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A cellular automata model of land cover change to integrate urban growth with open space conservation

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ABSTRACT

The preservation of riparian zones and other environmentally sensitive areas has long been recognized as one of the most cost-effective methods of managing stormwater and providing a broad range of ecosystem services. In this research, a cellular automata (CA)—Markov chain model of land cover change was developed to integrate protection of environmentally sensitive areas into urban growth projections at a regional scale. The baseline scenario is a continuation of the current trends and involves only limited constraints on development. The green infrastructure (GI) conservation scenario incorporates an open space conservation network based on the functional boundaries of environmentally sensitive areas. It includes variable buffer widths for impaired streams (as identified on the USEPA 303d list for stream impairment), 100-year floodplain, wetlands, urban open space and steep slopes. Comparative analysis of each scenario with landscape metrics indicated that under the GI conservation scenario, the number of urban patches decreased while the extent of interspersion of urban land with green infrastructure patches increased leading to improved connectivity among open space features. The analysis provides a quantitative illustration of how our process contributes towards achieving urban planning objectives while incorporating green infrastructure.

1. Introduction

Landscape alterations due to urban development have a profound effect on ecosystem functions, and can regulate or modulate the benefits that humans derive from physical, biological or chemical properties and/ or processes occurring in natural systems (Costanza et al., 1997). These benefits, often termed ecosystem services, include infiltration and evapotranspiration of stormwater runoff, groundwater recharge, protection of water resources against sedimentation, reduced risk of nutrient enrichment and contamination, and preservation of landscapes that provide aesthetic and recreational value (Osborne and Kovacic, 1993; Dosskey, 2001; Randolph, 2004). A wider vegetated riparian buffer zone can lead to a longer travel time and distance for runoff, increasing the number of infiltration opportunities, and thereby promoting deposition of eroded soil material, facilitating nutrient removal while also cooling stormwater before it reaches the streambed (Osborne and Kovacic, 1993; Dosskey, 2001). Moreover, terrain characteristics such as slope, vegetative cover, infiltration rates, soil moisture storage capacity, and slope can impact the effectiveness of a riparian buffer zone for water quantity and quality objectives (Polyakov et al., 2005). However, the importance of preserving and enhancing natural areas in an urbanizing landscape has often been understood after development has removed or altered vegetated areas.

A key principle of smart growth which attempts to minimize the negative side effects of urbanization through a set of planning and policy options, is preservation of open space, prime agricultural land and environmentally sensitive areas (Smart Growth Network, 1996). *The Smart Growth Manual* specifically emphasizes the role of regional planning in prioritizing areas for development beginning with the creation of a green footprint, i.e., mapping a region's "rural reserve" and other environmentally important areas (Duany et al., 2009). The concept of *green infrastructure* describes the interdependence of land conservation and land development (Benedict and McMahon, 2006) and refers to a contiguous, interconnected green network consisting of riparian areas, floodplains, aquifer recharge zones, wetlands, and forested areas. To incorporate green infrastructure into land management states of Florida, Georgia and Maryland have adopted programs aimed at enhancing connectivity of protected natural areas as part of a state-scale initiative to establish and maintain green infrastructure networks (Randolph, 2004;

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Benedict and McMahon, 2006). The *Trust for Public Land* works in collaboration with local governments to implement a Greenprinting program which envisions a symbiosis of future growth and conservation principles. A major component of the program is acquiring conservation lands on which communities depend for drinking water supply, stormwater management, recreation, and agricultural production (TPL, 2005).

There are planning opportunities to preserve, integrate, and otherwise connect green infrastructure as a part of a comprehensive regional conservation plan for landscapes anticipating development pressure. A model for expediting this type of analysis and forecasting involves the use of cellular automata, which are well-suited to represent geographic processes due to the similarities between a two-dimensional lattice and a raster grid (Longley and Batty, 1996; Clarke and Gaydos, 1998; Torrens, 2003; Batty and Xie, 2005). Torrens (2003) suggests that cellular automata can be useful in simulating urban systems because land use, concentrations of employment location and population change can all be modeled as automata; cells can effectively aggregate economic, demographic and transportation data; neighborhoods as part of the cityscape can be successfully simulated by equivalent neighborhoods of cells on the cellular lattice; and even urban theories based on spatial interaction models can be tested and represented.

Claggett et al. (2004) applied the results from SLEUTH (Clarke et al., 1997) to the assessment of future development pressure on forested and agricultural lands for the purposes of vulnerability assessment of productive lands at a regional scale. Syphard et al. (2005) used Clarke's Urban Growth Model (UGM) to estimate possible impact of urbanization around Santa Monica Mountain National Recreation Area through metrics such as total core habitat area, mean core patch area and number of patches, and concluded that important migration corridors will be affected if development of urban clusters does not take into consideration the spatial requirements of wildlife habitat (Syphard et al., 2005). Eppink et al. (2004) coupled a dynamic model of population growth and projected that draining wetlands can result in significant biodiversity loss and a cutback on such activities may counter to a certain extent the impact of rapid and sustained urbanization.

In this research, we develop a cellular automata model of urban growth to incorporate environmentally sensitive areas into a regional planning analysis of urban development. We established transition rules for a Markov-chain based CA model with multi-criteria evaluation (MCE), then apply this model to the task of better retaining green infrastructure in an urban build-out plan. Two scenarios are examined and compared. The baseline scenario projects urban growth without environmental constraints while the GI conservation scenario incorporates an open-space conservation network intended to incorporate environmentally significant areas. The GI conservation scenario includes establishment of variable buffer widths on impaired streams as identified on the USEPA 303d list for stream impairment, protection of floodplains, and preservation of wetlands, steep slopes, and urban open space. We then quantitatively compare landscape configuration under the two different scenarios with structural metrics at the landscape level and discuss how this approach may guide not only retention of preserved land, but also increase the provision and quality of the ecosystem services offered by this land mass. In this research, we made an effort to simulate the changes of several land cover classes simultaneously.

2. Materials and methods

2.1. Study area

The study area included twenty-seven counties in Ohio, Indiana, and Kentucky (Fig. 1). Fifteen of these are part of the Cincinnati-Middletown metropolitan statistical area. Twelve adjacent counties lie on the fringe of the MSA and were incorporated in order to account for the *edge effect* (Zheng and Chen, 2000), which defines dynamics at the boundary where spatial characteristics of the landscape structure change.

The geography of urban development in the Cincinnati-OH-KY-IN Metropolitan Statistical Area (MSA) at the end of the last century was markedly characterized by two prevailing features: rapid expansion of low-density greenfield development and decline of the urban core and older suburbs. As Fig. 2 indicates, between 1990 and 2000 the population and employment densities in the majority of census tracts in and around the City of Cincinnati have declined. Some urban core tracts have lost as many as 14,465 persons/sq km while the urban fringe continued to expand outwards. A recent study on measuring sprawl found that the Cincinnati-OH-KY-IN MSA ranked 23rd most sprawling among 83 metropolitan regions in the United States in terms of residential density, 25th in terms of accessibility to road networks, and 32nd most sprawling in terms of job, housing and services mix (Ewing et al., 2003).

The northern part of the region is characterized by agricultural land of high productivity, and this is also where development has been concentrated over the past decades as large proportion of the productive land had been converted to urban uses. Not surprisingly, most of the streams in this area tend to appear on the USEPA 303d listing of impaired streams. Given that the southern and western parts of the study region are particularly vulnerable to development – due to erosion risk, poor drainage, and seasonally shallow water tables – we focused on these areas as they might potentially profit from planning efforts informed by the results of our methods.

2.2. Data and data processing

Land-cover land-use (LULC) data were obtained from the Multi-Resolution Land Characteristics Consortium (Vogelmann et al., 2001; Homer et al., 2007) which provided 1992 and 2001 National Land Cover Dataset (NLCD) in ArcGIS grid format. The classifications schemes of the two datasets were regrouped to reduce the number of classes and prepare the data for the simulation. Five classes were derived from the initial 1992 and 2001 NLCD datasets: *water*, *woodland/open space*, *cropland/agricultural*, *wetlands*, and *urban/built-up land*. For brevity, these five categories are further referred to as *water*, *woodland*, *cropland*, *wetland* and *urban land*. The *water* layer was based on the open water features included in the 1992 and 2001 NLCD datasets and the perennial streams network provided by the USGS National Hydrography Dataset (NHD) (USGS, 2004). The surface waters on the USEPA 303d list of impaired streams obtained through the BASINS data download tool (USEPA, 2004) were included as part of the GI conservation scenario. *Woodland* included deciduous, evergreen and mixed forests as identified by the 1992 and 2001 NLCD datasets. For the purposes of simulating the open space GI conservation scenario, this layer was combined with the *open space* data layer, provided by the Cincinnati Area Geographic Information Systems (CAGIS) as the latter included conservation easements, state parks, wildlife areas, forests, scenic parks, camp areas, bike trails, nature centers, conservancy districts, preserves, and other designated urban green space. *Cropland* and *wetlands* were derived from the 1992 and 2001 NLCD datasets to include cultivated crops and pastures, and woody and herbaceous wetlands, respectively. Finally, *urban* land was derived from commercial/industrial/transportation and low and high density residential categories as identified by the 1992 NLCD dataset, and low, medium and high intensity developed land as identified by the 2001 NLCD dataset.

The road network for the study area was obtained from the USGS Seamless Server—National Atlas Roads database (USGS, 1999), which included major roads and ferry crossings (USGS, 1999). Population and employment data for the year 2000 and boundary files