Performance assessment of a new Vector-based Geographic Cellular Automata Model

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1. Introduction

Cellular automata (CA) are increasingly used to simulate a wide range of environmental phenomena. In these applications, geographic space is typically represented as a grid of regular cells. Scientists have recently demonstrated that these raster-based CA models are sensitive to cell size and neighbourhood configuration (Jantz and Goetz, 2005; Ménard and Marceau, 2005). A solution to this problem is to propose an alternative object-based CA model where space is defined as a collection of irregular objects that correspond to real entities composing the study area. Some authors have begun to implement irregular space in CA models using Voronoi polygons (Shi and Pang 2000) and the GIS vector format (Stevens et al. 2007). However, these models do not allow polygon's change of shape. Polygons are predefined; they can change state but not shape.

To overcome this limitation, a new vector-based geographic cellular automata (VecGCA) model has been proposed by Moreno et al. (2007) in which space is represented as a collection of geographic objects corresponding to meaningful entities of irregular shape and size. Each geographic object is represented by a polygon and changes state and shape due to the influence of its neighbours. Their results showed that VecGCA produces more realistic spatial patterns than the ones created by a raster-based CA. The definition of space as a collection of geographic objects with proper behaviour overcomes the sensitivity to cell size. However, the VecGCA sensitivity to neighbourhood configuration has not been evaluated. This is an important aspect since the neighbourhood size is a key component of the model.

The objectives of this paper are: (1) describe the VecGCA model and assess its performance to simulate land-use changes in two study areas of different spatial complexity, and (2) determine the impact of the neighbourhood size on the simulation outcomes.

2. Study areas

The first study area is the Maskoutains region, an agricultural region covering 1312 km^2, located in Southern Quebec, Canada. The landscape is characterized by small forest patches within a large agriculture matrix. The second study area is the Elbow river watershed, located in Southwest Alberta, Canada, which covers 1238 km^2. This landscape is more fragmented and composed of numerous polygons of smaller extent.

Two land-use maps generated from Landsat Thematic Mapper images at 30 m resolution were available for each region.

3. The land-use VecGCA model

In VecGCA, space is represented as a collection of patches of different land uses, where each patch corresponds to a polygon of the vector land-use map of the study area. The neighbourhood is defined as an external buffer of 10 m, 30 m, 60 m and 120 m. The influence function is given in Equation 1.

$$g_{ab} = 1 - e^{-p_{X_b(t) \rightarrow X_a(t+1)} * A(t)_a / d_{ab}} \quad (1)$$

where

g_{ab} is the influence of the neighbor a on the object b,

$A(t)_a$ is the area of the neighbor a within the neighborhood of the object b at time t,

$p_{X_b(t) \rightarrow X_a(t)}$ is the probability of transition from X_b to X_a,

$X_a(t)$ is the state of the neighbor a at time t, and

d_{ab} is the distance between the centroid of the neighbor a and the centroid of the object b.

The transition function that determines the area of change of each geographic object is provided by Equation 2.

$$f_1 = f_2 = \cdots = f_n = \begin{cases} A(t)_a * g_{ab} & \text{if } g_{ab} \geq \lambda_{ab} \\ 0 & \text{other case} \end{cases} \quad (2)$$

where λ_{ab} is a threshold value representing the resistance of the geographic object b to change its state for the state of its neighbour a.

The change of state in a portion of a polygon is performed in the procedure of geometrical transformation. This procedure consists in creating a buffer around each neighbour which intersection area with the geographic object is the area calculated by the transition function. Then, this intersection area is removed from the geographic object and added to the corresponding neighbour.

4. The raster-based CA models

A raster-based CA model was implemented in each study area. Probabilistic rules were calculated from the comparison between the land-use maps (1999 and 2002 for the Maskoutains region, and 1996 and 2001 for the Elbow river watershed). The spatial resolution for each model was 100 m for the Maskoutains region (based on a sensitivity analysis) and 30 m for the Elbow river watershed (original resolution of the data). The Moore neighbourhood and a temporal resolution of one year were chosen. The transition probabilities for one year were calculated using an exponential method (Yeh and Li, 2006).

5. Results

The results for the Maskoutains region reveal that for both models the proportions of land uses are similar to the proportions observed in the 2002 land-use map. The raster-based CA produced good results because a sensitivity analysis was conducted to determine the resolution that best represents the dynamics of the study area, whereas the results of VecGCA were obtained from the original land-use map. An overlay analysis shows that the land-use patterns generated by VecGCA for 2002 coincide in 99% with the 2002 land-use map, whereas the distribution produced by the raster-based CA coincide in 90% although an appropriate cell size has been used (Table 1). In addition, the landscape generated by VecGCA is characterized by large patches of well-defined boundaries, in comparison with diffuse boundaries produced by the raster-based CA (Figure 1).

Table 1. Proportion of simulated area that coincides with the state of the system in 2002 for each land use in the Maskoutains region

Land use	Proportion of simulated area (%)	
	VecGCA	Raster-based CA
Forest	100.00	77.47
Agriculture	99.00	93.04
Other	98.54	97.86

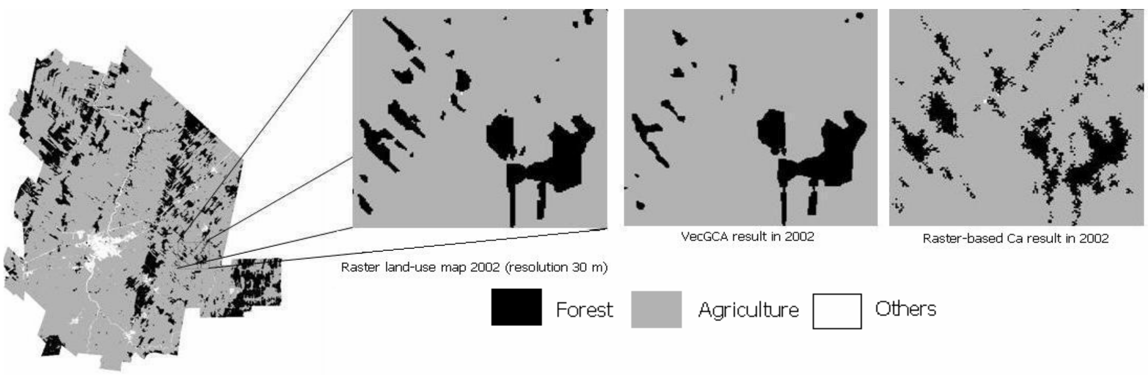

Figure 1. Detail on the polygons' boundaries produced by the VecGCA model and the raster-based CA model in the Maskoutains region.

In the Elbow river watershed, the results obtained with VecGCA reveal a land-use distribution similar to the one observed in the 2001 land-use map. An overlay between the land-use maps generated by VecGCA and the raster-based CA with the 2001 land-use map shows that 93% of the patterns obtained with VecGCA coincide with those in the study area, whereas the results obtained with the raster-based CA differ up to 70% (Table 2). In this case, no previous sensitivity analysis has been done to determine the best cell size to be used in the raster-based CA, while VecGCA is cell size independent and uses the patches present in the land-use map as initial conditions.

Table 2. Proportion of simulated area that coincides with the state of the system in 2001 for each land use in the Elbow river watershed

Land use	Proportion of simulated area (%)	
	VecGCA	Raster-based CA
Forest	93.79	88.96
Agriculture	98.67	85.67
Vegetation	83.13	21.19
Park/golf	100.00	60.93
Urban	80.80	54.45
Forest in Tsu Tina Reserve	92.69	87.33
Developed land in Tsu Tina Reserve	96.45	73.90
Undeveloped land in Tsu Tina Reserve	100.00	60.42

When varying the neighbourhood size in VecGCA, the results for the Maskoutains region reveal that for the neighbourhood sizes of 10 m and 30 m, the simulated proportion of forested and agricultural land for 2002 differs in less than 2% of the proportion calculated from the 2002 land-use map; for the neighbourhood of 60 m and 120 m, the difference might exceed 8%. However, for the Elbow river watershed the variation of the neighbourhood size does not produce significant variation in the simulation outcomes. These results are explained by the fact that the influence and the transition functions (Equations 1 and 2) are proportional to the neighbours' area within the neighbourhood and this area varies with the neighbourhood size and the landscape configuration (Figure 2).

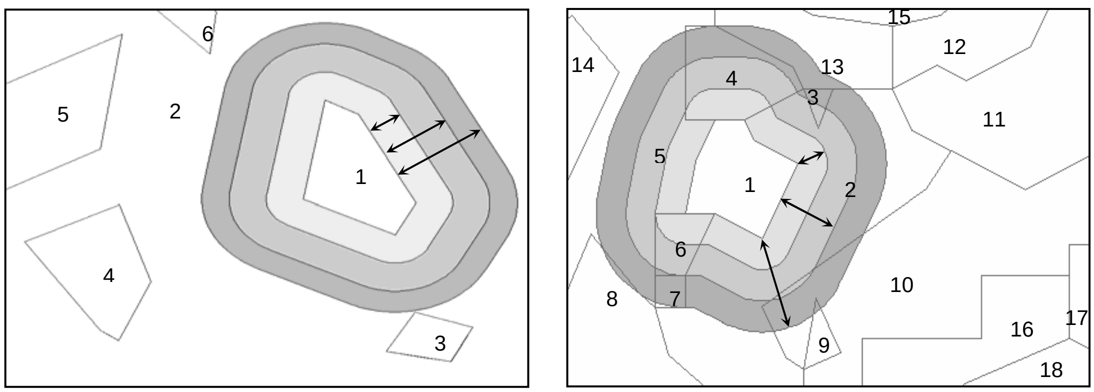

Figure 2. (a) Schematic representation of the landscape configuration of the Maskoutains region where the objects have only one neighbour for different neighbourhood sizes; when the neighborhood increases, the influence of this neighbour increases (b) Schematic representation of the Elbow river landscape configuration where the objects have several neighbours; when the neighbourhood size increases the number of neighbours and the neighbours' area within the neighbourhood also increase

6. Conclusion

VecGCA is a new modelling approach that overcomes the cell size sensitivity of the raster-based CA and the limitations of other proposed vector-based CA models by allowing the representation of space as a collection of irregular geographic objects that change state and shape. It generates more realistic spatial patterns (similar to the land-use maps used as reference data) than the ones produced by a raster-based CA.

VecGCA remains sensitive to the neighbourhood configuration and this sensitivity depends on the landscape configuration of the study area. Two possible solutions are envisioned to address this problem. The first one is the definition of independent influence and transition functions of the neighbours' area within the neighbourhood. The second is the use of a neighbourhood size adapted to each geographic object or class. Research is currently undergone to implement these solutions.

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