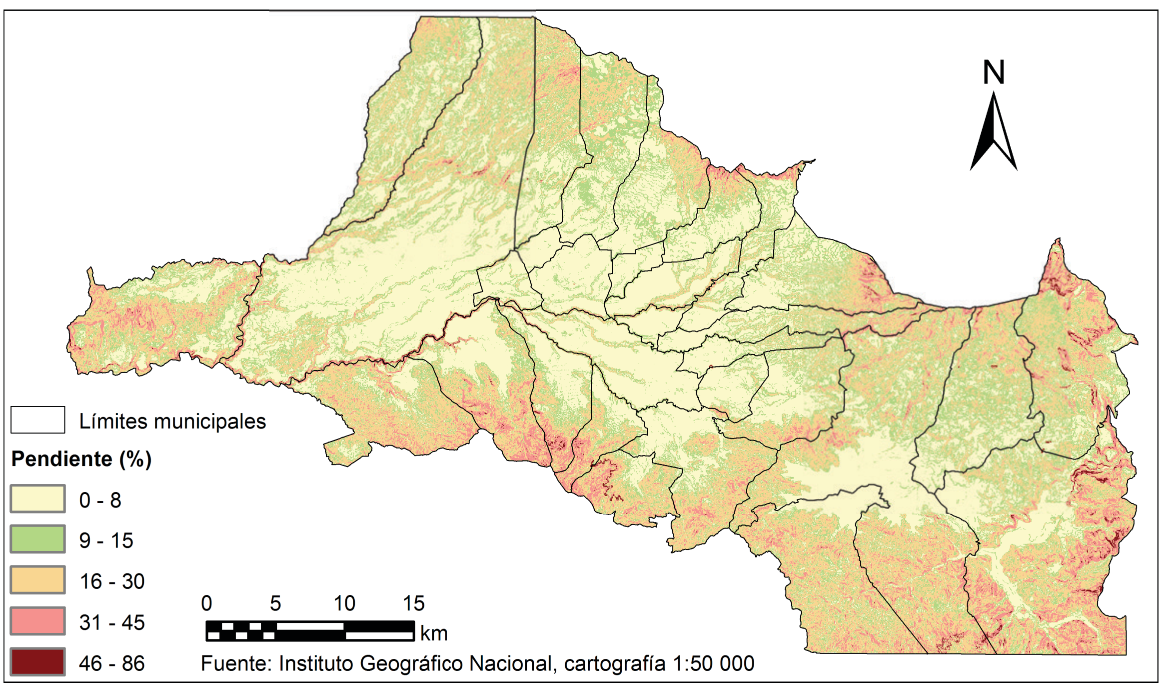
the most basic one, the total built-up area—did not appear reliable at the district level.[10] As the built-up area of some districts represents a very small percentage of the total, the value of the total build-up area for the municipality has, on average, lower levels of error than at district level.

Measures of Built-up Area, Urban Growth, and Sprawl Levels

This section summarizes the metrics used to describe the area and the urban growth of the San José Metropolitan Region. The indices and areas were calculated for the region as a whole and for each municipality. These metrics allow us to describe the urban development patterns, by dividing the space into units that are meaningful from the political, administrative, historical, and cultural points of view—and, in a certain sense, also from the physical point of view, as many intermunicipal boundaries are rivers or watersheds. The estimated areas and indices measured are the following:

- **Built-up Area and Urban Growth**: We quantified the areas delimited in the maps of urban land use along with thei respective growth area. This was done by adding the number of cells for each category and period. As the resolution of each matrix layer is 30 m., the area of each cell is 900 m^2, which is multiplied by the number of cells of each type.

Figure 5. Slope Variation in the San José Metropolitan Region

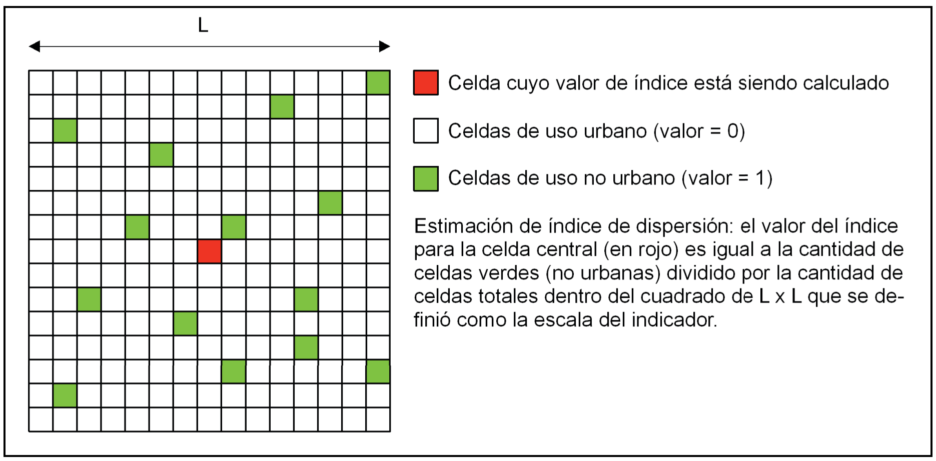


[10] We did not perform systematic comparisons with high resolution images, as done by Irwin and Bockstael (2008); but the review of results by visual inspection and the field knowledge of some of these rural districts allowed us to identify problems with the estimates of built-up areas in many districts.

- **Buildable Area**: According to the Urban Planning Act (INVU, 1983, *Plan regional metropolitano*), areas with a slope greater than 30 percent require special soil studies before they can be developed. Therefore, we only considered as buildable areas those with slopes lower than 30 percent. This parameter does not change with time and is obtained from the national charts.[11]

- **Sprawl Index**: Defined by Burchfield et al. (2006). For the cells that are analyzed (i.e. all the urban cells or all the cells that correspond to urban growth), we estimate the percentage of nonurban cells in a window of approximately 1 km x km[12], centered on the cell we are analyzing. We then average the value of all the cells (total built-up area or growth of built-up area) for the entire region or a municipality. If the value is very close to one, the levels of dispersion are very high because the urban development represented by the cell is isolated. In other words, is surrounded by many nonurban cells, is far from the consolidated built-up areas. Conversely if the value is very low, the level of sprawl is also low.

Figure 6. Schematic Estimate of the Value of the Sprawl Index for One Cell



- **Compactness Index**: Originally defined by Angel et al. (2005), this index is estimated as the principal consolidated built-up area, which is the largest contiguous urban footprint of each city divided by the buildable area. Angel et al. (2005) define the buildable area as the circle of minimum radius that contains the built-up area of the city, excluding developments that are much dispersed (i.e. considering only the built-up areas that occupy 25 contiguous hectares). This index was modified in the scope of the present study: We

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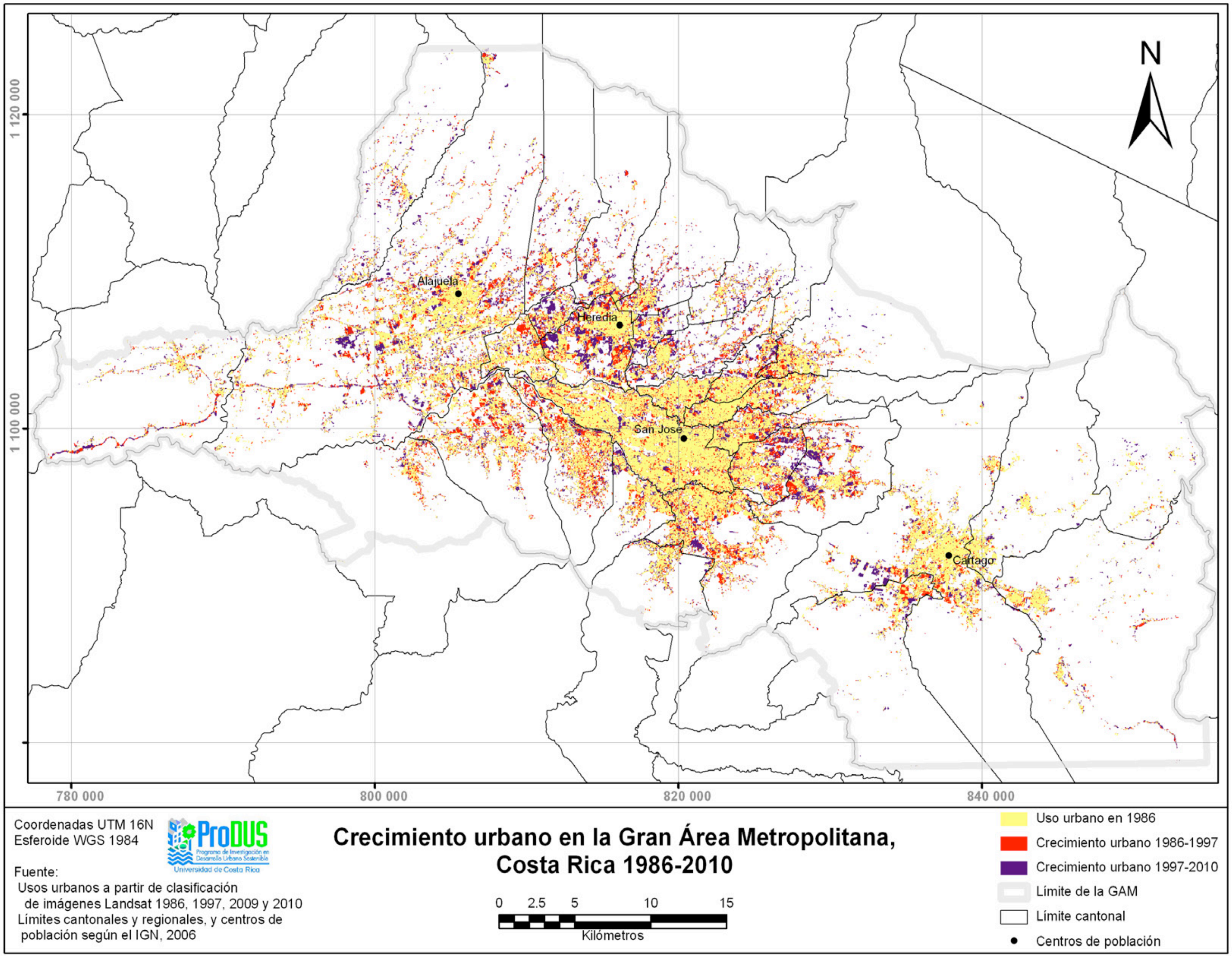
[11] This area includes all the area that, in principle, could be built under the Construction Act, independently of it being built or not. The area that is free to be built is that which meets the slope restrictions and has not yet been built; this is an approximate measure of the area available for future development. There are other legal and physical restrictions (e.g. on river channels, sources of drinking water or geological faults) that were not considered.

[12] As in Burchfield et al. (2006) and given that the resolution of the matrix layer that represents the built-up area is 30 m, we define the window as a 990 x 990 m square (30 x 30 cells).

calculate the built-up area of each municipality divided by the total buildable area (with a slope lower than 30 percent) of that municipality.

- **Contiguity Index**: Originally defined by Angel et al. (2005), it is estimated as the largest continuous urban area of the city, divided by the total built-up area. This index was modified in the present study: We calculate the largest contiguous built-up area within the limits of the municipality, divided by the total built-up area of that municipality. Doing that, we assume that each municipality is isolated in its border from the rest of the city. In other words, we assume that the urban footprints are interrupted at the county limits, even if they are physically contiguous. We calculate the compactness index for the region as a whole as the largest continuous built-up area (centered in San José) divided by the total built-up area.

Figure 7. Urban Growth in the Greater San José Metropolitan Region, Costa Rica, 1986–2010



Evolution of Urban Growth in the San José Metropolitan Region, 1986–2010

Table 2 summarizes the indicators describing the evolution of the built-up area in the region. A first and very interesting finding is that, contrary to the global trend identified by Angel et al. (2010a), the population density in the region *has increased*. Other cities in Latin America, as for example Guatemala City and Santiago, Chile, with populations of about 3 million people, and also located in mountainous regions, showed reductions in population density over the last two decades: Guatemala City went from 87 to 76 inhabitants per ha from 1980 to 2000 and in Santiago, population densities fluctuated from 98 inhabitants per urban ha in 1980, to 113 in 1990, and 102 in 2000. In San José, in contrast, population densities increased from 68 to 73 inhabitants/urban hectare from1986 to 2010.

Table 2. Evolution of Urban Growth in the San José Metropolitan Region

Indicator	1986	1997	2010
Built-up area (ha.)	20 986.5	27 044.9	33 088.1
Growth from initial period (ha.)		6058.4	6043.1
Equivalent year-to-year growth rate of the built-up area		2.33%	1.56%
Population	1 434 242	1 931 255	2 493 076
Population density (inhabitants/urban ha)	68.34	71.41	75.35
Indices			
Built-up area sprawl	0.5248	0.4457	0.3956
Built-up area sprawl — modified index (per Angel et al., 2010b)	0.5248	0.4850	0.4329
Growth sprawl from initial period		0.4783	0.4768
Compactness of built-up area	0.1712	0.2206	0.2699
Contiguity of built-up area	0.3153	0.4216	0.4247

Angel et al. (2010a) stated that "Efforts to make cities denser require the reversal of a very powerful and sustained global tendency for densities to decline" (Angel et al., 2010a, p. 103). This certainly does not seem to be the case in the San José Metropolitan Region. Another difference observable in the San José Metropolitan Region is that population densities are lower than in other cities in Latin America, although higher than in cities of more developed countries. The origin of the metropolitan region as a collection of clusters of rural villages implies that there was a large amount of rural space within the boundries of the region. Much of that rural space acquired, over the years, physical and accessibility characteristics similar to those of urban developed areas. The evidence suggests that this is precisely the main change observable in the last two decades, namely that we are running out of accessible, relatively flat, buildablet land in the region.

One possible explanation for this trend is that, due to the rapid expansion of the limits of the existing built-up areas, the best areas for urban development have started to run out, although there are still areas potentially buildab le within the metropolitan region. But the topography of the region creates important barriers to the expansion of infrastructure networks (particularly highways), and many of the potential expansion areas contain natural systems that are of strategic importance for the city and could become degraded if build-up (e.g., the aquifers of the Northeastern region). This means that, due to the scarcity of buildable land, the residents of the new urban developments will probably confront higher transportation costs than the rest of the population without necessarily acquiring, in turn, larger houses, as predicted by the theoretical model. It is not clear if this unplanned process of densification is detrimental, so any expansion of the public infrastructure network, especially the regional highway system, must be studied carefully.

The hypothesis of depletion of buildable land is reinforced by the behavior of the indices that measure the levels of sprawl and compactness in the region. These indices show: (a) urban growth has occurred in the perimeter of the existing built-up areas; (b) as in the prior studies (Burchfield et al., 2006; Angel et al., 2010b), the levels of sprawl in the urban growth area remain approximately constant over time (the sprawl index for the urban growth area stood steady at 0.477 for both periods); and (c) the sprawl index for the region fell over time, and the levels of compactness and contiguity, in general, grew. This means that the San José Metropolitan Region has grown by developing empty spaces on the perimeters or in consolidated urban areas (infill), and not by scattering urban developments far from the existing built-up areas (leapfrogging).[13]

Once again, it is important to highlight that the levels of sprawl in the San José Metropolitan Region are relatively higher than in other Latin American cities. The sprawl index estimated for the San José Metropolitan Region is in the range of 0.52 (1986) to 0.40 (2010). In the year 2000, Atlanta and Pittsburgh, which are two of the most sprawling cities in the United States, had indices of 0.58 and 0.57, respectively. An index greater than 0.40 is higher than Los Angeles (0.33 in 2000) or Houston (0.39 in 2000); see Burchfield et al. (2006).

In sum, using Angel et al. (2010b) modified sprawl index estimated at a 1 km radius, we find:

- Sprawl metrics for the San José Metropolitan Region with 1 km circles are: 0.5248 (for 1986), 0.4850 (in 1997) and 0.4329 (in 2010).

- Angel et al. (2010b) reported values of 0.281 and 0.254 for Santiago, Chile; 0.383 and 0.323 for San Salvador, El Salvador; 0.387 and 0.314 for Guatemala City; 0.296 and 0.268 for Guadalajara, Mexico; 0.306 and 0.230 for Tijuana, Mexico; 0.462 and 0.440 for Montevideo, Uruguay, and 0.487 and 0.433 for Caracas, Venezuela. In all these cases, the first value is circa 1990 and the second circa 2000.

- For United States cities, which are much more scattered and have a lower utilization of public transportation compared to Latin American cities, Angel et al. (2010b) estimated

[13] In other words, the main process has been the occupation of vacant land in former rural areas that shaped the urban space in the region. The vacant land possibly originated from rural spaces that existed between population centers. The main point is that the expansion of the built-up area has been more organic than would have been expected, given the very scattered structure of the region. Nevertheless, the original dispersion with the consequent high level of vacant spaces, still dominates the regional landscape.

0.548 and 0.519 for Pittsburgh, 0.237 and 0.210 for Los Angeles, and 0.503 and 0.365 for Houston (also, in all these cases the first value is circa 1990 and the second circa 2000).

While not having levels of sprawl as high as the most extreme cases in the United States, where cities have a structure that is completely oriented toward the use of private vehicles, it is pretty clear that San José is considerably more dispersed than most cities in Latin America. Similar cities, such as Guatemala City or Santiago, Chile, have sprawl indices under 0.35, while the value for San José, even in 2010, is greater than 0.40 (similar to Montevideo, although the terrain in Montevideo is much flatter than in San José).

Finally, we would like to comment on the significance of the sprawl index defined by Burchfield et al. (2006) and, in general, on the results for cities in the United States. These indices (see Burchfield et al., 2006; Angel et al., 2005, 2010a) were originally designed to investigate sprawl in urban developments in the United States. This phenomenon has very specific typological causes, namely urban structures that resulted from very long periods of dominance of private vehicles and low transportation costs. Glaeser and Kahn (2004) give a formal explanation for the US urban growth patters. See also Galster et al., (2001) and Angel et al. (2010a).

Therefore, even though the index measures sprawl in all cases, the type of urban development that is measured varies from one context to another, particularly when comparing the United States with Costa Rica. High sprawl indices in the United States imply very low density urban developments, with all the features that are connected with sprawl, such as high incomes and a dependency on the automobile.

In San José, in contrast, the periphery of the metropolitan region was already occupied by population centers with a rural economic base.[14] Urban developments on the periphery, in many cases, replaced coffee plantations. The new urban residents generated more negative externalities than the original rural inhabitants as local agricultural jobs wer eliminated forcing workers to travel to the urban centers to work, a fact that can be interpreted as an increase in negative externalities of urbanization. The paradox is that these newer peripheral developments, because they are relatively large, reduce the level of sprawl (defined as the undeveloped area that surrounds each location). In this sense, the reduction in the sprawl indices reflects primarily the continuous conurbation process and not the effective reduction in preexisting sprawl, suggesting a higher negative environmental impact of urban growth.

Determinants of the Urban Structure and Growth of San José

In this section we summarize the results that explore the influence of various factors on the urban growth and its characteristics for the San José Metropolitan Region. As discussed above, this analysis, as other mesoscale studies, allows the verification of the assumptions embedded in

[14] Notice that as the conurbation process advanced, the economic structure of employment changed in these population centers, even without taking into account the new urban residents. The proportion of people that entered the urban labor market increased because the transportation costs were reduced and the urban salaries are better than the rural salaries (and, in general, the opportunities for social interaction are greater and more diverse in the urban centers than in the periurban interface).

macroscale models (e.g. Burchfield et al., 2006; Angel et al., 2010a and 2010b). The macroscale studies generate indices and variables for a city or region assuming, implicitly, that the fundamental relationships of the monocentric city model apply to the variety of situations that can be found in their databases. Mesoscale studies verify if this assumption is true for specific cases providing information that is useful both methodologically and substantively.

To estimate models to explain the number, growth and structure of build-up areas in the region is important for two reasons. First, by themselves the models allow the identification of the factors that cause change in the levels and structure of built-up areas. A better understanding of the phenomena associated with urban growth may guide efficient interventions in the land markets, as to their goals, choice of instruments, and implementation. Second, as a general exploration of the context in which specific phenomena occur, explanatory models provide critical information about the variables that must be controlled to appropriately isolate the phenomenon. In particular, in developing causal models it is critical to identify the influences that may affect the measurements of the impacts that are being investigated.

Determinants of the Urban Growth Process and the Monocentric City Model

According to Burchfield et al. (2006), the factors that determine urban growth and its form can be classified in two groups. First, there are factors that represent the interactions formalized in the microeconomic model of the monocentric cities (which explains the actions of individuals and derives aggregated consequences from them). The most notable aspects of such factors include: accessibility to the city center, family income, housing demand (which in an analysis of an isolated city is taken as an exogenous factor), urban regulation, and the economic return to rural land (the opportunity cost). Second, there are factors that reflect the limitations of the monocentric city model, and specifically the assumption of spatial isotropy.

Following the traditional model of probabilistic analysis, a causal relationship is assumed based on a substantive theoretical argument, in this case the model of the monocentric city, both in its derivations and in its limitations. In this framework, the various determinant factors are conceived as independent variables, and the dependent variable reflects the different formalization of concepts explained by the theoretical model. The main tenet of the model predicts that the central locations have higher returns on land, because the transportation costs to get to them from different places are lower. In other words, the intensity of land use is greater in central locations than further away from the center, and the density of urban activities has to be higher in central locations and the levels of sprawl lower.

The expected relationships between a set of variables and the characteristics of urban development that we explore in this paper are originally derived from the Alonso-Mills-Muth model and have incorporated findings from previous studies (Burchfield et al., 2006; Angel et al., 2005; Deng et al., 2008). Thes findings are supported by rigorous mathematical analyses (e.g. Brueckner, 1987; Glaeser and Kahn, 2004; Glaeser, 2008). The variables used in our models are described below.

In this study we selected the following variables to to represent *accessibility* to central locations:

- **Distance to San José**. Distance between the center of San José and the geometric centroid of the urban footprint of the municipality, measured on the national highway network.

- **Distance to the city**. Distance between the center (the intersection between the central streets and avenues, known as the historical center) of a city in the region (San José, Alajuela, Cartago or Heredia) and the geometric centroid of the urban footprint of the municipality,[15] measured on the national highway network. The Annex shows where each municipality is located in relation to these four cities.[16]

- **Distance to an industrial zone**. The distance between the closest main industrial zones (El Coyol, Ochomogo or Heredia-Belén) and the geometric center of the urban footprint of the municipality, measured on the national highway system.

In terms of accessibility, our hypotheses are (a) that a municipality located further away from an important centrality has a greater level of urban development sprawl; (b) its population density is lower; (c) the level of urban growth is higher, since the more central municipalities are essentially already developed; and (d) the urban growth away from the center is comparatively more dispersed.

In our model, we estimated the *demand for land* in the city as follows:

- **Workers (normalized)**. The number of workers in the formal economy per county, using data from the Social Security Agency of Costa Rica (*Caja Costarricense del Seguro Social*). The data assigned to 1985 were reported in 1986 (in González, 1994; the 1986 data were not available). The variables were normalized according to the formula:

$$TRAB_{normalizados} = \frac{TRAB_{it} - \sum_i \sum_t TRAB_{it} \big/ n}{desvest(TRAB_{it})} \qquad [3]$$

  where n is 93 in models that include three periods, and 62 if they include two.

- **Estimated population**. Population estimated by municipality, according to joint estimates by the Central American Center of Population (CCP), the University of Costa Rica and the National Institute of Statistics and Census. These data were downloaded from the CCP web site (http://www.ccp.ucr.ac.cr/).

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[15] The geometric centroid of the built-up area of a municipality was estimated (a) transforming the urban areas into polygons, and estimating an area (A_i) and a center of symmetry with coordinates (x_i,y_i) for each one. The coordinates of the geometric center were estimated as: $x_C = \sum_i x_i \cdot A_i \Big/ \sum_i A_i$, and similarly for y_c.

[16] The first digit of the three-digit code for each municipaly denotes the city where the municipality is located. As follows: 1 denotes the city of San José; 2 denotes the city of Alajuela; 3 denotes the city of Cartago (except in the case of the municipality of La Unión) and 4 denotes the city of Heredia.

Our hypotheses concerning demand for land are: (a) we expect that the build-up area will be larger if the number of workers and inhabitants is higher; (b) there will be less sprawl; and (c) the urban growth will be larger and more compact.

To measure the effect of *income* on household behavior, we constructed the following index:

- **Income index**. We assume that the average income in a county is (a) spatially proportional to the residential electricity consumption per customer in that county; and (b) proportional in time to the GDP per capita in real terms. However, the average income is *not* proportional in time to the residential electricity consumption, because technological changes have had a strong impact on consumption levels in the past three decades. From these assumptions we define the average income index as:

$$Ing\,\mathrm{Pr}\,el_{it} = \frac{QER_{it}}{promedio_t(QER_{it})} \cdot \mathrm{QERPROM}_{1980} \cdot \frac{PIB_s}{PIB_{1985}} \qquad [4]$$

$$IndIng_{it} = \frac{Ing\,\mathrm{Pr}\,el_{it} - \sum_i \sum_t Ing\,\mathrm{Pr}\,el_{it} / n}{desvest(Ing\,\mathrm{Pr}\,el_{it})} \qquad [5]$$

  where $\mathrm{IngPrel}_{it}$ is a preliminary index that represents income variations, normalized in (IndIng_{it}), the final income index; QER_{it} is the residential electricity consumption of a municipality in year t (where t is 1980, 2000 or 2008), $\mathrm{promedio}_t$ (QERit) is the average consumption of year t (taking the consumption value of 31 municipalities in year t); $\mathrm{QERPROM}_{1980}$ is the sum of QER_{i1980}/31 (the average residential electricity consumption per customer in the municipalities in 1980); PIB_s is the GDP in 2010 colones in year s (where s is 1986, 1997 or 2010); and PIB_{1986} is the estimated 1986 GDP (in 1991 colones); and n is 93 for databases with three periods and 62 for databases with two periods.

Because we could not find residential electricity consumption data for 1986, 1997, and 2010, we used instead, for 1986, data reported in the regional plan diagnostic for 1980 (INVU, 1983); for 1997, we used data for 2000, and for 2010, data for 2008. These datasets were generated based on information provided by the Costa Rican Institute of Electricity. The estimated GDP per capita was obtained from (for 2000–2010) the GDP estimates from the Central Bank of Costa Rica in 1991 colones (http://www.bccr.fi.cr/). The GDP estimates for previous years were obtained projecting backward, using GDP growth rates adjusted by Rodríguez-Clare et al. (2003).

We expect that the average income level will be directly related to the levels of sprawl, both of the built-up areas and the urban growth area, and development will be at lower density, because the higher the income, the lower the budgetary restrictions. Thus, the municipalities with higher average income probably have larger housing units than the municipalities with lower income.

The impact of the *regional regulation* is represented by:

- **Percentage of the municipal area within the boundaries of urban growth**. In principle, urban development beyond this limit (defined in 1982 by the regional plan) is prohibited. Only low density residential developments are allowed, intended for the agricultural producers that live in the area. Thus, the percentage of build-up area within the growth boundaries is expected to be related to lower levels of sprawl, number and growth of the built-up area.

The effect of the *agricultural income* is represented as follows:

- **Agricultural use, vegetables** (1 = yes): Municipalities where vegetable cultivation prevails, when visually inspecting the Landsat images.

- **Agricultural use, coffee** (1 = yes): Municipalities where coffee cultivation occurs close-by and/or adjacent to built-up urban areas, when visually inspecting the Landsat images.

A higher differential economic return to agricultural activity is expected to reduce the probability of urban development. Given that vegetables have the highest returns of all agricultural crops at the edge of the metropolitan region, we expect that municipalities where vegetable crops are cultivated will have lower levels of urban development and sprawl than the rest of the metropolitan region. On the other side, the development and subdivision of coffee plantations is a process with a long history in the region (see Hall, 1976). It has been demonstrated that coffee cultivation cannot prevent real estate development, neither financially or economically (Garita, 1994). For this reason, municipalities where coffee cultivation prevails experience high levels of urban growth.

Finally, we include two variables that account for the effect of *spatial variations*:

- **Average slope (%)**: Estimated from a gradient map which idealizes the space in 30 x 30 m cells. The value assigned is the average of all the cells within the boundaries of each municipality. The existing urban development in a county that is topographically more irregular is expected to be more compact, and its possibility of urban expansion to be lower.

- **Density of water wells (2 years)**: This factor was identified as important by Burchfield et al. (2006). It assumes that the possibility of extracting underground water leads to sprawl, as it reduces the infrastructure costs associated with the expansion of aqueducts. The effect of this factor in the Metropolitan Region of San José is expected to be less important given the plentiful availability of surface water in practically the entire region. This indicator is estimated by the number of permits issued by the National Water, Irrigation and Sewer Service (SENARA) for well exploration in a targeted year and in the year immediately preceding. For example, for 1986, permits granted in 1985 and 1986. Using the permit data, we estimated the density of wells for a map of 30 x 30 m cells within a 10 km radius from the center of each cell. On this continuous map we calculated the average value of the cells located within the boundaries of each municipality in each period.

Our analytical approach considers that a factor has an impact on the quantity, growth or structure of urban development if its regression coefficient is significant and has the expected sign, i.e. if the f-test indicates that the coefficients are all different than 0. If the regression coefficient has the opposite sign, the theory and the variable relevance must be revised, because the assumption of causality relies heavily on the theoretical argument supporting the model.

The analysis uses two databases. The first is a cross section of 31 municipalities and three time periods (1986, 1997, and 2010) that is used to estimate the following dependent variables: population density, the indices of sprawl, compactness and contiguity of the total built-up area. The independent variables are all those described above. The second dataset, consisting of two periods and a cross section of the 31 municipalities, is used to analyze urban growth. In this case, we estimated the following dependent variables: growth of built-up area (newly constructed areas) in hectares, the equivalent year-to-year growth rate of the built-up area,[17] and the sprawl index of urban growth. We used as independent variable all those described above, for the initial time period, under the assumption that the growth characteristics are a consequence of the variables that determine the initial urban structure of the city.

Econometric Strategy, Limitations, and Extensions

The datasets were constructed as stacked temporal series. As such, they share the structure of panel type data and are subject to the same biases—in particular, the existence of an error component associated with membership in a group (municipality). This implies that if we applied ordinary least squares, the results obtained would be biased by construction.

Given the structure of the datasets, we used the econometric developments applicable to panel data. Specifically, we estimated random effects models (Hsiao, 2003). A random effects model uses a data transformation and an "optimum" estimator derived from the generalized least square models (see Hsiao, 2003).

The standard methodological decision in panel data econometrics consists of selecting a focus, either of random effects or fixed effects. However, in our case the models developed can only be estimated with random effects because certain variables—notably physical variables, such as distance or slope—are constant or almost constant over time, and the estimation of fixed effects cannot include this type of variable. By using random effects, we gain an additional advantage. Although we consider models of random effects to be less robust than the fixed effect focus, the resulting estimates are more universal. That is because fixed effect models are conditioned by the sample, partially they are representations of the researcher's ignorance, while the random effect models are generally interpreted as an inference about the population (Hsiao, 2003), in this case about the magnitude and characteristics of the urban development per municipality in the San José Metropolitan Region.

Estimates of the Models that Describe the Built-up Area and its Structure

We estimated the random effect models based on data describing the urban structure of the region. We used the natural logarithms of population density (model 1), of all the distances, and

[17] Estimated as: $TasaCrecEq = \sqrt[p]{\frac{ÁreaUrbTotal_{final}}{ÁreaUrbTotal_{inicial}}} - 1$ where p is the number of years between the initial and final years.

the density of wells. Other variables are nondimensional. With this approach, the regression coefficients can be interpreted as elasticities. All the regressions were estimated using the R program (R Development Core Team, 2011). Table 3 summarizes the results for the dependent variables generated by the models, which are: population density (model 1), sprawl index (model 2), contiguity index (model 3) and compactness index (model 4).

We find the coefficients of determination to be generally acceptable. Although the value of the coefficient of determination for population density is low, the other models have adjusted R^2 values greater than 0.50 (and 0.70, in the case of the sprawl index and the contiguity index). All the f-tests are significant to 90 percent, clearly rejecting the null hypothesis that all the coefficients are 0.

As for the distance variables, the distance to San José is significant in all the models: the distance to industrial zones is significant in models 1 (population density) and 2 (sprawl index), and the distance to the cities is significant in models 2, 3, and 4 (sprawl index, contiguity index and compactness index). The relationship between the indices and the distance to San José behaved as anticipated by the theory, that is, density, contiguity in urban development and compactness are higher the closer we are to San José, and the levels of sprawl increase with the distance to San José. The distance to the center of each city also has a negative elasticity with respect to the compactness index, and has a lower absolute magnitude than the elasticity of the distance to San José, suggesting that the distance to San José is a more dominant factor that of the four cities in the region.

The signs of the regression coefficients of distance to the cities in models 2 and 3 are the opposite of what we expected, and in model 1 the coefficient is not significant. In fact, distance to cities seems to be a relatively weak variable. The reason for the weakness of this variable maybe the high degree of correlation with the distance to San José, note also that the t-test is consistently higher for the distance to San José than for the distance to the cities. This second explanation may imply that the metropolitan region has been more integrated than what has been traditionally interpreted.

The distance to industrial centers in the region has a direct relationship with the population density. In principle, this is consistent with the peripheral location of the industrial zones and their requirements of relatively large parcels and low land prices. The relationship between the distance to the industrial centers and the sprawl index is also direct, contrary to what would be expected, considering that sprawl and population density are expected to have an inverse relation. One possible explanation is that industrial developments reduce, by themselves, the levels of sprawl. In the metropolitan region of San Jose, industrial developments occupy relatively large areas that are densely—by necessity because land zoned for industry is very limited, compared with other urban uses—and this effect dominates other effects.

The estimated population is significant for models 2, 3, and 4. In model 1 this variable is not included because of endogeneity; and the density was estimated as the population between built-up areas. The signs exhibit the expected values, i.e. negative for model 2, when a larger population leads to less sprawl in the built-up area; and positive for models 3 and 4. The variable "workers" is not significant in model 2 (sprawl index) and shows ambiguous, though significant, signs in models 3 and 4. Its sign is positive in model 3 (contiguity index) and negative in model 4 (compactness index).

The income index, in general, behaves contrary to what was expected: Higher incomes result in lower sprawl, and greater contiguity and compactness. This finding suggests that the higher income households favor accessibility over housing area, a process than may be reinforced by the increasing levels of congestion in the region. However, we must remember that this variable is a distribution proxy. The real variable is household income, which should present a large variability within each municipality. Therefore, the result may also be a consequence of the limitations of the proxy, an aspect that should be studied further with more disaggregated data in future research.

The density of wells behaves as predicted by the theory, namely, a greater density of wells indicating an area where hydrogeological resources can be readily used, is associated with more disperse, less dense, less compact and less contiguous development. The variable is significant in all cases, and as expected, the elasticity is modest (in the order of 1 to 2 percent for the three indices) while elasticities for the distance to San José are 5 to 10 times greater. The average slope is not significant in any of the cases.

The variable representing land regulations is not significant in models 1 and 2, but is significant in models 3 and 4 measuring contiguity and compactness indices. In these last two models, the coefficients are positive and very strong. In the case of the compactness model (4), there is possibly some bias due to endogeneity since the growth boundaries were defined, among other things, to include more areas in the region that are flat.[18] In the case of the continuity index (model 3), the coefficient reflects the fact that the larger urban footprints of the region are in central locations.

Finally, with regard to the variables measuring agricultural returns, both reflect the same phenomenon, i.e. when agricultural returns are high, as for vegetables cultivation, the number of developments is low and, conversely, when the returns are low, as for coffee plantations, the number of developments is high. When one variable is significant, the other is not. In terms of population density (model 1), municipalities where vegetables are cultivated are 25 percent denser than the others. For sprawl, (model 2), the build-up areas in coffee plantation zones are more scattered; similarly, the elasticities for coffee cultivation are significant, and negative as explanation for continuity (model 3) and compactness (model 4).

Table 3. Determinants of the Urban Structure in the San José Metropolitan Region, 1986–2010

Variable	**Model 1** *Population Density*	**Model 2** *Sprawl Index*	**Model 3** *Contiguity Index*	**Model 4** *Compactness Index*
Intercept	**6.2186**	-0.4285	0.0645	1.4183
	(4.190)	(0.806)	(0.125)	(1.529)

[18] The growth boundary was defined by different criteria, depending on the physical context. To the south, the predominant criterion was the value of the slope; in other areas, the importance of the agricultural zones for the region, as well as the protection of the aquifer recharge zones, were prioritized (see INVU, 1983),

Variable	Model 1 *Population Density*	Model 2 *Sprawl Index*	Model 3 *Contiguity Index*	Model 4 *Compactness Index*
Distance to San José	**-0.3454** (3.311)	**0.1672** (5.031)	**-0.0940** (2.925)	**-0.1959** (3.369)
Distance to city	-0.0844 (1.652)	**-0.0249** (1.985)	**0.0308** (2.167)	**-0.0176** (0.600)
Distance to industrial area	**0.2045** (2.198)	**0.0574** (2.078)	0.0138 (0.507)	0.0133 (0.264)
Workers (normalized)	-0.0229 (0.561)	0.0018 (0.167)	**0.0199** (1.687)	**-0.0397** (1.679)
Estimated population	–	**-0.0869** (5.329)	**0.0465** (2.769)	**0.0931** (2.921)
Income index	-0.0356 (1.216)	**-0.0240** (3.470)	**0.0256** (3.206)	**0.0654** (3.765)
Average slope	-0.0057 (0.406)	0.0023 (0.520)	0.0043 (1.021)	0.0018 (0.232)
Density of wells (2 years)*	**-0.0867** (2.908)	**0.0189** (3.157)	**-0.0137** (1.910)	**-0.0161** (0.996)
Percentage of area within the boundaries of urban growth	-0.2081 (0.924)	-0.0806 (1.164)	**0.4803** (7.184)	**0.1954** (1.606)
Agricultural use, vegetables (1 = yes)	**0.2586** (1.706)	-0.0332 (0.715)	-0.0134 (0.298)	-0.0280 (0.343)
Agricultural use, coffee (1 = yes)	0.0402 (0.552)	**0.0610** (3.972)	**-0.0502** (2.771)	**-0.0897** (2.261)
f-test	**4.717** (10 and 82 g.l.)	**40.884** (11 and 2,86 g.l.)	**43.309** (11 and 2,86 g.l.)	**16.175** (11 and 2,86 g.l.)
Adjusted R^2	0.322	0.738	0.855	0.599
Theta	0.455	0.697	0.598	0.451
N	93	93	93	93

* The variables correspond to the initial year of the growth period.

All the indices are estimated for the total built-up area. Sprawl Index per Burchfield et al. (2006)—using neighboring squares for each urban cell.

Bolded: Significant to a 90 percent confidence level.

Estimates of Models Describing Urban Growth and Its Structure

The random effects models were also estimated based on data describing urban growth in the region (table 4). We used the natural logarithms of all the distances, the estimated population, the density of wells, the total built-up area (model 5), and the equivalent year-to-year growth rates (model 6). Other variables are nondimensional. With this approach, regression coefficients can be interpreted as elasticities. All the regressions were estimated using the R program (R Development Core Team, 2011). The dependent variables of the models are: urban growth (new built-up area in ha), equivalent year-to-year growth rate and sprawl index. The growth rates are expressed in percentages. However, because growth rates are distributed very asymmetrically, there are very few possibilities of obtaining even two-digit values. In other words, the distribution of this variable is far from normal and therefore the estimated elasticities, when used without a logarithmic transformation, are very low.

In general, the models that explain urban growth have lower coefficients of determination than those used to explain the urban structure, a finding that is somewhat consistent with the initial results of Angel et al. (2005). All coefficient are greater than 0.50 and, in the case of the sprawl index, it is even greater than 0.70.

The elasticities of the distances to San José for the three variables (built-up area, growth rate and sprawl index) are all positive and significant. This means that the expansion of the region occurs in municipalities far from San José. In contrast, the distance to the center of each of the cities is negative in model 6 (equivalent year-to-year growth rate). This suggests the existence of interactions between the accessibility variable and the metropolitan area. For the San José Metropolitan Region, growth occurred in the peripheral counties, indicating an inverse relation between the distance to the center and the growth of the built-up area. For the cities of Alajuela, Cartago, and Heredia, growth occurred in the central counties, where there is still vacant land with good access, especially in Heredia. The central counties of Alajuela, Cartago, and Heredia are as far away from San José (or more) as the peripheral counties in the metropolitan area. This explains why the elasticity of the distance to San José has positive effect and, once this effect is normalized, the distance to the center of the city is negative. Note that the regression coefficient of distance to the center of the city is not statistically different than 0 for models 5 and 7, although the parameter itself is negative.

The effects of population on growth are significant for all three models. The new built-up area is positively correlated with population. In other words, in absolute terms the the built-up area is larger the larger the population. Population is negatively correlated with the growth rate and with sprawl levels of this growth. Both of these conditions are consistent with the rapid expansion of built-up areas. The pattern of how urban expansion took place changed from more scattered growth occurring in small areas (because they were surrounded by large nonurban areas), to more compact growth patterns.

The municipalities with higher incomes grew more rapidly. This finding reflects strong empirical evidence regarding access to mortgage credit, which is effectively restricted to the higher income sectors (see Pujol et al., 2009; Román, 2008). In fact, it has been shown that more than half the households in Costa Rica do no have enough income to access mortgage credit. Nevertheless, the State has systematically reduced its role as purveyor of social housing, to the point that the real estate market went from a ratio of private/public housing of 1:1 at the end of the 80s to more than 8 to 1 during the past decade (Pujol et al., 2009). This explains why the city mainly grows in the higher income areas and why income is not significant for the growth rates or for the sprawl levels of urban growth.

Returns to agriculture behave essentially as theoretically predicted. Municipalities with high return cultivations (vegetables) show lower urban growth in absolute terms and lower growth rates, although this factor does not affect the sprawl level of the urban growth. On the other side, the municipalities where coffee cultivation prevails are significanty correlated with urban growth in the three models and the signs of the coefficients match the historic realities of the region. Where there are many coffee farms, the absolute urban growth and growth rates are higher and the urban growth is more sprawled.

A last comment on the magnitude of elasticities: for the build-up area (model 5), the elasticities are all relatively high. This suggests that there are very important differences in the growth area of counties with different characteristics. In general, the elasticities for year-to-year growth rate (model 6) are lower, except for land uses. It is possible that the opportunity cost, and the use of coffee cultivation areas as speculative real estate, play an important role in the expansion processes. However, the sprawl levels of that growth are mainly determined by accessibility as measured by the distance to San José.

Table 4. Determinants of Urban Growth in the San José Metropolitan Region, 1986–2010*

Variable	**Model 5** *New built-up area*	**Model 6** *Equivalent year-to-year growth rate*	**Model 7** *Sprawl index*
Intercept	**-6.9762**	**-4.7587**	**-1.2350**
	(2.173)	(2.110)	-(2.734)
Distance to San José	**0.6118**	**0.2397**	**0.1955**
	(3.072)	(1.712)	(6.975)
Distance to city	-0.1811	**-0.1886**	-0.0013
	(1.492)	(2.238)	-(0.075)
Distance to industrial area	0.1498	**0.2297**	**0.0510**
	(0.807)	(1.772)	(1.955)
Workers (normalized)	0.0879	-0.0187	**0.0393**
	(0.764)	(0.229)	(2.415)
Estimated population	**0.5732**	**-0.2397**	**-0.0446**
	(4.694)	(2.782)	-(2.591)
Income index	**0.1553**	0.0468	0.0038
	(1.883)	(0.687)	(0.309)
Average slope	**0.0508**	0.0308	-0.0032
	(1.892)	(1.605)	-(0.848)
Density of wells (2 years)**	**0.2184**	0.0020	-0.0029
	(2.118)	(0.026)	-(0.195)
Percentage area within the boundaries of urban growth	0.2673	0.1213	**-0.1825**
	(0.647)	(0.419)	-(3.139)
Agricultural use, vegetables (1 = yes)	**-0.9145**	**-0.7213**	0.0020
	(2.994)	(3.326)	(0.046)
Agricultural use, coffee (1 = yes)	**0.5259**	**0.5646**	**0.0449**
	(3.510)	(4.840)	(2.053)
f-test	**9.310**	**7.808**	**32.294**
	(11 and 50 g.l.)	(11 and 50 g.l.)	(11 and 50 g.l.)
Adjusted R^2	0.542	0.510	0.707
Theta	0.319	0.136	0.266
N	62	62	62

* The independent variables correspond to the initial year of the growth period.

**Number of underground water operational permits on wells approved by SENARA in the year the data was collected and the preceding year.

Sprawl index estimated only for the urban growth area. Sprawl index per Burchfield et al. (2006)—using neighboring squares for each urban cell.

Bolded: Significant to a 90 percent confidence level.

Discussion of Selected Results

From Coffee Cultivation to Development: A Historical Perspective

Historically, it is important to analyze carefully the growing trend of locating real estate developments in municipalities where coffee plantations are predominant. To do that, we would need specific models not only of the change in land use (incorporating uses that are not explicitly urban) but also a deeper understanding of the relationships between economic agents, and their respective incentives.

One possible explanation for the higher propensity of coffee plantations to be converted into urban subdivisions rather than to other agricultural crops is that the owners of coffee plantations have a greater speculative capacity to capitalize in the price of land the expected change to urban land use, compared to other rural landowners. Barring possible accessibility effects, this means that the productive dynamics of the coffee industry, for economic but also cultural and historical reasons,[19] created a closer relationship between the urban real estate market and the supply of land, conducive to the creation of urban developments in the landscapes traditionally dominated by coffee plantations.

The theoretical models of location in monocentric cities predict the expansion of the city in the form of an increase in sprawl and a decrease in density, when the agricultural returns on the edge of the city are lower than the price of land in the city proper. Although it has been shown that urban growth boundaries reduce the value of peripheral rural land (Pérez et al., 2011; Pujol and Pérez, 2012), this does not mean that the real estate market is segmented into rural and urban sectors. Land speculation in peripheral rural areas implies that the value of land in these locations has already incorporated, at the very least, the expectation of urban development. Paradoxically, the incredibly high levels of speculation in the San José metropolitan region land market may be contributing to block precisely the urban development that generated this expectation of high returns in the first place.

Another important aspect to note is the high degree of endogeneity that exists (historically generated) between accessibility and coffee production. The impulse given to coffee cultivation since 1840 modified the historical demographic patterns of the region. The population evolved from living in villages and cultivating on "common lands," as customary during colonial times, to the privatization of public lands for coffee production. As all the lands close to a village were occupied, new families tended to emigrate and the remaining land was transformed into coffee plantations (Gudmunson, 2010). This process led to the creation of trails between the original villages and the new coffee plantations. This system of trails was eventually improved to transport the coffee production more efficiently, and became the basis for the current highway system.[20]

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[19] Coffee was the traditional export product that built Costa Rica's prosperity in the second half of the nineteenth century. Large coffee producers controlled the coffee value added process and generated large sums of capital, which were later—already in the twentieth century—invested in other businesses, such as banking and finance. This is not the case with farming or livestock; these historical relations may have facilitated the conversion of coffee plantations to urban developments, either residential or commercial, for many coffee plantation owners.

[20] Not the regional highway system, whose structure was defined by the need to connect the metropolitan region with other areas of the country: national routes 10 and 32 with the Caribbean coast; national routes 1 and 27 with the

Agricultural Returns and Urban Growth

The spatially explicit models of change in land use (e.g. Irwin and Geoghegan, 2001) propose that the conversion of land from nonurban to urban use occurs when the net benefits of urban development for the economic agent (landowner) exceed the expected return of keeping the land in nonurban use. This process occurs in the period in which the net benefit of the conversion, minus the opportunity cost, exceeds the net benefit of the conversion if done in the next period. In other words, if the landowner can obtain more benefits by waiting (because the value of the urban land will grow without any intervention), the conversion will be delayed.

The map entitled "Land Prices and Agricultural Returns of Four Crops, Analysis for the City of Heredia" (figure 8) compares land price (returns) with the agricultural returns generated by the four main crops in the region. Pujol and Pérez (2012) estimated an econometric model for Heredia with spatial effects, demonstrating the impact of the urban growth boundary on the use of land. This model produced a map of land prices for the entire Heredia metropolitan area. The results are expressed in 2007 United States dollars.

We then analyzed this map to identify the areas in which agricultural returns exceeded the market value of land (land price) in Heredia. When this happens, the best decision of the landowner would be to continue cultivating and not convert the land to urban development. What we found is:

- The agricultural returns to coffee cultivation, which in 2007 represented a present value of \$6.8/m^2 (assuming 30 years of land ownership), and sugarcane cultivation (\$7.4/m^2), were less than a third of the minimum land price in Heredia (\$24/m^2).

- The agricultural returns to potato (\$28/m^2) and onion cultivation (\$49/m^2), in contrast, were greater than the minimum price of land in Heredia. The 20 percentile value in the land prices map is \$28/m^2, meaning that only in some isolated areas to the north of the metropolitan area could potato cultivation compete with urban development. In the case of onion cultivation, \$49/m^2 corresponds to the 60th percentile in the land price map, which comprises a larger area. In any event, these areas are the least accessible, mostly located beyond the boundaries of urban growth. It must be noted that both the potato and onion productions are extraordinarily profitable in Costa Rica, in part because they are protected from international market competition by fees, and also because of scarcity. The areas planted with potatoes and onions in Costa Rica represent only between 2 and 6 percent of the total area of coffee planted during the past two decades (see SEPSA, 2012). Thus, strictly speaking, if the cultivation area increases because many landowners in the region decide to switch to these crops, the prices and the net profits of onion and potato cultivation will probably decline substantially.

The data clearly suggest that the benefits of urban use exceed both the cost of convertion and the opportunity cost of agricultural use. One can speculate on the reasons that have blocked this change. In Heredia, there is a trend for land prices to grow (Pérez et al., 2011) and interest rates

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Pacific coast; the province of Guanacaste and the population to the west of the Central Valley; national route 2 with El General Valley and the southern Pacific area of Costa Rica.

in the Costa Rican financial market are relatively high. These circumstances imply a significant reduction in the present value of land, since capital can be invested with high returns in other activities than urban development. Furthermore, the regional regulations restrict the permissible land use in a great part of the periphery (Pujol and Pérez, 2012). A better description of the aggregated dynamics of land use change in peripheral locations (using spatial statistical models) would contribute to improve our understanding of the mechanisms prompting such change.

A caveat: although it is true that the conditions described for Heredia are representative of most of the region, there are numerous areas where the values of land are lower than in Heredia. For example, the average price of land in Alajuela and Cartago is probably lower than in Heredia.

Figure 8. Land Prices and Agricultural Returns of Four Crops
Analysis for the City of Heredia

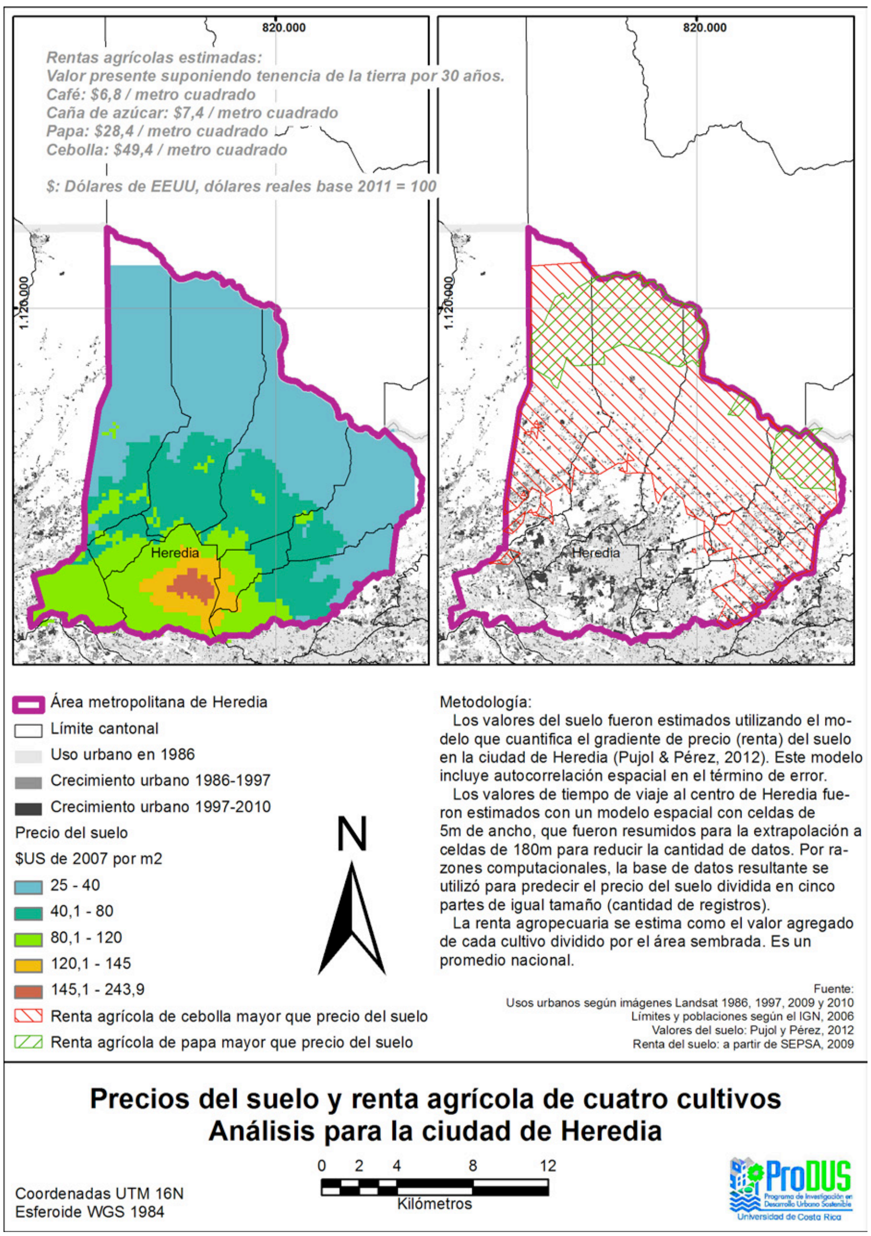
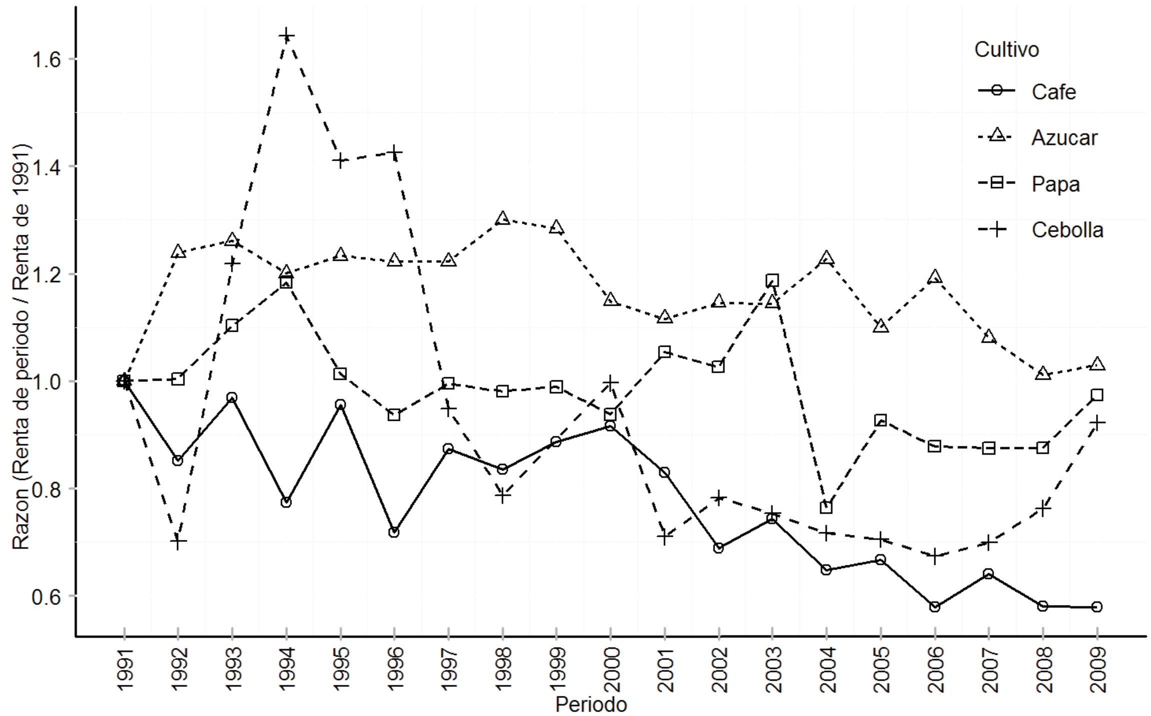


Figure 9. Evolution of Agricultural Returns per Crop in Costa Rica, 1991–2009



Renta agricola $EEUU/m2	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Cebolla	70	49	86	116	99	100	67	55		70	50	55	53	50	49	47	49	53	65
Papa	32	32	35	38	32	30	32	31	32	30	34	33	38	24	30	28	28	28	31
C. de azucar	6	8	8	8	8	8	8	8	8	7	7	7	7	8	7	8	7	6	7
Cafe	10	8	10	8	10	7	9	8	9	9	8	7	7	6	7	6	6	6	6

Note: Estimated as the value added of the agricultural production by the estimated planted area. Annual income per ha originally in 1991 colones, deflated to 2011 colones, then converted to US dollars using the currency exchange rate from July 2011. The present value of the agricultural returns is estimated as the annual income during 30 years (assumes ownership of the production for 30 years)

Source: Statistical bulletins of the Secretary of Agricultural System Planning (SEPSA), http://www.infoagro.go.cr/boletines.htm.

Infrastructure, Regulation, and Urban Growth

The maps entitled "Coverage of Sewer Systems in San José, Costa Rica" (figure 11) and "Built-up Area and Regulation in the San José Metropolitan Region, Costa Rica" (figure 12), together with figure 10, show the overlap of urban growth and infrastructure systems, as well as the effect of urban regulations.

Most of the city of San José is served by a sewer system, except for its northeast corner where growth in consists basically of occupation of scattered vacant land parcels. The continuous growth areas are larger and are located beyond the area served by the sewer system, especially to the south and east of San José. These development areas are likely to have their own sewer treatment systems, built and paid for by the developer, especially if they are new neighborhoods,. However, despite the added infrastructure costs, this is where most of the city expansion is taking place, since there are not many vacant parcels in the city proper.

A similar observation can be made about the relation between the build-up area of San José and the growth boundaries, with the difference that the urban boundaries encompass a larger area than the area served by the sewer system, and therefore more unoccupied land can be found. In particular, there are areas that can be developed around national route 27, in the municipalities of Escazú, Santa Ana and Mora. For that reason, much of the urban development in San José has occurred on the edges of Escazú, and more recently along national route 27. Besides availability of vacant land, this expansion also reflects the greater accessibility given by the proximity to national route 27.

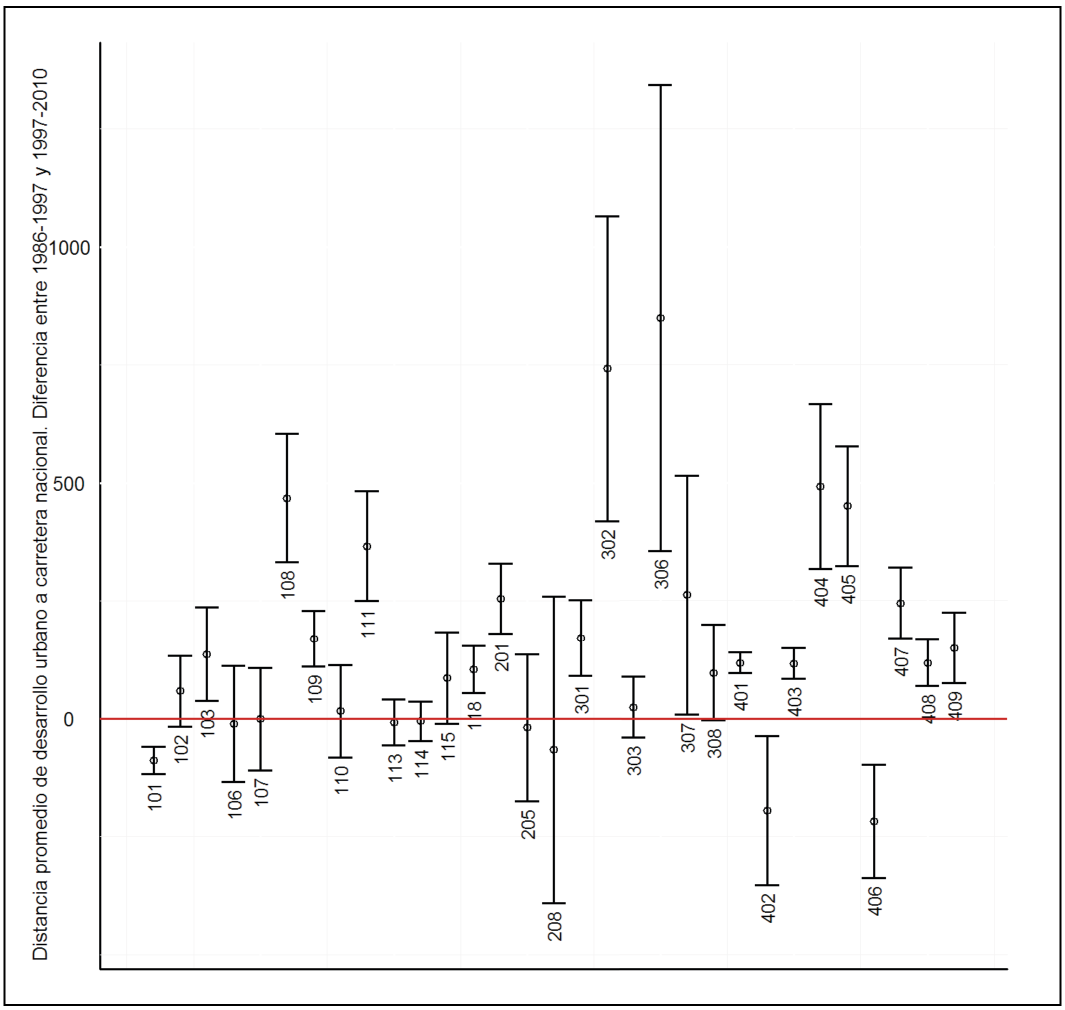
In contrast with San José, the other cities in the region have ample space to expand within their growth boundaries. However, the remaining areas available for development are less accessible, and the consolidated areas of Heredia and Alajuela have reached their respective growth boundaries on the north. Cartago, has experienced slower expansion, at least until 2010, and still has some vacant land, but is also reaching its northern limit. The centers of both Alajuela and of Heredia are located north of national routes 1 and 3 which connect San José with the Pacific coast. Vacant land parcels in Alajuela are mainly to the south, and that may help explain why they have not yet been developed. However, with the additional accessibility given by the completion of national route 27 in 2009, development of this area may start shortly.

Figure 10 shows the difference in the average distance between new developments and the national highway system by county, comparing the first period of analysis (1986–1997) with the second (1997–2010). In general, the counties may be classified in three main groups. First, counties where new developments are located closer to the regional highway system (negative difference); this is the case of San José (101), Barva (402), and San Isidro (406). Second, a larger group of counties where the difference is not statistically significant (the value of 0 is within the 95 percent confidence level). This group includes the counties of the city of San José (except for some in the periphery) which are Santa Ana (109); Coronado (111); Curridabat (118); and Goicoechea (108), as well as the rural counties of Alajuela. The third group includes the county of Alajuela (201), the aforementioned counties on the periphery of San José, and the counties of the cities of Cartago and Heredia, except Barva (402) and San Isidro (406) in Heredia, which are part of the first group.

The first group of counties exhibits two main trends. For San José, new development takes place closer to the regional highway system because elsewhere vacant lots remain unutilized as objects of speculation. The occupied area is relatively small and a densification process is occurring in formely underutilized land within the city limits, promoting the construction of relatively high buildings (more than ten floors).

The urban development in Barva, particularly the most recent expansion, has been concentrated to the south of the county center (between Barva and Heredia centers) and to the west, including locations closer to the system of primary roads and to the center of Heredia. In the case of San Isidro, urban development has concentrated around national route 32, inaugurated in the late 80s changing radically the accessibility of the county to the center of San José.

Figure 10. Differences in Average Distance to National Highways for Areas Built between 1986 and 1997, and Areas Built between 1997 and 2010 [with confidence intervals of 95 percent]



The main characteristic of the third group of counties is expansion in the periphery and rapid conversion from rural to urban land use. In those counties, growth is concentrated outside San José, anticipating migration out of San José to other cities. In particular, recent growth patterns and census information (2011) suggest that the city of Heredia is attracting new residents from among the San José middle class.

Figure 11. Coverage of Sewer Systems in San José, Costa Rica

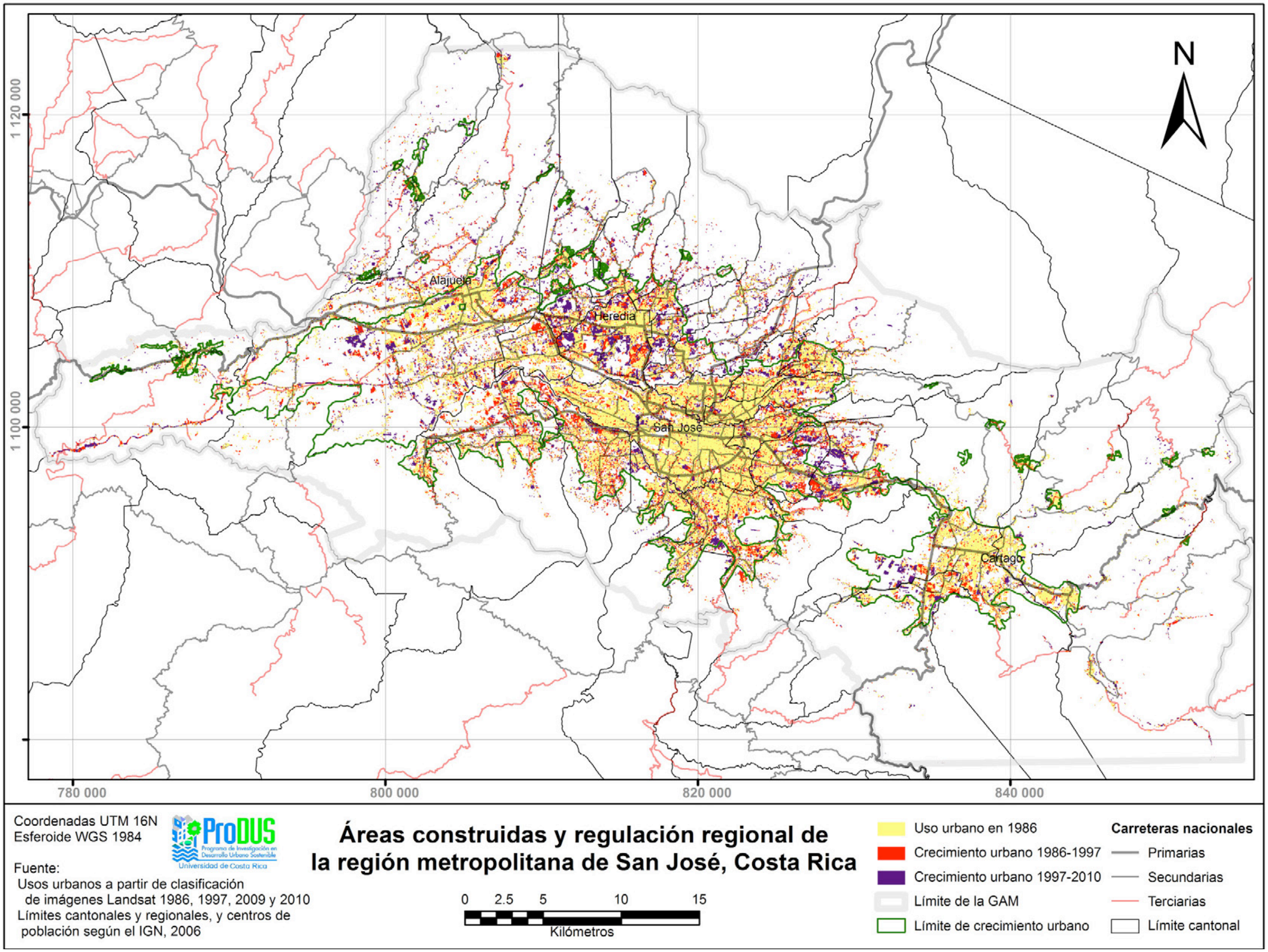
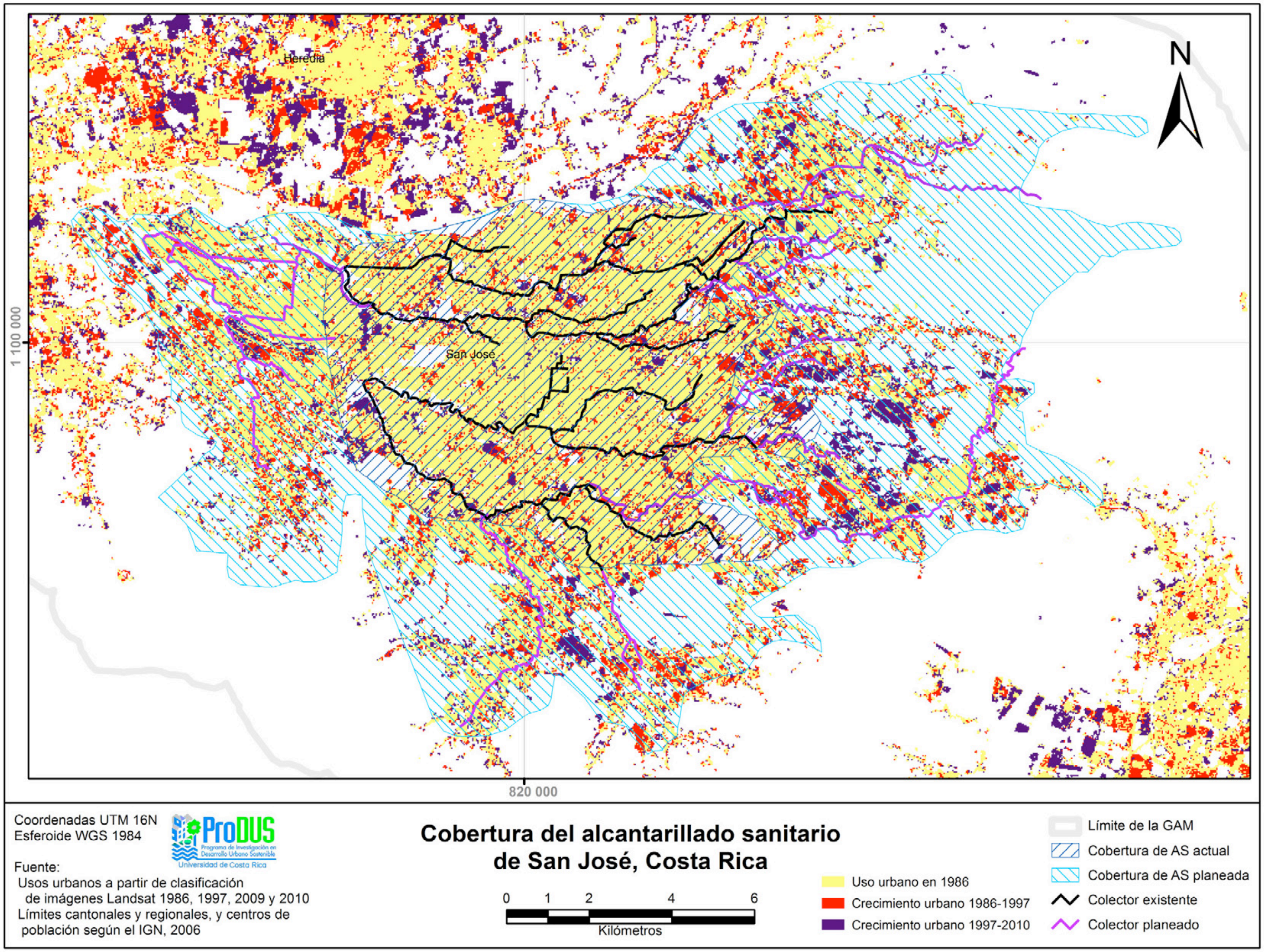


Figure 12. Built-up Area and Regulation in the San José Metropolitan Region, Costa Rica



In general, the counties whose growth occurs approximately at the same distance from the regional highway system in both periods (groups in which the value of 0 is in the range defined with a 95 percent confidence level) are those located at the edge of the city of San José. Eventually, this growth at the edge gave place to a combination of expansion on vacant peripheral areas and consolidation of vacant lots (infill), a consequence of the first expansion process. The exception to this trend is the country of Poás which experienced very high levels of dispersion with respect to distance to a primary national highway, suggesting relatively low growth in very different locations.

Agglomeration Economies and Public Transportation

The patterns of urban development in a city are closely linked to the transportation technology dominant in the historical period of its development (e.g. Newman and Kenworthy, 1999). The sprawling urban growth, currently a typical feature of many cities in the world, is not an exception to this.

Glaeser and Kahn (2004) have argued that sprawl is essentially a consequence of the massive use of the private automobile. In fact, in a monocentric city (under the classic model of Alonso-Mills-Muth), lower transportation costs imply that the city is expanding at its edge at reduced densities, due to a higher land consumption per household. In a polycentric city, the change from public transportation to private vehicles, as the main transportation medium for the labor force, reduces the cost of creating new subcenters. This in turn, promotes greater decentralization (see Glaeser and Kahn, 2004). If transportation costs are sufficiently low, Tabuchi (1998) has demonstrated that decentralization will occur despite the economics of agglomeration. Furthermore, the decentralization process will tend to reduce general welfare.

In this context, the San José Metropolitan Region can be considered a very particular case. The income of the population has increased in real terms (the GDP of Costa Rica increased 2.5 times in real terms during the past two decades). Higher income has fostered a greater preference for more consumption of land together with more purchases and use of private vehicles (see Ingram and Liu, 1998, for estimates of the relationship between income and motorization). Given these trends, we would expect more sprawl in new urban developments. However, the population densities have increased, and the urban areas have become more compact.

There are three possible explanations for the observed trends in San Jose, although a definitive answer would require additional research. First, it is important to consider that San José Metropolitan Region is structurally dispersed, as discussed above: The current cities are the product of the conurbation of many small rural villages, and the largest cities (San José, Alajuela, Heredia and Cartago) were converted into city centers. The conurbation was achieved by developing rural lands between these original population centers. This process was aided by the public service infrastructure and the roads that connected the towns, providing relatively easy access to essential services. This dynamic is reflected in the estimated indices as an increase in compactness.

Secondly, there is some evidence (see Pérez et al., 2011) that land values have increased more rapidly than income. This suggests, in turn, that the additional income available due to lower transportation costs have not offset the increase in price associated with greater land area per house. In fact, it is possible to detect some early trends toward densification in a reduction of the area and the number of floors in new housing devlopments. We have also noted that the value of rural land already incorporates a speculative component of its potential urban development. This also promotes greater densities and smaller area per housing unit.

Finally, we need to account for the impact of road congestion. Although it is true that higher incomes resulted in a larger number of vehicles on the road, the regional highway system has not expanded in the same proportion. This means that much of the savings in time (transportation costs) of the change to private vehicles has been lost rather quickly. Even more, the same location that was considered accessible a decade ago may be relatively inaccessible now, due to the increase in travel time from the center of the city or, in general, from other areas of the metropolitan region.

Monocentricity vs Polycentricity

The San José Metropolitan Region has been characterized as polycentric reflecting its origins. It was composed of four main population centers and a string of smaller towns and villages. These population centers have been conurbating, resulting in a region with four cities. There are deficiencies in the transportation system associated with the limitations imposed by physical barriers such as rivers with deep canyons and mountainous areas, preventing the formation of a single big city—even though the prominence of San José is clearly evident. The most recent data from the 2011 census help quantify this reality. The city of San José has 56 percent of the region population, Heredia 16 percent, and Cartago and Alajuela 14 percent each. The total population counted in the census was 2.27 million, occupying 681,000 housing units.

For some of its functions, the city behaves as monocentric. The center maybe San José or other regional city depending on the type of urban activity considered. But the city also shows polycentric tendencies, most apparently in the development of office buildings and industrial centers clustered along the regional highway system. For the users of public transportation, the city is monocentric, and it is more a problem of levels of monocentricity because the road system is such that all roads converge toward the traditional centers. The urban resident using public transport decides where to stop, either at the municipal center, or continue to the city center, or transfer to San José once he reaches the city center.

To explore this concept of function of several urban agents, which is applicable to most of the population and urban activities although not all,[21] we introduced econometric variables in the different models that estimate the distance to city centers and to the center of San José.[22] It must be noted that, in general, the correlation between these distances was very strong, mostly because 13 of the 31 municipalities of the city of San José are located at the same distance to all four city centers in the region. Moreover, the distances to the center of San José tended to be more

[21] Two notable exceptions are the aforementioned employees of office centers and high technology industries, who access their work using the highway system, and elementary students. Costa Rican schools provide basically a local service; the great majority of elementary students walk to school.

[22] The data plugged into the models correspond to a municipal cross section. Future spatial-statistical models will probably also require measures of the distance to the municipal center.

significant than other location measures, possibly because of differences in the urban form of the other cities that are partially captured by the variable “distance to San José.”

Conclusions

The generation and analysis of maps of urban land use showing comparable indices of urban sprawl, has allowed us to partially characterize the regional urban development of the built-up area in the historic context of the San José Metropolitan Region, and in the Latin American and global context.

Comparing our results with those of Burchfield et al. (2006) and Angel et al. (2005, 2010a, 2010b, 2010c), it is possible to state that the San José Metropolitan Region is less dense and more dispersed than the majority of Latin American cities, but not reaching the levels observed in the United States. The fundamental difference lies in the process of formation of the urban system in the region. Sprawl, in its classic formulation (Glaeser and Kahn, 2004) is a process triggered by lower costs of transportation. The sprawl in the built-up area of the San José Metropolitan Region, however, is a consequence of a structure that was originally scattered, and has been consolidating as spaces closer to the existing population centers are been built-up. The limitations of the road network, added to a growing population, have created incentives for a growth pattern that is more organic than leapfrogging.

The indicators that characterize the patterns of the built-up areas reflect increases in the levels of compactness and reductions in sprawl, which are a consequence of the regional demographic growth. As population increases; the built-up area also grows but population grows slightly more rapidly than the built-up area, generating an increase in density. This is probably a product of the limitations of the road network, which generates greater transportation costs due to congestion. Note, however, that the locations of new construction are characterized by constant levels of sprawl, both in the period of 1986–1997 and 1997–2010. The consolidation occurs because the growth in these two periods occurred in areas with lower levels of sprawl than the sprawl of the total built-up area; although this is not true for 2010. Thus, if the sprawl levels in the built-up growth area are maintained, the trend toward a greater compactness of the total built-up area should change.

The determinants of urban development in San José are, in general, consistent with the monocentric city model of Alonso-Mills-Muth and with the results of prior macroanalyses. When developments are further away from the center of San José, growth is more sprawled and the built-up area is smaller. Similarly; the growth that occurs in the municipalities farther away from San José is of greater magnitude, speed and level of sprawl. The associations that we detected, although estimated at a rather coarse spatial scale, suggest the existence of processes theoretically derived from microeconomic models of activity location. More spatially detailed causal models (e.g. Pérez and Pujol, 2012) have detected other significant impacts that were not possible to capture with the general models estimated in this paper. The extension of the results using a finer spatial scale would allow us to describe the causal mechanisms of urban growth patterns and to quantify the impact of these mechanisms. It would be particularly interesting to extend the assessment of the impacts of regulation (growth boundaries) and the variations in transportation costs over time.

Finally, we want to highlight two very relevant aspects of the land market and the urban growth patterns in San José. Sprawling development should produce a very large negative environmental externality, particularly north of Heredia and Alajuela, because of the potential impact on the aquifers located there. The organic growth of built-up areas will allow the treatment of wastewater in plants, while sprawling growth implies wastewater treatment in septic systems which allow the filtration of partially contaminated water. A significant contamination of these aquifers could restrict access to drinking water consumed by more than half of the regional population. This impact *is not incorporated in the land values at the periphery*. There is, however, some evidence that the aesthetic value of the region's rural landscape has been added to the prices of land (see Pujol and Pérez, 2012). Secondly, a comparative analysis of agricultural returns and land values suggests that in the areas of more intense urban growth, the mechanism that controls land occupation by new urban activities (construction) is not the difference in returns between urban and nonurban use, at least not in the way described by Irwin and Geoghegan (2008).[23] More detailed analysis is required to better understand the impact of growing incomes and growth of the built-up areas on expectations of added value of rural properties. Similarly, more research is needed to gauge the differential impact of transportation costs which may be restricting the development in the periphery in favor of greater densities in the center of San José.

[23] Except in the Cartago Metropolitan Area where the land prices are lower because it is a less accessible area and the crops produced (potatos and onions) have greater returns.

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Appendix

Table A-1. Summary of Built-up Area Indicators per Municipality

County	Total area	Buildable area	Available buildable area		Built-up area		Density	Indices		
	Ha.	*Ha.*	*Ha.*	*% of total*	*Ha.*	*% of total*	*Popul./Urban Ha.*	*Sprawl*	*Compactness*	*Contiguity*
1986										
101 San José	4481.7	4234.6	1082.8	25.57%	3226.7	70.33%	82.77	0.2551	0.7620	0.9637
102 Escazú	3462.5	2398.7	1582.9	65.99%	846.1	23.56%	44.45	0.5563	0.3527	0.3695
103 Desamparados	5972.5	3711.3	2517.0	67.82%	1225.3	20.00%	96.10	0.4830	0.3301	0.5841
106 Aserrí	2955.0	1215.6	960.7	79.03%	267.7	8.63%	93.95	0.6062	0.2202	0.6543
107 Mora	6329.1	2935.0	2771.7	94.44%	178.6	2.58%	47.68	0.7543	0.0608	0.2422
108 Gocioechea	3173.1	2344.8	1510.8	64.43%	845.7	26.28%	107.25	0.3705	0.3607	0.6492
109 Santa Ana	6145.4	3395.3	2612.5	76.95%	837.7	12.74%	26.86	0.7050	0.2467	0.1120
110 Alajuelita	2151.4	1189.2	804.1	67.62%	398.9	17.90%	91.33	0.5130	0.3354	0.6877
111 Coronado	5206.5	3835.0	3416.0	89.08%	422.6	8.05%	68.60	0.5415	0.1102	0.6705
113 Tibás	835.9	766.3	209.7	27.37%	562.3	66.58%	120.15	0.2952	0.7339	0.9850
114 Moravia	2917.4	2453.2	1959.7	79.88%	499.5	16.92%	76.64	0.4259	0.2036	0.6165
115 Montes de Oca	1557.5	1421.9	877.4	61.71%	550.7	34.96%	78.76	0.3810	0.3873	0.8671
118 Curridabat	1623.1	1545.2	899.1	58.19%	658.8	39.81%	58.46	0.4610	0.4263	0.6519
201 Alajuela	26146.4	22194.9	19084.8	85.99%	3176.3	11.90%	45.42	0.6541	0.1431	0.3417
205 Atenas	8391.8	4709.0	4427.9	94.03%	308.3	3.35%	38.74	0.8206	0.0655	0.2219
208 Poás	6646.7	5300.8	5091.0	96.04%	221.9	3.16%	72.23	0.8443	0.0419	0.1833
301 Cartago	19008.5	11203.4	9634.7	86.00%	1613.2	8.25%	56.68	0.5125	0.1440	0.4619
302 Paraíso	16960.1	8478.9	8057.6	95.03%	429.8	2.48%	74.08	0.6598	0.0507	0.3251
303 La Unión	4454.4	3373.5	2791.7	82.75%	617.0	13.06%	79.03	0.6717	0.1829	0.4297
306 Alvarado	7980.1	4332.0	4241.8	97.92%	98.4	1.13%	94.36	0.8991	0.0227	0.1737
307 Oreamuno	7177.1	5573.8	5165.3	92.67%	415.2	5.69%	66.47	0.5959	0.0745	0.4792
308 El Guarco	8396.2	3823.1	3439.5	89.97%	395.3	4.57%	59.28	0.6565	0.1034	0.4419
401 Heredia	2523.4	2473.1	1516.8	61.33%	962.9	37.90%	66.79	0.4878	0.3894	0.3949
402 Barva	5613.7	4719.2	4471.8	94.76%	248.5	4.41%	88.08	0.7411	0.0527	0.1987
403 Santo Domingo	2527.1	2274.0	1872.5	82.34%	412.1	15.89%	66.25	0.6799	0.1812	0.3856

County	Total area	Buildable area	Available buildable area		Built-up area		Density	Indices		
	Ha.	*Ha.*	*Ha.*	*% of total*	*Ha.*	*% of total*	*Popul./Urban Ha.*	*Sprawl*	*Compactness*	*Contiguity*
404 Santa Bárbara	5216.0	3817.5	3577.0	93.70%	246.2	4.61%	78.81	0.7978	0.0645	0.1963
405 San Rafael	4812.7	4003.7	3732.4	93.22%	271.9	5.64%	97.03	0.6157	0.0679	0.6332
406 San Isidro	2652.8	2202.1	2025.2	91.97%	177.6	6.67%	55.56	0.8176	0.0806	0.1550
407 Belén	1248.2	1184.7	705.8	59.58%	496.1	38.37%	27.73	0.5603	0.4187	0.2838
408 Flores	674.6	669.5	482.4	72.05%	187.2	27.74%	55.52	0.6410	0.2796	0.4265
409 San Pablo	834.8	832.3	644.3	77.41%	188.3	22.52%	73.89	0.6454	0.2262	0.6684
GAM Greater Metropolitan Area	*178075.4*	*122611.5*	*102166.8*	*83.33%*	*20986.5*	*11.48%*	*68.34*	*0.5248*	*0.1712*	*0.3153*
1997										
101 San José	4481.7	4234.6	689.9	16.29%	3632.6	79.09%	84.43	0.1704	0.8578	0.9850
102 Escazú	3462.5	2398.7	1213.2	50.58%	1232.5	34.24%	40.71	0.4073	0.5138	0.7990
103 Desamparados	5972.5	3711.3	2095.7	56.47%	1668.8	27.05%	101.41	0.3524	0.4496	0.8896
106 Aserrí	2955.0	1215.6	902.4	74.24%	332.7	10.60%	103.51	0.5378	0.2737	0.8737
107 Mora	6329.1	2935.0	2692.5	91.74%	265.9	3.83%	47.59	0.6561	0.0906	0.4240
108 Gocioechea	3173.1	2344.8	1346.1	57.41%	1015.3	31.47%	113.31	0.2720	0.4330	0.9420
109 Santa Ana	6145.4	3395.3	2249.1	66.24%	1221.8	18.65%	26.34	0.5927	0.3599	0.4306
110 Alajuelita	2151.4	1189.2	714.2	60.05%	494.3	22.08%	122.68	0.4157	0.4157	0.7422
111 Coronado	5206.5	3835.0	3284.3	85.64%	556.2	10.58%	88.96	0.4166	0.1450	0.7451
113 Tibás	835.9	766.3	123.5	16.11%	649.6	76.89%	120.70	0.1974	0.8478	0.9914
114 Moravia	2917.4	2453.2	1836.7	74.87%	626.0	21.13%	79.74	0.3417	0.2552	0.7965
115 Montes de Oca	1557.5	1421.9	713.9	50.21%	716.5	45.46%	69.92	0.2530	0.5039	0.9501
118 Curridabat	1623.1	1545.2	654.8	42.37%	910.7	54.86%	64.53	0.3442	0.5894	0.9336
201 Alajuela	26146.4	22194.9	18162.0	81.83%	4125.1	15.42%	49.95	0.6027	0.1859	0.4585
205 Atenas	8391.8	4709.0	4327.8	91.91%	426.3	4.54%	36.98	0.7940	0.0905	0.2267
208 Poás	6646.7	5300.8	5029.8	94.89%	287.3	4.08%	80.65	0.8173	0.0542	0.1949
301 Cartago	19008.5	11203.4	9317.2	83.16%	1940.9	9.92%	60.99	0.4471	0.1732	0.5898
302 Paraíso	16960.1	8478.9	7959.1	93.87%	532.7	3.07%	90.19	0.6362	0.0628	0.5000
303 La Unión	4454.4	3373.5	2513.5	74.51%	914.5	19.31%	82.15	0.5661	0.2711	0.6999
306 Alvarado	7980.1	4332.0	4230.4	97.65%	111.6	1.27%	106.48	0.8892	0.0258	0.1653
307 Oreamuno	7177.1	5573.8	5129.6	92.03%	452.4	6.19%	83.07	0.5603	0.0812	0.5036

County	Total area	Buildable area	Available buildable area		Built-up area		Density	Indices		
	Ha.	*Ha.*	*Ha.*	*% of total*	*Ha.*	*% of total*	*Popul./Urban Ha.*	*Sprawl*	*Compactness*	*Contiguity*
308 El Guarco	8396.2	3823.1	3317.9	86.79%	523.7	6.02%	61.51	0.5363	0.1370	0.5128
401 Heredia	2523.4	2473.1	1167.3	47.20%	1313.4	51.75%	74.67	0.3726	0.5311	0.7358
402 Barva	5613.7	4719.2	4351.2	92.20%	369.3	6.56%	83.44	0.6634	0.0782	0.4400
403 Santo Domingo	2527.1	2274.0	1705.1	74.98%	582.1	22.52%	59.03	0.6232	0.2560	0.4180
404 Santa Bárbara	5216.0	3817.5	3455.0	90.50%	370.2	6.95%	75.21	0.7260	0.0970	0.2936
405 San Rafael	4812.7	4003.7	3618.5	90.38%	386.1	8.00%	93.19	0.5283	0.0964	0.6944
406 San Isidro	2652.8	2202.1	1972.6	89.58%	230.5	8.65%	64.29	0.7700	0.1047	0.2472
407 Belén	1248.2	1184.7	568.2	47.96%	639.7	49.39%	29.53	0.4355	0.5400	0.8039
408 Flores	674.6	669.5	398.9	59.58%	270.8	40.12%	53.33	0.5072	0.4045	0.9114
409 San Pablo	834.8	832.3	587.1	70.53%	245.6	29.38%	81.93	0.5535	0.2951	0.8072
GAM Greater Metropolitan Area	*178075.4*	*122611.5*	*96327.3*	*78.56%*	*27044.9*	*14.76%*	*71.41*	*0.4457*	*0.2206*	*0.4216*
2010										
101 San José	4481.7	4234.6	480.2	11.34%	3860.0	83.77%	90.45	0.1228	0.9115	0.9929
102 Escazú	3462.5	2398.7	1020.8	42.56%	1448.5	39.80%	42.01	0.3408	0.6039	0.8825
103 Desamparados	5972.5	3711.3	1868.4	50.34%	1911.0	30.86%	147.48	0.2927	0.5149	0.9257
106 Aserrí	2955.0	1215.6	826.1	67.96%	417.2	13.18%	93.11	0.4614	0.3432	0.9012
107 Mora	6329.1	2935.0	2643.6	90.07%	320.9	4.60%	52.37	0.6053	0.1093	0.4529
108 Gocioechea	3173.1	2344.8	1243.5	53.03%	1123.1	34.71%	117.21	0.2175	0.4790	0.9392
109 Santa Ana	6145.4	3395.3	2033.9	59.90%	1458.6	22.15%	29.98	0.5223	0.4296	0.6273
110 Alajuelita	2151.4	1189.2	618.7	52.02%	599.9	26.52%	209.45	0.3445	0.5044	0.9072
111 Coronado	5206.5	3835.0	3180.2	82.92%	662.9	12.58%	122.73	0.3548	0.1728	0.8042
113 Tibás	835.9	766.3	86.6	11.30%	689.6	81.31%	89.60	0.1511	0.8999	0.9927
114 Moravia	2917.4	2453.2	1716.0	69.95%	752.9	25.27%	72.84	0.2889	0.3069	0.8261
115 Montes de Oca	1557.5	1421.9	606.2	42.64%	824.5	52.37%	65.84	0.1708	0.5798	0.9709
118 Curridabat	1623.1	1545.2	446.0	28.86%	1127.4	67.73%	64.36	0.2500	0.7296	0.9825
201 Alajuela	26146.4	22194.9	17037.2	76.76%	5289.0	19.73%	53.01	0.5491	0.2383	0.6087
205 Atenas	8391.8	4709.0	4195.5	89.10%	586.3	6.12%	33.25	0.7615	0.1245	0.3730
208 Poás	6646.7	5300.8	4865.0	91.78%	461.8	6.56%	67.84	0.7751	0.0871	0.1840
301 Cartago	19008.5	11203.4	8992.7	80.27%	2280.1	11.63%	63.61	0.4207	0.2035	0.7416

County	Total area	Buildable area	Available buildable area		Built-up area		Density	Indices		
	Ha.	*Ha.*	*Ha.*	*% of total*	*Ha.*	*% of total*	*Popul./Urban Ha.*	*Sprawl*	*Compactness*	*Contiguity*
302 Paraíso	16960.1	8478.9	7839.0	92.45%	658.8	3.77%	104.54	0.6413	0.0777	0.4601
303 La Unión	4454.4	3373.5	2201.5	65.26%	1242.7	26.31%	84.98	0.4519	0.3684	0.8435
306 Alvarado	7980.1	4332.0	4195.0	96.84%	151.3	1.72%	90.50	0.8829	0.0349	0.1340
307 Oreamuno	7177.1	5573.8	5069.6	90.95%	515.1	7.02%	86.69	0.5464	0.0924	0.4933
308 El Guarco	8396.2	3823.1	3212.6	84.03%	634.5	7.27%	59.28	0.4798	0.1660	0.5858
401 Heredia	2523.4	2473.1	753.4	30.46%	1731.5	68.15%	76.18	0.2448	0.7001	0.8926
402 Barva	5613.7	4719.2	4183.4	88.65%	538.6	9.55%	72.54	0.5779	0.1141	0.4731
403 Santo Domingo	2527.1	2274.0	1446.4	63.60%	851.0	32.75%	44.04	0.5317	0.3742	0.5527
404 Santa Bárbara	5216.0	3817.5	3294.6	86.30%	534.2	10.03%	64.67	0.6600	0.1399	0.4933
405 San Rafael	4812.7	4003.7	3458.6	86.39%	547.4	11.33%	79.27	0.4742	0.1367	0.6374
406 San Isidro	2652.8	2202.1	1848.4	83.94%	355.5	13.33%	61.73	0.7112	0.1614	0.2656
407 Belén	1248.2	1184.7	495.6	41.84%	715.7	55.20%	32.77	0.3680	0.6041	0.8201
408 Flores	674.6	669.5	262.7	39.24%	407.0	60.31%	43.26	0.3481	0.6079	0.8886
409 San Pablo	834.8	832.3	442.1	53.11%	391.4	46.75%	60.57	0.3947	0.4703	0.9269
GAM Greater Metropolitan Area	*178075.4*	*122611.5*	*90563.4*	*73.86%*	*33088.1*	*18.00%*	*75.35*	*0.3956*	*0.2699*	*0.4247*

Source: Estimated from the analysis of Landsat images

Table A-2. Summary of Urban Growth Indicators per Municipality

		County	Total area (2nd period) *Ha.*	Growth *Ha.*	Growth *% of total*	Growth *% of constructed area in initial period*	Equivalent year-to-year rate *%*	***Sprawl index***
1986-1997	101	San José	3632.6	405.9	9.06%	12.58%	1.08%	0.2081
	102	Escazú	1232.5	386.4	11.16%	45.67%	3.48%	0.4378
	103	Desamparados	1668.8	443.5	7.43%	36.20%	2.85%	0.4098
	106	Aserrí	332.7	65.1	2.20%	24.31%	2.00%	0.5765
	107	Mora	265.9	87.3	1.38%	48.89%	3.68%	0.6724
	108	Gocioechea	1015.3	169.6	5.34%	20.05%	1.68%	0.3424
	109	Santa Ana	1221.8	384.1	6.25%	45.85%	3.49%	0.6029
	110	Alajuelita	494.3	95.4	4.43%	23.92%	1.97%	0.4457
	111	Coronado	556.2	133.7	2.57%	31.63%	2.53%	0.4250
	113	Tibás	649.6	87.3	10.44%	15.52%	1.32%	0.2328
	114	Moravia	626.0	126.5	4.33%	25.32%	2.07%	0.4364
	115	Montes de Oca	716.5	165.8	10.64%	30.10%	2.42%	0.3137
	118	Curridabat	910.7	251.9	15.52%	38.24%	2.99%	0.4243
	201	Alajuela	4125.1	948.8	3.63%	29.87%	2.40%	0.6709
	205	Atenas	426.3	118.1	1.41%	38.31%	2.99%	0.8364
	208	Poás	287.3	65.3	0.98%	29.44%	2.37%	0.8455
	301	Cartago	1940.9	327.7	1.72%	20.31%	1.70%	0.5119
	302	Paraíso	532.7	103.0	0.61%	23.96%	1.97%	0.7450
	303	La Unión	914.5	297.5	6.68%	48.21%	3.64%	0.5999
	306	Alvarado	111.6	13.2	0.17%	13.45%	1.15%	0.8960
	307	Oreamuno	452.4	37.3	0.52%	8.97%	0.78%	0.5790
	308	El Guarco	523.7	128.4	1.53%	32.49%	2.59%	0.5061
	401	Heredia	1313.4	350.5	13.89%	36.40%	2.86%	0.4255
	402	Barva	369.3	120.8	2.15%	48.61%	3.67%	0.7165
	403	Santo Domingo	582.1	170.0	6.73%	41.25%	3.19%	0.6925
	404	Santa Bárbara	370.2	123.9	2.38%	50.33%	3.78%	0.7490
	405	San Rafael	386.1	114.2	2.37%	42.01%	3.24%	0.6032
	406	San Isidro	230.5	52.9	1.99%	29.80%	2.40%	0.7779
	407	Belén	639.7	143.6	11.51%	28.96%	2.34%	0.4224

	County		Total area (2nd period) Ha.	Growth Ha.	% of total	% of constructed area in initial period	Equivalent year-to-year rate %	*Sprawl index*
	408	Flores	270.8	83.6	12.39%	44.66%	3.41%	0.5196
	409	San Pablo	245.6	57.3	6.87%	30.45%	2.45%	0.5847
	GAM Greater Metropolitan Area		*27044.9*	*6058.4*	*3.40%*	*28.87%*	*2.33%*	*0.4783*
1997–2010	101	San José	3860.0	227.4	5.07%	6.26%	0.47%	0.1720
	102	Escazú	1448.5	216.0	6.24%	17.53%	1.25%	0.4099
	103	Desamparados	1911.0	242.2	4.06%	14.51%	1.05%	0.3789
	106	Aserrí	417.2	84.5	2.86%	25.40%	1.76%	0.5255
	107	Mora	320.9	55.0	0.87%	20.68%	1.46%	0.6402
	108	Gocioechea	1123.1	107.8	3.40%	10.62%	0.78%	0.3350
	109	Santa Ana	1458.6	236.8	3.85%	19.38%	1.37%	0.5390
	110	Alajuelita	599.9	105.6	4.91%	21.36%	1.50%	0.4264
	111	Coronado	662.9	106.7	2.05%	19.17%	1.36%	0.4968
	113	Tibás	689.6	40.0	4.78%	6.15%	0.46%	0.1912
	114	Moravia	752.9	127.0	4.35%	20.29%	1.43%	0.4319
	115	Montes de Oca	824.5	108.0	6.93%	15.07%	1.09%	0.2260
	118	Curridabat	1127.4	216.7	13.35%	23.80%	1.66%	0.3299
	201	Alajuela	5289.0	1164.0	4.45%	28.22%	1.93%	0.6238
	205	Atenas	586.3	159.9	1.91%	37.51%	2.48%	0.8065
	208	Poás	461.8	174.5	2.63%	60.75%	3.72%	0.8197
	301	Cartago	2280.1	339.2	1.78%	17.48%	1.25%	0.5747
	302	Paraíso	658.8	126.1	0.74%	23.67%	1.65%	0.8182
	303	La Unión	1242.7	328.2	7.37%	35.89%	2.39%	0.4671
	306	Alvarado	151.3	39.7	0.50%	35.56%	2.37%	0.9171
	307	Oreamuno	515.1	62.6	0.87%	13.85%	1.00%	0.7033
	308	El Guarco	634.5	110.8	1.32%	21.15%	1.49%	0.5699
	401	Heredia	1731.5	418.1	16.57%	31.84%	2.15%	0.2863
	402	Barva	538.6	169.3	3.02%	45.84%	2.95%	0.6426
	403	Santo Domingo	851.0	268.8	10.64%	46.18%	2.96%	0.5919
	404	Santa Bárbara	534.2	164.0	3.14%	44.30%	2.86%	0.7069
	405	San Rafael	547.4	161.3	3.35%	41.77%	2.72%	0.6236
	406	San Isidro	355.5	125.0	4.71%	54.24%	3.39%	0.7552
	407	Belén	715.7	76.0	6.09%	11.87%	0.87%	0.4105

	County	Total area (2nd period) *Ha.*	Growth *Ha.*	*% of total*	*% of constructed area in initial period*	Equivalent year-to-year rate *%*	***Sprawl index***
	408 Flores	407.0	136.2	20.19%	50.28%	3.18%	0.4074
	409 San Pablo	391.4	145.8	17.47%	59.36%	3.65%	0.4407
	GAM Greater Metropolitan Area	*33088.1*	*6043.1*	*3.39%*	*22.34%*	*1.56%*	*0.4768*

Source: Estimated from the analysis of Landsat images

Table A-3. Determinants of the Urban Structure of the San José Metropolitan Region, 1986–2010
Estimates with Ordinary Least Squares

Variable	Model 1		Model 2		Model 3		Model 4	
	Population Density		*Sprawl Index*		*Compactness Index*		*Contiguity Index*	
	Coeff.	**t-test**	**Coeff.**	**t-test**	**Coeff.**	**t-test**	**Coeff.**	**t-test**
Intercept	**6.9355**	(3.400)	0.3935	(0.576)	-0.3609	(0.571)	1.0545	(0.784)
Distance to San José*	**-0.3959**	(2.489)	**0.1217**	(2.990)	**-0.0776**	(2.061)	**-0.2058**	(2.568)
Distance to city*	-0.0726	(0.911)	-0.0469	(1.301)	**0.0557**	(1.670)	0.0892	(1.256)
Distance to industrial zone*	0.1359	(1.361)	**0.0643**	(1.888)	0.0032	(0.101)	-0.0859	(1.281)
Workers (normalized)	-0.0464	(0.972)	**0.0318**	(2.692)	0.0111	(1.015)	**-0.0604**	(2.598)
Estimated population	-		**-0.1187**	(4.581)	**0.0627**	(2.616)	**0.1465**	(2.870)
Income index	**-0.1265**	(3.250)	-0.0153	(1.260)	**0.0245**	(2.178)	0.0249	(1.040)
Average slope	-0.0070	(0.556)	0.0064	(1.443)	0.0039	(0.954)	-0.0077	(0.889)
Density of water wells (2 years)**	**-0.1773**	(4.296)	0.0086	(0.704)	-0.0019	(0.172)	-0.0158	(0.658)
Percentage of area within the boundaries of urban growth	-0.0495	(0.230)	**-0.1024**	(1.675)	**0.4913**	(8.682)	0.1352	(1.122)
Agricultural use, vegetables (1 = yes):	0.2303	(1.493)	-0.0438	(0.913)	0.0158	(0.357)	0.0796	(0.843)
Agricultural use, coffee (1 = yes)	0.0773	(0.977)	**0.0921**	(3.803)	**-0.0454**	(2.024)	**-0.1237**	(2.593)

Table A-4. Determinants of Urban Growth in the San José Metropolitan Region, 1986–2010 Estimates with Two-stage Ordinary Least Squares*

Variable	Model 5		Model 6		Model 7	
	New built-up area		*Equivalent year-to-year growth rate*		*Sprawl index*	
	Coef.	**t-test**	**Coef.**	**t-test**	**Coef.**	**t-test**
Intercept	-5.3985	(1.333)	-0.7966	(0.257)	**-1.0690**	(2.068)
Distance to San José**	**0.6135**	(2.453)	0.0456	(0.239)	**0.1845**	(5.778)
Distance to city**	**-0.4847**	(2.571)	**-0.4108**	(2.849)	-0.0110	(0.457)
Distance to industrial zone**	**0.4218**	(1.925)	**0.3419**	(2.040)	**0.0591**	(2.113)
Workers (normalized)	0.1306	(1.130)	-0.0308	(0.349)	**0.0441**	(2.986)
Estimated population	**0.4122**	(2.780)	**-0.3842**	(3.387)	**-0.0532**	(2.811)
Income index	**0.2456**	(2.311)	0.0642	(0.790)	0.0095	(0.702)
Average slope	**0.0747**	(2.562)	**0.0470**	(2.108)	-0.0009	(0.253)
Density of water wells (2 years)***	**0.2174**	(1.851)	-0.0605	(0.673)	-0.0050	(0.335)
Percentage of area within the boundaries of urban growth	0.4191	(0.978)	0.1734	(0.529)	**-0.1735**	(3.170)
Agricultural use, vegetables (1 = yes):	**-1.1879**	(3.510)	**-0.8910**	(3.441)	-0.0025	(0.058)
Agricultural use, coffee (1 = yes)	**0.5056**	(2.968)	**0.5574**	(4.278)	**0.0614**	(2.824)

* The variables correspond to the initial year of the growth period.

** Endogenuous variables; instrumented with distances to the center of each city according to the 2008 Atlas of the Costa Rican Institute of Technology (ITCR)

***Number of underground water operational permits on wells approved by the National Water, Irrigation and Sewer Service (SENARA) in the year of the data, and the preceding year.

Red color with grey background: Coefficients significant to 90 percent.