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Assessing spatial dynamics of urban growth using an integrated land use model. Application in Santiago Metropolitan Area, 2010–2045

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ABSTRACT

Scenario analysis of urban dynamics from spatial land use models can support urban, planning and policy. An integrated modeling approach, linking assessment of urban spatial dynamics, was applied to the Santiago Metropolitan Area (SMA). The integrated land use change model combines, a logistic regression model, Markov chain, and cellular automata. This model was calibrated with data, from 1975 to 2010, and was used to make predictions for the years 2030 and 2045, using two datasets of, urban and non-urban explanatory variables. Urban change estimates showed the highest fit during the, model calibration phase. The true-positive proportion and standard Kappa value (κ) were of 99% and, 0.87 respectively when validating against an urban cover reference map from 2010. Urban growth was, equal to +27,000 ha (72%) for the period 1975–2010, and the city of Santiago is projected to, reach approximately 93,000 ha by 2045 (+43% from 2010). In the SMA the most important, urban growth pattern is peri-urban development, referring to widespread boundaries and higher, fragmentation in peripheral municipalities. Predictions for 2030 estimate that ~15% of the projected, urban expansion will occur outside the boundary set by the current Regulatory Plan proposal. These, results demonstrate the capacity of the integrated model to establish comparisons with urban plans, and its utility to explain both the amount and constraints of urban growth. The integrated approach of, urban dynamic assessment using land use modeling is useful for spatiotemporal representation of, distinct urban development forms.

Introduction

Urban sprawl has been a large focus of land use planning due to its complex driving forces and interactions (Weber, 2003). There is a great need to understand both sprawl as well as its explanatory factors (Batisani and Yarnal, 2009). Decision makers and urban planners require precise and detailed information about potential urban growth and land conversion in order to assess new development needs, their location, characteristics, as well as consequences of prior and subsequent urban development (Jiang and Yao, 2010). The implementation of spatial land use change (LUC) modeling can contribute to a better understanding of the environmental and socioeconomic factors that promote urbanization patterns (Batisani and Yarnal, 2009).

In recent years, interest in LUC modeling has grown rapidly (Liu and Andersson, 2004); several statistical and geospatial urban models have been implemented, such as logistic regression (e.g. Cheng and Masser, 2003; Huang et al., 2009; Luo and Wei, 2009; Aguayo et al., 2007), cellular automata, and Markov Chains (e.g. Pontius and Malanson, 2005; Arsanjani et al., 2011; Henriquez et al., 2006; Azocar et al., 2007). More recently, two researchers groups have proposed the use of integrated approaches, combining these models (Poelmans and Rompaey, 2010; Arsanjani et al., 2013). Most of these urban models depend on neighborhood functions, such as cellular automata (CA, Poelmans and Rompaey, 2010). The ability of CA to simulate spatial urban growth is based on the assumption that past urban development affects future patterns through local interactions among land uses (Santé et al., 2010). Markov chain (MC) models have historically been one of the most commonly used tools for predicting changes among categorical states. MC models are used to model changes over time among categories within a landscape, whereby each pixel on the landscape is classified as one category, and each pixel has some probability of making a transition to another category at every time step (Pontius and Malanson,

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2005). Logistic regression analysis has also been a commonly used approach to predict land use modeling over the last two decades (Verhagen, 2007). This method is capable of establishing functional relationships between the potential for LUC and the drivers of that change, represented by a set of explanatory factors (Huang et al., 2009).

Recently CA, in combination with landscape metrics, has been commonly implemented in the prediction of future urban trends (Herold et al., 2003). As urban areas have changed rapidly over the last decade, analysis of urban dynamics has become increasingly common due to the fact that they can be produced rapidly and are easy to use in comparative analyses (Uuemaa et al., 2013). An application of the integrated land use model of CA, MC and logistic regression in conjunction with spatial metrics of urban dynamics can be useful to assess development needs; this still requires be researched. Thereby our objective was to employ a combined approach using the integrated land use modeling, along with spatial analysis of urban dynamics, in order to prove the utility of modeling to explain the scale and constraints of urban growth, as well as its use in predictions of future development paths, using the Metropolitan Region of Santiago as a case study.

Case study

Boundary of study area

Santiago is located in the central part of the country in the Metropolitan Region, between 33°15′ S and 33°40′ S. The Santiago Metropolitan Area (SMA) covers 37 municipalities of the Metropolitan Region, outlined in Fig. 1. Beyond the municipalities that comprise the SMA, we also included two sub-urban centers that have developed around Santiago, namely Lampa and Colina.

The SMA is situated in the Maipo river valley (350 masl); it is bound to the east by the Andes Mountains (5500 masl) and to the west by the costal foothills (1800 masl). The entire study area covers nearly 4400 km^2. This region has been identified as a semiarid ecosystem within the Mediterranean bioclimatic zone (Luebert and Pliscoff, 2006). The SMA is part of the sclerophyllous forest formation (Luebert and Pliscoff, 2006). *Urban* land use and agriculture are dominantly concentrated in the center of the valley geographically. The dominant classes of LUC in this area are urbanization and deforestation (CONAF et al., 1999).

Santiago's urban development

SMA was chosen as a case study for investigating the spatial dynamics of urbanization through land use modeling because this region has experienced rapid urbanization, which has in turn generated complex patterns that require a better understanding to make predictions about future urbanization in the region.

The process of urbanization in Santiago is comparable with other large Latin American cities. It has been characterized by a concentration of the urban population, attributed mainly to market forces (Cohen, 2004). The city of Santiago is part of the Metropolitan Region, with a population of 6.6 million people, about 40% of country's population, and an annual average growth rate of 1.01% in the period 2002–2012 (INE, 2012). The proportion of land classified as *urban* use within the region increased by around 80% from 1975 to 2009, at an estimated rate of 800 ha/year (Romero et al., 2012).

Other authors have described various urban growth patterns within the SMA; among these, peri-urban growth is the most dominant, which indicates a continued expansion of constructed area around the urban core. Peri-urban development has been particularly intense in the Northern and Southeastern sectors of the SMA (Banzhaf et al., 2013). In environmental terms, urban expansion has significantly affected the degradation of ecosystem functions and services, such as high levels of atmospheric and water contamination, mudslides and floods (Romero and Vásquez, 2005; Muller et al., 2011). The principal factors driving this type of urban development are the construction of highways and infrastructure, population growth, and in recent decades, the real estate market (Hidalgo et al., 2008; Hidalgo and Arenas, 2009).

The majority of immaterial production within Chile takes place in the SMA, such as the financial sector and corporate headquarters, giving the city an advanced functional structure (Escolano and Ortiz, 2009). The convergence of new information technologies and globalization throughout the country are responsible, in large part, for the processes shaping the Metropolitan Region (Pinto, 2002; Azocar et al., 2007). As a result, Santiago presents a second noteworthy pattern of development, related to a phase of *metropolitan expansion*. This type of expansion is related to sprawl, fragmentation of spatial growth, and the triggering of new socio-territorial processes.

Based on the knowledge of present day development within the SMA, as well as the assumption that urbanization dynamics will continue in much the same manner into the future, we propose that the existing patterns of urbanization for the SMA can be spatially represented and understood using a set of explanatory factors from an integrated model of LUC that combines CA, MC and logistic regression modeling. Subsequently, we intend to establish comparisons between built land of our simulated maps and the urban policy of the Metropolitan Region of Santiago.

Data and methods

The urban growth dynamics of the city of Santiago were estimated through the validation and simulation of a spatial model of LUC, which integrated three techniques: CA, MC and logistic regression modeling. The model was constructed using data from multiple time scales, which was obtained from remote sensors, census data, and data provided by private institutions. Calibration of the model was based on LUC data from 1975 to 2010, while simulations were conducted for the years 2030 and 2045. This next section describes the study area of the LUC model. The data and processes implemented are shown in Fig. 2.

Data bases

Reference land use maps

Land use maps were obtained from summertime Landsat imagery and using a Support Vector Machine (SVM) algorithm. We obtained land maps with balanced misclassification errors from the adjustment of predicted probabilities for each land use class following the approach described by Puertas et al. (2013), which is based on minimizing the differences between area proportions obtained with unbiased statistical reference estimates. Fig. 3 shows multi-temporal land use maps and Table 1 shows accuracy estimates calculated on a training data set, which are necessary for the calculation of the Markov transitions matrix. The four land use

Table 1
Accuracy estimates of land use classifications for reference maps with balanced misclassification errors.

Parameter	Reference land use map		
	1975 (L2-MSS)	1999 (L7-ETM+)	2010 (L7-ETM+)
Overall accuracy	80%	86%	84%
κ	0.68	0.78	0.76