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Uncertainty awareness in urban sprawl simulations: Lessons from a small US metropolitan region

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ABSTRACT

Land use change modeling and simulation is a popular tool in land use planning and policy formulation. However, the outputs of land use change simulation are not always accompanied with information on uncertainty. The goal of this paper is to demonstrate the inherent uncertainty in sprawl simulation, which is attributable to error in the input parameters and to limitations in our understanding of land use systems. To reach this goal, the paper determines sprawl simulation accuracy and uncertainty for a small US metropolitan region as produced by the CLUE-S modeling framework. The model simulates sprawl location in the region accurately, but the certainty of sprawl location projections decreases with time. This uncertainty in the simulation suggests that modelers should report uncertainty with their output over all time horizons so that, on the one hand, land use planners and decision makers do not place too much confidence in any single sprawl simulation (which could lead to unwarranted and expensive urban growth management policies) and, on the other hand, do not place too little confidence in sprawl models (which could have severe socioeconomic and environmental consequences). Thus, reporting uncertainty with simulation output provides planners and decision makers with a platform for more informed land use policy.

Introduction

Land use planning has drawn increased attention over the last decade because of the growing negative impacts of urban sprawl, such as consumption of prime agricultural land and open space (Hanink and Cromley, 2005). Although urban areas make up a small proportion of Earth's land surface area (Grubler, 1994), the loss of land to sprawl cannot be ignored, for urban sprawl causes greater environmental impacts than other land uses (Heilig, 1994; Folke et al., 1997; Lambin et al., 2001). The focus on urban sprawl in land use planning comes also from its complex driving forces and their interactions (Rusk, 1995; Gimblett et al., 2001; Ligtenberg et al., 2001; Cheng and Masser, 2003; Weber, 2003). Thus, there is great need to understand sprawl and its driving factors.

There is also a need to improve models of land use change. Veldkamp and Lambin (2001) emphasized the importance of land use change modeling as a planning tool for projecting alternative land use pathways into the future, whereas Fang et al. (2005) noted that the first step in finding solutions to ecological and human dimensions problems of urban sprawl is through dynamic land use change modeling and simulation. The importance of modeling and simulation in urban sprawl studies is further emphasized by Clarke and Gaydos (1998), Batty et al. (1999) and Wu (2002). Klostermann (1999) underscored the importance of dynamic spatial urban models in assessing future growth and creating planning scenarios. Crosetto et al. (2002) agreed and pointed out that politically and environmentally sensitive decisions on land use are increasingly based on information derived from spatial models.

However, land use and land cover change models can only be as accurate as the knowledge and data from which they are produced (Fang et al., 2002, 2006). Data error comes from many sources. Lunetta et al. (1991) concluded that remotely sensed data, which are increasingly employed in land use change modeling, contain uncertainty and error related to the sensor systems and image processing software. Errors in spatial modeling and simulation may also occur during initial tracing of boundaries (Thappa and Bossler, 1992; Youcai and Wenbao, 1997; Burrough and McDonnell, 1998). Secondary error and uncertainty can enter during subsequent data processing when changing between vector and raster formats (Congalton, 1997). Conversion quality and boundary representational accuracy depends highly on the cell size of the resulting digital raster map. Rae et al. (2007) noted that using a large cell size during geoprocessing and subsequent modeling can lead to some

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features being "lost." Morris (2003) underscored the problems inherent in querying features that exhibit partial fuzzy membership. Other processing errors occur when querying information from data layers and buffering features (Veregin, 1989; Congalton, 1997; Morris, 2003). The influence of uncertainty in spatial inputs on spatial modeling predictions is therefore a cause for concern (Hansen et al., 1999; Elith et al., 2002).

Lanter and Veregin (1992) found that while the visual output of GIS and simulation models is compelling, it does not always include information on reliability and uncertainty. This shortcoming can be critical because most land use planners are unaware of the uncertainty inherent in land use change model products (Stoms et al., 1992; Hunter et al., 1995; Heuvelink, 2002). Consequently, land-planning decisions based on misinterpreted or erroneous land use change model output can be costly due to their irreversibility (Norton and Williams, 1992). Ultimately, uncertainty and error in model output lead to inappropriately high or low confidence in the results, which can harm the land use planning decision-making process (Foody and Atkinson, 2002; Rae et al., 2007). Pontius and Spencer (2005) further argued that land use change modeling can either facilitate or hinder the decision-making process depending on how scientists present the results.

Based on this background, the objective of this paper is to evaluate uncertainty in sprawl simulation output. Specifically, the paper seeks to determine the ability of the CLUE-S model to simulate urban land use location and the temporal decay in certainty of the simulation outputs. The paper further seeks to determine the sensitivity of urban land use location simulation output to variation in input parameters and decision rules about the land use system.

Materials and methods

Study area

Centre County, Pennsylvania (Fig. 1) typifies a growing debate regarding the tradeoffs between socioeconomic growth and development and their impacts on the landscape. Although it is the fifth largest county in Pennsylvania, two thirds of its land area (2888 km^2) is protected conservation area. The county has one of the highest median housing values in Pennsylvania with a single-family housing median price of $156,000 in 2005, and rates highly as a retirement destination (Centre County, 2005).

A wide range of land uses and land covers coexist within Centre County, with forests and agricultural lands being important components of the landscape. Forests are mainly concentrated where topography is steep and land is marginal for agricultural purposes, whereas agriculture is concentrated mainly in the fertile limestone and shale soils of the valleys (Centre County, 2005). Over the years, the number and size of farms have decreased as the number of rural non-farm residents has increased, leading to a loss of 1618 ha of prime farmland between 1977 and 2005 (Goetz et al., 2004).

Therefore, the competition for land between residential and agricultural uses in the valleys and anticipated housing demand increases make Centre County a good place to study sprawl and its effect on the landscape. Land use decisions in the United States, especially in Pennsylvania, are based on jurisdiction, so it is imperative that studies on sprawl are carried out at local level where land use decisions are made.

Data

Land use/land cover data classified at Anderson level 1 (Anderson et al., 1976) from Landsat TM images of Centre County for 1993 and 2000 were used to, respectively, parameterize and validate the simulation model and were obtained from the Centre for Integrated Regional Assessment, The Pennsylvania State University. The land use maps had six-land use categories: Urban, Forest, Agriculture, Water, Rangeland and Abandoned mining sites. These classifications were performed by an experienced analyst from the United States Geological Survey, were ground truthed extensively, and are considered to be highly reliable with producer and user accuracies of 90 and 83%, respectively. The Water, Rangeland and Abandoned categories were aggregated into a single land use category called 'Others' for the purposes of this analysis. GIS layers of potential drivers of urban land use location used in the simulation were obtained from the Land Analysis Lab, The Pennsylvania State University. The soil layer was obtained from the Soil Survey Geographic (SSURGO) database of The Natural Resources Conservation Service (NRCS). The SSURGO database is at a scale of 1:24,000 resulting in 30,000 polygons for Centre County. Each polygon has three components, with the dominant component accounting for 90% of the variance in the polygon (NRCS, 2001). The 30 m resolution land use maps were aggregated to 250 m based on cubic convolution method.

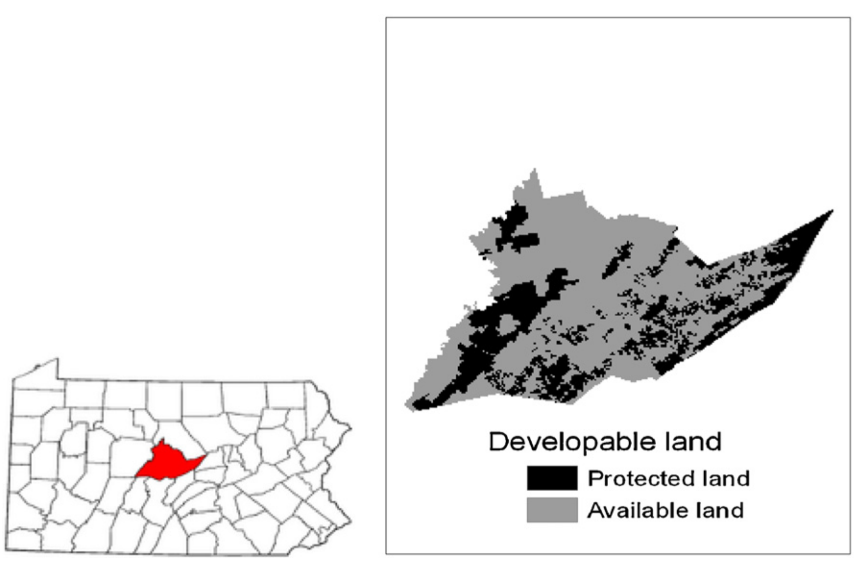

Fig. 1. The location of Centre County in Pennsylvania.