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A vector-based geographical cellular automata model to mitigate scale sensitivity and to allow objects' geometric transformation

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by

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February, 2008

UNIVERSITY OF CALGARY

A vector-based geographical cellular automata model to mitigate scale sensitivity and to allow objects' geometric transformation

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Abstract

Raster-based cellular automata (CA) models have been increasingly used over the last decades to simulate a wide range of spatial phenomena, but recent studies have illustrated that they are scale sensitive, that is their results vary with the cell size and neighbourhood configuration. Two solutions have been proposed to mitigate this problem: a sensitivity analysis to determine the most appropriate cell size and neighbourhood configuration that capture the dynamics of the study area, and the implementation of an object or vector-based cellular automata model independent of the cell size and the neighbourhood configuration. Several researchers have begun to implement vector-based CA models that define space based on the GIS (Geographic Information Systems) vector model, but these models have several limitations. First, the polygons and the neighbouring relationships are mainly based on Voronoi boundaries which are automatically defined in the model. The polygons do not necessarily correspond to meaningful entities and spatial relationships; characteristics such as attractivity, connectivity or accessibility are not taken into account. Second, their sensitivity to the neighbourhood configuration has not been tested; the number and distribution of the neighbours determine the change of state of an object, therefore their selection could affect the simulation outcomes. Finally, these models do not allow the change of shape of the objects, which represent an essential component of their spatial evolution through time.

In this research, a new vector-based cellular automata (VecGCA) model is proposed to overcome the cell size and neighbourhood configuration sensitivity of the classical raster-based CA models and the limitations of the previous implementations of vector-based CA models. In the VecGCA model, space is represented as a collection of geographic objects where each object corresponds to a real-world entity of irregular shape and size (e.g. a forest, a city, a lake). Each geographic object has its own geometric representation (polygon) which evolves through time according to a transition function that depends on the influence of its neighbours. This evolution is expressed by the change of shape and size of the objects and it is performed using a geometric transformation procedure. This procedure reduces the area of an object in the region nearest to the neighbour that exerts an influence on it and increases the area of that neighbour.

Two neighbourhood definitions were tested: a buffer of influence and a dynamic neighbourhood. In the first case, the neighbourhood is considered as the region of influence on each geographic object, where the neighbours are all geographic objects located within the region of influence; the transition function determines the area of an object that must change state for the state of its neighbours. In the dynamic neighbourhood, the neighbourhood is the whole geographic space and the neighbours are defined based on the properties of each geographic object; two objects are neighbours if they are separated by 0, 1 or more objects whose states favour the state transition between them. The transition function defines the distance, from the closest point to the neighbour to a point in its interior, where the influence of that neighbour is equal to a threshold value, which represents the resistance of an object to change state.

The model was used to simulate land-use/land-cover changes in two regions of different landscape complexity, in southern Quebec and southern Alberta, Canada. The results obtained show that VecGCA represents well the dynamics in the study areas through an adequate evolution of the geometry of the geographic objects which are independent of the cell size. The geometric transformation procedure introduced in VecGCA executes the change of shape of a geographic object by changing its state in a portion of its surface, allowing a more realistic representation of the evolution of the landscape. Additional results reveal that when using the first neighbourhood definition, VecGCA is sensitive to the neighbourhood size and that this sensitivity varies with the landscape configuration. When applying a dynamic neighbourhood, the land-use patterns generated by the model are very similar to the reference maps in each study area. With the implementation of a dynamic neighbourhood, VecGCA becomes independent of spatial scale, including both cell size and neighbourhood configuration.

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Dedication

To

Jose Gregorio and Isabella

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List of abbreviations and symbols

CA	Cellular automata
GCA	Geographical cellular automata
VecGCA	Vector-based geographical cellular automata
GIS	Geographic information systems
MAS	Multi-agent system
f_a	Transition function of object *a*
g_{ab}	Influence of the object *a* on the object *b*
λ_{ab}	Threshold value to change from the *b*'s state to *a*'s state
A_a	Area of the object *a*
$P_{b \rightarrow a}$	Probability to change from *b*'s state to *a*'s state
d_{ab}	Distance between the centroid of the object *a* and the centroid of the object *b*
$dmin_{ab}$	Minimum distance between the object *a* and the object *b*

CHAPTER 1

INTRODUCTION

Cellular Automata (CA) are dynamic systems defined by a large tessellation of finite-state cells whose states are updated at discrete time steps according to deterministic or probabilistic rules, which dictate how the state of each cell might change based on the state of its neighbouring cells. They were introduced by Ulam and Von Neumann in the 1940's to investigate self-reproductive systems (Von Neumann 1966). Formally, a CA is defined by five basic elements: *space*, *set of states*, *neighbourhood*, *transition rules* and *time*. In the classic definition of CA, *space* is defined as an infinite and regular tessellation of cells of discrete states. Each cell can take one state from a *set of states* that defines the outcomes of the system. The state of any cell depends on the states and configurations of other cells in the *neighbourhood* of that cell, where the *neighbourhood* is the adjacent set of cells to that cell. *Transitions rules* (also known as *transition functions*) drive the change of state in each cell; they are usually specified as a table of rules that define the next state of a cell for each possible configuration of neighbourhood. Finally, *time* represents the minimum necessary time interval for a cell to change state.

The best-known example of a CA model is the Conway's "Game of Life" (Gardner 1970) (Figure 1.1). It is a two-dimensional CA with a Moore neighbourhood composed of the eight adjacent cells. Any cell can be "alive" or "dead", and two transition rules are used to determine if a cell is alive or dead: (1) a cell that is not alive becomes alive if there are exactly three alive cells in its neighbourhood; and (2) a cell remains alive if there are two or three alive cells in its neighbourhood, otherwise it dies. The popularity of this model is due to its simplicity; it can reproduce complex global behavior based only on two allowed states and two very simple transition rules. It is a good example of emergence and self-organization. Emergence, because the repeated application of the very simple rules produce interesting spatial patterns not defined in the transition rules. Self-organization, because they produce unique spatial patterns depending on the initial configuration, including static patterns that do not change from one iteration to the next, repeating patterns that return to their original state, and patterns that move in space, that is, patterns that reappear after a certain number of iterations in a different position.

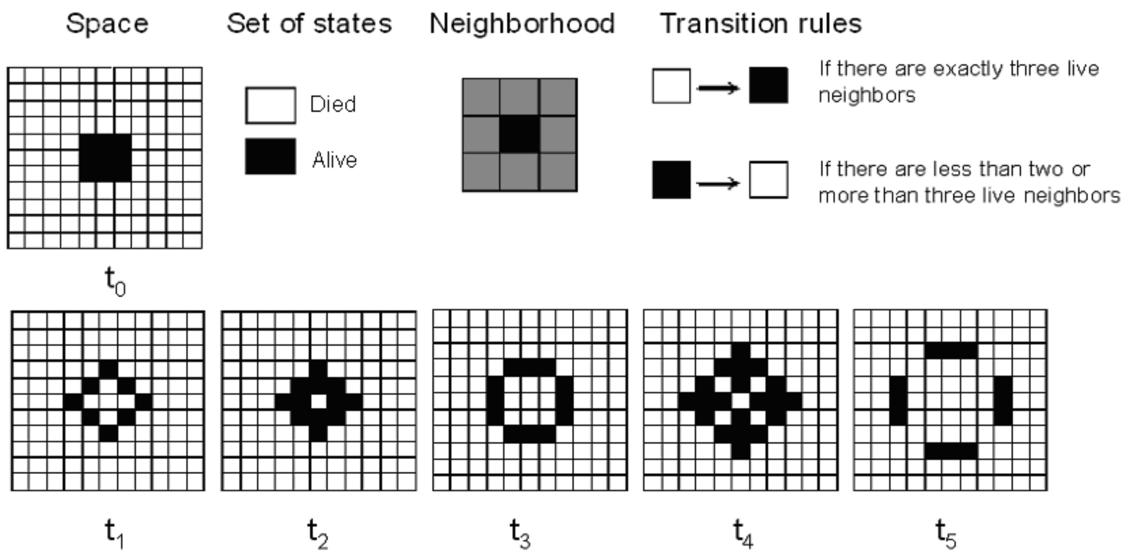


Figure 1.1. Illustration of Conway's "Game of Life"

In 1984, Stephen Wolfram presented the CA model as a modelling paradigm for complex systems due to its capacity to generate complex patterns from simple local iterations. He studied the complex behaviour produced by a very simple class of CA (one-dimensional, two-states CA) capable of universal computation (Turing machine) and suggested that the complexity in nature could be generated by the same principle, that is the cooperation of many simple identical components. In his book "*A New Kind of Science*" (Wolfram 2002), he argues that simple programs, such as CA, are able to capture the essence of almost any complex system.

Theoretical applications of CA, such as the Game of Life or the CA model presented by Wolfram (1984) that reproduces the Turing machine, generally consist in taking a given rule and discovering its properties, referred to as the forward problem (Gutowitz 1990). This approach is generally applied in formal language theory, computation theory, physics and mathematics. In social and natural sciences, most applications follow an inverse approach, which consists in discovering the rules that produce the observed patterns in the studied phenomenon, and frequently in using these rules to forecast its future behavior.

Due to their computational simplicity and their explicit representation of space and time, CA models constitute a powerful tool to model complex natural and human systems. However, the classical definition of CA assumes certain characteristics that make their application difficult for simulating real-world phenomena:

1. the transition rules are uniformly applied to all cells at fixed time intervals;
2. the same neighbourhood is defined for all cells, and
3. every change in state must be local, that is the transition rules define the change of state of a single cell based on its neighbourhood configuration.

To overcome these limitations, several CA extensions have been proposed. In a pioneer work, Couclelis (1985) presented a model allowing the separation of the neighbourhood set and the transition rules for each cell. Takeyama and Couclelis (1997) developed a mathematical framework, called Geo-Algebra, which expresses the modelling paradigm of CA in the form of map equations. In addition, Geo-Algebra generalizes the structure of standard CA to accept arbitrary, spatially variant neighbourhoods and transition rules. Other studies conducted by White et al. (1997) and O'Sullivan (2001a) extend the definition of neighbourhood as the set of all cells (adjacent or not) that influence the state of a particular cell, defined as a radius of influence and as a graph of influence, respectively. Additionally, White et al. (1997) introduced the use of constrained CA where a CA model is linked to an external sub-model that defines the number of cells that change state at each time step.

Others authors have contributed to improve different aspects related to CA modelling, including model calibration and validation (Li and Yeh 2000; Li and Yeh 2002; Wu 2002; Liu and Phinn 2003; Li and Yeh 2004; Straatman et al. 2004; Dietzel and Clarke 2007; Hasbani and Marceau 2007), neighbourhood definition, and the analysis of neighbourhood relationships (O'Sullivan 2001a,b; Verburg et al. 2004).

Thanks to all these advances, in the last few years, numerous studies involving the application of CA in a geographic context have been undertaken. Geographic cellular automata (GCA) have been used to simulate land-use and land-cover changes (Li and

Yeh 2002; Wu 2002; Almeida et al. 2003; Ménard and Marceau 2007), fire propagation (Berjak and Hearne 2002; Favier et al. 2004; Yassemi et al. 2007), vegetal succession (Soares-Filho et al. 2002; Rietkerk et al. 2004), and urban growth and development (White 1998; Li and Yeh 2000; Liu and Phinn 2003; Dietzel and Clarke 2005; Lau and Kam 2005).

All these applications have been done using a discrete space representation and a regular tessellation of cells of same size and shape similar to the Geographic Information System (GIS) raster model. However, recent studies have demonstrated that such raster-based CA models are sensitive to spatial scale, that is the simulation outcomes might vary with the cell size and the neighbourhood configuration.

1.1 Scale sensitivity of the raster-based CA models

Many factors must be considered when elaborating a CA model; the spatial scale is certainly amongst the most important. Scale generally represents the window of perception through which reality is observed (Marceau 1999). In a GCA, spatial scale is defined by three components: the spatial extent, the cell size and the neighbourhood configuration. The spatial extent corresponds to the geographic area to be modelled. The cell size specifies the area covered by each cell. The neighbourhood configuration determines the distribution and number of neighbours that have an influence in the change of state of a cell. Selecting the appropriate value for these components is a key step in the definition of a GCA. If this selection is wrong, the model cannot adequately capture the dynamics of the study area. The problem is that the selection of cell size and neighbourhood configuration is generally arbitrary; they are usually determined by a mixture of data availability, intuition, computing and resource considerations, trial and error, and information about spatial unit size or influence. There are no standard methods to determine the appropriate cell size that represents key entities of a study area, or to identify the best neighbourhood configuration that drives the change of state of a cell.

Several researchers have studied the effect of the cell size and neighbourhood configuration in the simulation outcomes of raster-based CA models. Jenerette and Wu (2001) developed a Markov-cellular automata model to simulate land-use changes in the central Arizona – Phoenix region, USA, and performed simulation using two spatial resolutions of 250 m and 75 m. Their results revealed that the resolution affects the ability of the model to simulate land-use changes, the coarser resolution generating more realistic spatial patterns than the finer resolution.

Chen and Mynett (2003) investigated the impact of cell size and neighbourhood configuration in a raster-based CA prey-predator model (EcoCA). They tested four different scenarios (two cell sizes and two neighbourhood configurations) and observed that the cell size affects the spatial patterns generated by the model, while the neighbourhood configuration influences both the spatial patterns and the system stability. A smaller cell size produces more segmented spatial patterns although the general statistics (mean and standard deviation of population density) do not show significant differences. They propose to use the spatial scale of relevance in the ecosystem under study as cell size and the standard Moore neighbourhood in order to achieve a consistent model behavior independent of the cell size. Spatial auto-correlation and Wavelet analysis are proposed as methods to find the relevant spatial scale in the studied ecosystem.

Jantz and Goetz (2005) presented the results of a sensitivity analysis of a cellular urban land-use change model, SLEUTH, by testing its performance when the cell size is changed. SLEUTH is a CA-based urban growth model coupled with a land-cover change model that simulates the urban dynamics using four growth rules: spontaneous new growth, new spreading centre growth, edge growth and road-influence growth. Four cell sizes were tested (45 m, 90 m, 180 m, and 360 m) and four separate calibration procedures were performed, one for each cell size. Their results showed that SLEUTH was able to capture the rate of growth across all cell sizes, but its ability to replicate urban growth patterns varies with the cell size. They suggest performing a sensitivity analysis to assess the impact of the cell size on the simulation outcomes and to identify the cell size with which the model can better capture the dynamics of the study area.

In a study undertaken to assess the spatial scale sensitivity in a land-use change CA model, Ménard and Marceau (2005) tested five different cell sizes (30 m, 100 m, 200 m, 500 m and 1000 m) and six neighbourhood configurations (Moore, Von Neumann and three circulars, of approximately two-cell, three-cell and five-cell radius), which create thirty different scenarios. Their results demonstrated that the choice of cell size and neighbourhood configuration has a considerable impact on the simulation results in terms of land-cover area and spatial patterns. They also revealed that using the finest resolution available is not always the best selection. In that model, 30 m resolution generates a highly fragmented landscape that does not correspond to a realistic dynamics in the study area. The authors propose to systematically conduct a sensitivity analysis to identify the appropriate cell size and neighbourhood configuration and advocate the development of an object-based CA model to mitigate scale sensitivity.

Kocabas and Dragicevic (2006) explored the impact of changing the cell size and neighbourhood configuration on the outcomes of a raster-based CA urban growth model. Two neighbourhood types (rectangular and circular) and 54 neighbourhood sizes were used. Four spatial resolutions were also tested (50 m, 100 m, 150 m and 250 m) for a total of 432 scenarios being evaluated. A visual inspection of the simulation outcomes showed that different neighbourhood types generate different spatial patterns for the same neighbourhood size. Also, decreasing the spatial resolution produces different spatial patterns in the simulation results for the same neighbourhood size. Changing the spatial resolution did not produce significant changes in the Kappa index, but changes were significant when neighbourhood size and type vary. Finally, the analysis of spatial metrics showed that both neighbourhood sizes and types have a strong influence on the simulation outcomes and that the spatial resolution affects the spatial patterns generated by the model. The authors proposed to conduct a sensitivity analysis approach combining qualitative and quantitative measures to improve the accuracy, precision and relevance of the simulation outcomes of a CA model.

1.2 Solutions proposed to overcome the scale sensitivity in the raster-based CA models

Most of the researchers who have investigated the spatial sensitivity in raster-based CA models advocate the application of a sensitivity analysis to determine the appropriate cell size and neighbourhood configuration that adequately capture the dynamics of the system under study (Jenerette and Wu 2001; Jantz and Goetz 2005; Ménard and Marceau 2005; Kocabas and Dragicevic 2006; Samat 2006). However, this procedure has limitations. First, the sensitivity analysis is performed on a sub-set of the possible combinations of cell size and neighbourhood configurations. Testing all possible combinations is practically impossible and the choice of such combinations remains arbitrary. Second, sensitivity analysis can guide the choice of cell size and neighbourhood configuration in a particular application, but does not solve the problem of scale sensitivity. Each new application will require a sensitivity analysis, which is time consuming and still imprecise.

Another solution, advocated by Ménard and Marceau (2005), is the development of alternative CA models, such as vector- or object-based models where space is defined as a collection of irregular entities that correspond to real entities composing the study area which evolve through time. The evolution of an object is then driven by the behaviour of the represented real entity, which is independent of scale. For example, an object representing a city expands when its population increases and this behaviour is the same at any spatial scale.

Some researchers have begun to implement irregular space in CA models through the use of Voronoi polygons (Flache and Hegselmann 2001; Shi and Pang 2000). In these models, space is represented by a Voronoi spatial model generated from a collection of spatial objects (i.e. point, line or area); the neighbourhood relationships are defined with the Voronoi boundaries, that is two spatial objects are neighbours if they share a common

Voronoi boundary. These Voronoi-based CA models allow the representation of irregular space and different neighbourhood configuration (number and distribution of neighbours) for each spatial object. However, this approach also has some limitations. A Voronoi polygon represents a region grouping the set of points closest to a spatial object, but it does not necessarily correspond to a real-world entity. In addition, the neighbourhood relationships are automatically generated by the model and cannot be explicitly defined by the user.

In other studies, the GIS vector format is used to define space, where each polygon represents a real-world entity. Two models have been presented using this approach: the vector CA of Hu and Li (2004) and the *iCity* model proposed by Stevens et al. (2007). The vector CA model is an extended CA model based on geographic objects, where a geographic object is the conceptual representation of a real entity such as a city, a farm, a land parcel, or a school. Each geographic object has a spatial representation under the Cartesian coordinate system (a point, a line, a polyline or a polygon). Neighbourhood relationships among geographic objects are defined using Voronoi diagrams. The transition rules determine the next state of a geographic object, based on the state and area of its neighbours, the distance between a geographic object and its neighbours, and the length of their common border.

The *iCity* model extends the traditional formalization of CA to include an irregular spatial structure, asynchronous urban growth (different development time for each land use), and a high spatio-temporal resolution to aid in spatial decision making for urban planning. Space is defined as a collection of irregular cadastral land parcels and the neighbourhood considers both Voronoi boundaries and connectivity among objects. Each parcel has an attribute representing its level of development from fully undeveloped to fully developed land. The appearance of new parcels is based on a set of predefined parcels that change state from undeveloped to develop.

These two models present two disadvantages. The first one is the lack of an explicit definition of the neighbourhood relationships. They are mainly determined by the Voronoi boundaries, which are automatically generated from the vector map that represents space. The second disadvantage is that the models do not implement the change of shape of objects that continuously occur in the real world and that should be taken into account. For example, urbanization involves the expansion of urban areas at the expense of non-developed areas, which produces geometrical transformations in the urban and non-urban patches that define that geographic area. Similar transformations characterize deforestation or any other land-use/land-cover change processes.

To overcome the neighbourhood configuration sensitivity in CA models, various approaches have been proposed. In the raster-based CA models, an enlarged circular neighbourhood was introduced by White (1993) that incorporates a weighting function depending on distance. The circular neighbourhood treats all directions equally, so it eliminates the sources of differences in the distance between the neighbourhood and the central cell. However, the radius of the circle still affects the modelling results. Verburg et al. (2004) proposed a method to analyse the neighbourhood interactions based on an empirical analysis of changes in land-use patterns. This method calculates a measure of the over- or under-representation of different land-use types in the neighbourhood of a specific location. This measure, called the enrichment factor, is defined by the occurrence of a land-use type in the neighbourhood of a location relative to the occurrence of this land-use type in the whole study area. The method was applied in the Netherlands and the results shown that neighbourhood interactions among land-use types differ in different parts of the study area. The authors suggested parameterizing CA models using derived neighbourhood characteristics. Stewart-Cox et al. (2005) used two kinds of neighbourhood in their raster-based CA model, global and local, for simulating pollination and seed setting process. They achieved more realistic results when compared to using one uniform neighbourhood. However, the configuration of the local neighbourhood still influences the modelling results.

In vector-based CA models, no research has been done to test the sensitivity to the neighbourhood configuration. Moreover, as previously mentioned, the neighbourhood in these models is principally defined using Voronoi boundaries, which cannot represent specific neighbourhood relationship among objects such as connectivity, accessibility or attractivity, because they are automatically generated from the vector map that represents space.

1.3 Problem statement and research objectives

The following problem statement can be derived from the previous discussion about CA models, their applications and limitations: *raster-based CA models are sensitive to the cell size and the neighbourhood configuration, and the solutions proposed so far are still incomplete*. While a sensitivity analysis might guide the selection of cell size and neighbourhood configuration, it does not remove the problem of scale sensitivity. In addition, the vector-based CA models recently proposed do not implement the change of shape of the spatial objects that define geographic space, their neighbourhood based on Voronoi boundaries limits the neighbouring relationships among objects, and their sensitivity to the neighbourhood configuration has not been evaluated.

Based on this problem statement, the primary objective of this research is *to develop a new vector-based CA model that overcomes the problem of spatial scale sensitivity of* *classical raster-based CA models and of recent implementations of vector CA by allowing an irregular space tessellation where the neighbourhood definition and the transition functions are associated to the real properties of each geographic object within the study area, and that allows the geometric transformation of the geographic objects as a result of the transition functions.*

In order to reach this objective, the incremental development of a new vector-based geographical CA model, called VecGCA, is presented, first to address the issue of cell size sensitivity, to define explicitly the neighbourhood configuration and to allow the change of shape of the objects, and second, to overcome the sensitivity to the neighbourhood configuration.

The major contributions of this research are summarized below:

1. Using the space definition presented in the previous vector-based CA model, a new geometric transformation procedure is developed to allow the change of shape of the geographic objects and to represent their evolution through time.
2. A new neighbourhood definition is presented that removes the concept of fixed distance to identify the neighbouring relationship among geographic objects. The new neighbourhood definition overcomes the sensitivity to the neighbourhood configuration of the classical raster-based CA models.

1.4 Research scope

The scope of this research is:

1. To design and implemented a new vector-based geographical cellular automata model to allow geometric transformations of polygons and to overcome the scale sensitivity of the classical raster-based CA models.
2. To test the model using real data to simulate land-use changes in two specific study areas.
3. To compare the obtained results with the results of a classical raster-based CA model and to analyze the generated spatial patterns by VecGCA compared with the reference land-use maps available for each study area.

1.5 Assumptions and limitations

The following assumptions and limitations of this research are:

- The land-use change models implemented to test the new VecGCA model were defined based on transition probabilities between different land uses present in each study area; others factors such as land fertility, distance to river or road, slope, have not been considered. We assumed that the changes of landscape configuration observed in the historical data represent the dynamics of the study area; therefore transition probabilities are calculated from the comparison of historical land-use maps.

- The available data for each study area is limited (two land-use maps for the Maskoutains region, and three for the Elbow river watershed). The calibration and validation of the land-use change models were made using the same data.
- The developed model is limited to applications were the geographic objects are represented as polygons; other representations as points or lines have not been implemented.

1.6 Thesis outline

This thesis is organized into five chapters. In Chapter 2, the Vector-based geographic cellular automata (VecGCA) model is introduced. This chapter contains a detailed description of the first version of the VecGCA model including the conceptual model and the implementation details. The methodology applied to simulate land-use changes and the comparison with a raster-based CA model is described, followed by a description of the results and a presentation of some limitations of the model.

Chapter 3 describes an improved version of the VecGCA model and presents a sensitivity analysis to the neighbourhood size. The improved version includes a new implementation of the geometric transformation procedure to reduce the computation time and other limitations described in Chapter 2. Two land-use change models are implemented to assess the performance of the model associated with the spatial complexity of the landscape and its sensitivity to the neighbourhood size. The methodology for the definition of these models is described, and the results and limitations are presented.

In Chapter 4, a dynamic neighbourhood is described and the update of the VecGCA model is presented. The methodology to define two land-use change models and testing the new neighbourhood definition is presented. The results and interpretation are provided at the end of the chapter. Finally, the general conclusions from this research and recommendations for future work are presented in Chapter 5.

CHAPTER 2

DESCRIPTION OF *VecGCA* MODEL AND COMPARISON WITH A RASTER-BASED CA MODEL

This chapter presents a new vector-based geographic cellular automata model (VecGCA), its conceptual model and the details of its implementation. The first version of VecGCA is proposed to overcome the cell size sensitivity of the raster-based CA models, to define explicitly the neighbourhood in the model and to allow the change of shape of the geographic objects. A test of the model to simulate land-use changes in the Maskoutains region, in Quebec, and the comparison with a raster-based CA model are also presented.

2.1 Conceptual model

VecGCA is an extension of the classical CA models; it is defined by the same five basic elements: space, set of states, neighbourhood, transition functions and time. However, the space, neighbourhood and transition functions are redefined in order to overcome the sensitivity to the cell size in the raster-based CA models, to define explicitly the neighbourhood and to allow the geometric transformation of the objects.

In VecGCA, *space* is composed of a collection of georeferenced geographic objects of irregular shape that represent real-world entities. Each geographic object is represented as a polygon that is in a specific state and can define its proper transition function and neighbourhood. Each geographic object is connected to each other through adjacent sides composing the whole space of a study area.

The neighbourhood is a key component of the model, because it defines which objects determine the change of shape of a central object. In geographic applications, such as land-use/land-cover changes or urban development, a geographic entity is generally influenced by adjacent or non-adjacent entities separated by a distance *d*. In this first version of VecGCA, the *neighbourhood* is defined as an external buffer (region of influence) around each geographic object and the neighbours are all the objects (adjacent or non-adjacent) that are totally or partially within the region of influence (Figure 2.1). The size of the buffer that delineates the region of influence is expressed in length units and is explicitly defined by the user.

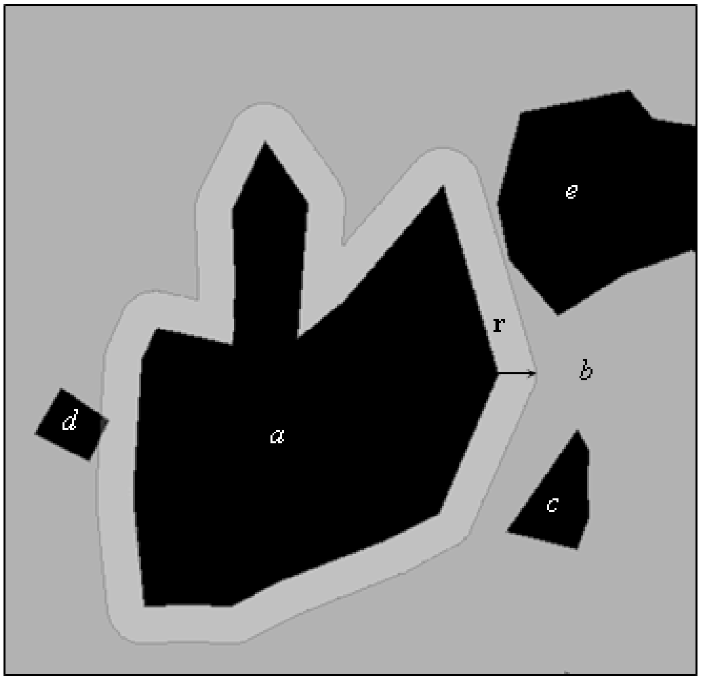


Figure 2.1. Geographic space composed of five objects: *a*, *b*, *c*, *d* and *e*. The neighbourhood around *a* is defined by *r* and the neighbours of *a* are the objects *b* and *d*

Each neighbour exerts an influence on the central object that can produce a change of shape regulated by the transition function, which is evaluated for each neighbour of the geographic object. This *transition function* quantifies the area that changes state from the state of the central object to the state of its neighbours. That area is related to the area of the neighbour within the neighbourhood and its influence on the specific geographic object (Equation 2.1). The transition function has 0 as lower limit, when the influence of the neighbour is smaller than a threshold value (λ), and the total area of the geographic object as upper limit, when the whole area of the geographic object changes state. The threshold value represents the resistance of a geographic object to change state for the state of its neighbour.

$$f_b(t+1) = f\left(A(t)_a, g_{ab}\right) \tag{2.1}$$

where

f_b is the transition function of object *b*,

$A(t)_a$ is the area of the neighbour *a* within the neighbourhood of the object *b* at time *t,* and

g_{ab} is the influence of the neighbour *a* on the object *b.*

The *influence* quantifies the pressure of a neighbour on the central object to take a portion of its surface. Its value varies between 0 and 1, where 0 indicates no influence and 1 the highest influence. The influence value is defined by three main parameters: the neighbours' area within the neighbourhood, the probability that a geographic object changes its state for the state of its neighbours, and the distance between a neighbour and a geographic object (Equation 2.2). In order to consider distances greater than 0 and to give relevance to adjacent and non-adjacent neighbours, the distance between the centroids of the polygons is used. Other parameters could be included to represent specific aspects of the dynamics of the study area.

$$g_{ab} = g\left(A(t)_a, P_{b \to a}, d_{ab}\right) \tag{2.2}$$

where

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

$A(t)_a$ is the area of the neighbour *a* within the neighbourhood of the object *b* at time *t,*

$P_{b \to a}$ is the probability to change from the *b*'s state to *a*'s state*,*

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

The change of state of a portion or the totality of the geographic object calculated in the transition function is performed in the procedure of geometric transformation. This procedure is called *n* times, one for each neighbour which transition function is greater than zero. The execution order is descendant from the neighbour having the highest influence to the neighbour having the lowest influence. The geometric transformations are synchronous; all geographic objects composing a study area are considered during the same time step and their changes of shape are executed as needed.

2.1.1 Procedure of geometric transformation

The evolution of an object consists in its change of shape and size through time. These changes are performed in the geometric transformation procedure. This procedure reduces the area of the geographic object in a quantity (expressed in area unit and calculated in the transition function) from the region nearest to the corresponding neighbour. The principle is to remove small portions of the geographic object at the frontier with its neighbour until the area calculated in the transition function is removed. The problem is to determine the shape and size of these small portions to be removed from the geographic object. The solution applied in this first version of the VecGCA model is to rasterize the geographic object, using a regular grid which resolution is defined by the user, and eliminate the necessary cells (nearest to each respective neighbour) to satisfy the area that has been calculated by the transition function. The number of cells to be eliminated is given by Equation 2.3.

$$Nc = \frac{f_b(t+1)}{(R)^2} \tag{2.3}$$

where

Nc is the number of cells that change state,

f_b is the transition function of object b, and

R is the resolution of rasterization.

The removed cells define a new object that is later combined to the corresponding neighbour. The cells that remain in the state of the geographic object are vectorized and define the new geometric representation of the geographic object.

A hypothetical example illustrating this procedure is presented in Figure 2.2. The polygon b is a neighbour of the object a and exerts an influence on it (Fig. 2.2.a). Let us suppose that a's state is 0, that b's state is 1, A_b= 2 m^2, $P_{0\rightarrow 1}$= 0.8, d_{ab}= 2.2 m and $\lambda_{0\rightarrow 1}$= 0.6. Let us also suppose that $\{\exists\, g \mid g(2,0.8,2.2) = 0.65\}$, then as $0.65 \geq 0.6$, a region of a will change its state to the state of b. The area of this region is calculated using the transition function of a. a is transformed into a raster format (Fig. 2.2.b) and the number of cells corresponding to the area that must change state is calculated. Let us suppose that $\{\exists\, f \mid f(2, 0.65) = 0.21\, m^2\}$ and the resolution of rasterization is 0.1 m, then $Nc = 0.21\, m^2 / (0.1\, m)^2 = 21$. The cells of a that are nearest to the neighbour b are assigned the state of b until the number of cells previously calculated is reached (Fig. 2.2.c). a is transformed into a vector format again and a new polygon is created with the area that has changed and incorporated to b (Fig. 2.2.d). The topology of each polygon is updated after each geometric transformation.

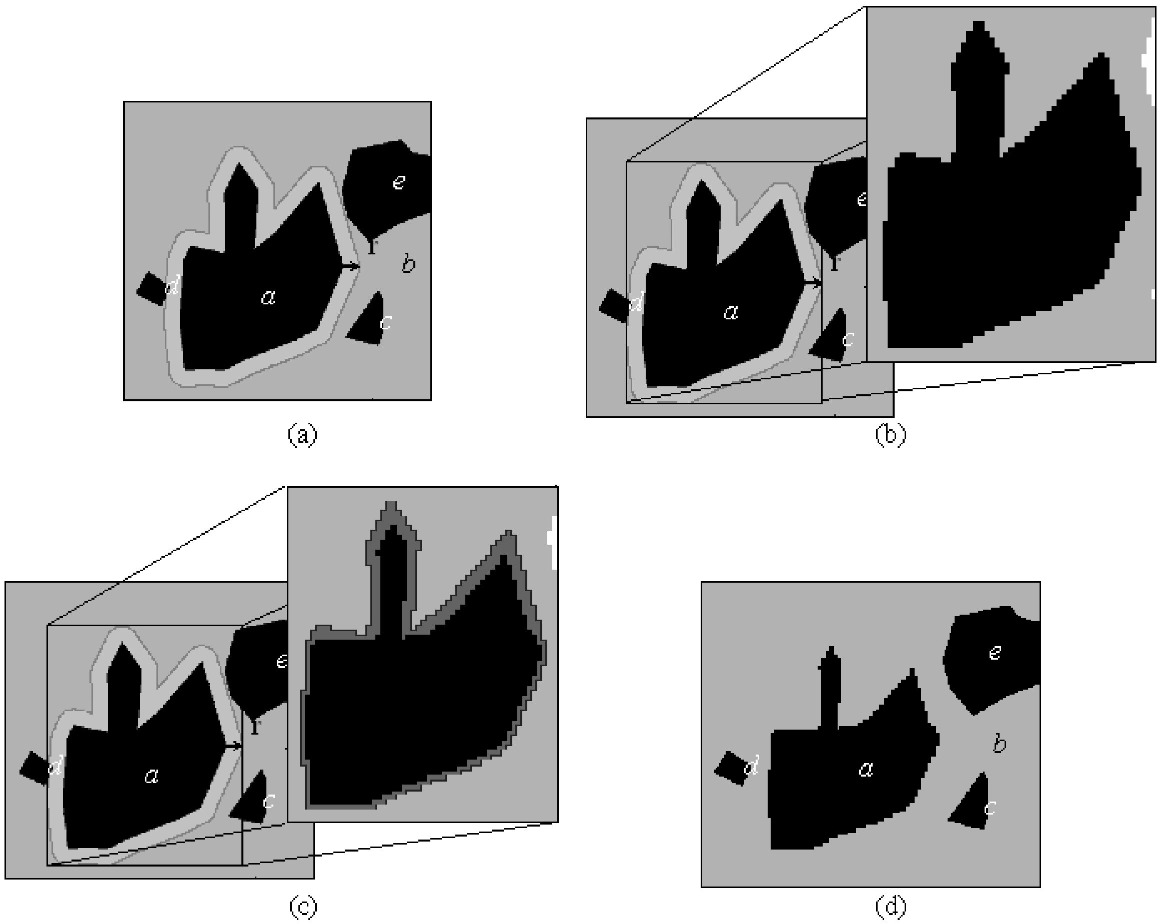


Figure 2.2. Illustration of a performed geometrical transformation procedure

2.2 Implementation

The design of the VecGCA model was done using the Oriented-Object Methodology (OOM) and implemented in Java. Our library uses two additional libraries: OpenMap library (OpenMap 2005) for the handling and display of shape files, and JTS Topology Suite (JTS 2004) for the handling of geometric objects (points, lines, polygons, polylines), buffer construction and geometric operations (intersection, difference, union, etc).

The VecGCA model is presented as a library of software organized into four packages (Figure 2.3):

1. Conceptual model. It includes the set of main classes composing VecGCA, the geographic space and other additional classes that support the procedure of geometric transformation of polygons.
2. Graphic. It is a set of classes that display the collection of geographic objects that define space; these classes are implemented as subclasses of JFrame of the package java.swign.
3. Utilities. It includes additional classes that allow the handling of raster data and the calculation of the transition probabilities and thresholds from the comparison of two raster maps of different dates.
4. Interface. It contains classes that transform data from shape files to geographic objects and vice versa, using OpenMap and JTS libraries.

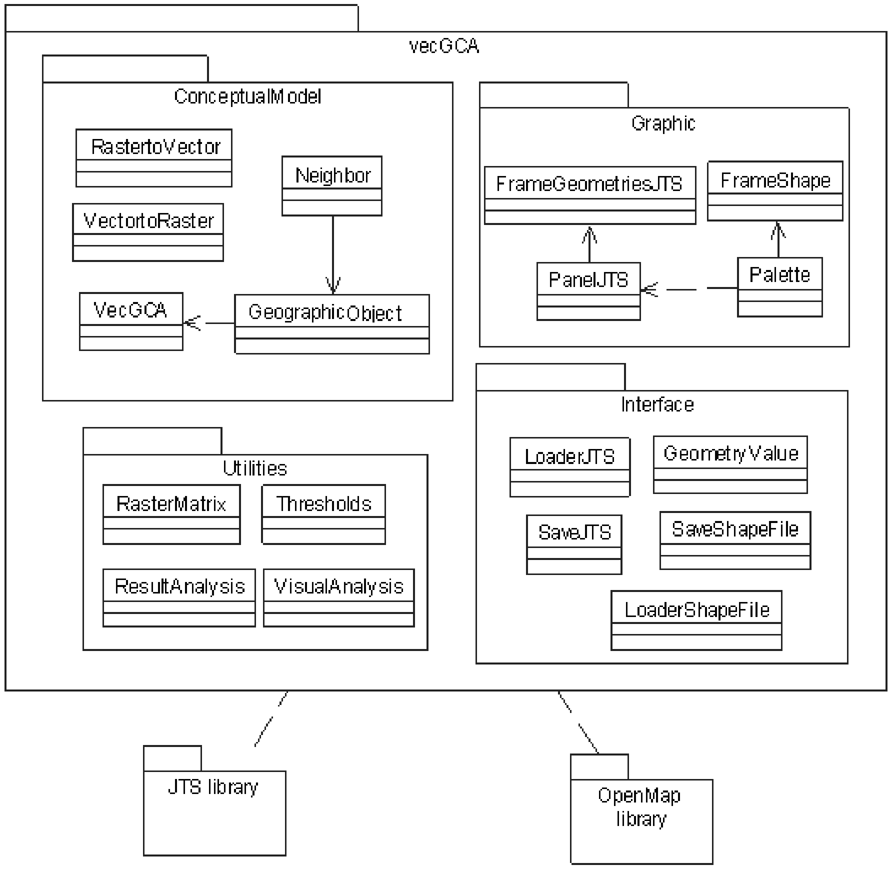


Figure 2.3. UML diagram of the library of components that defines the VecGCA model

Description of the Conceptual model package

The classes contained in this package are:

1. VecGCA. It is the primary class in the VecGCA model. It allows the definition of the model that represents the system under study. It has a collection of attributes that document the model: its name, the description of the system and the time unit that defines the evolution of the system. Another set of attributes describe the characteristics associated with space (defined as a collection of geographic

objects), and the resolution used in the procedure of geometric transformation. The methods of this class allow the handling of all attributes, the main control of the simulation model, and the execution of the geometric transformation procedure on geographic objects. Details of the simulation and the geometric transformation procedure are described in the sections 2.2.1 and 2.2.2, respectively.

2. GeographicObject. It defines each geographic object of the VecGCA model, its behavior, its neighbourhood, and the transition function. The attributes of this class store the information related to the actual state of the geographic object, its geometry, its neighbourhood size and its neighbours' list; it also stores the information about its behavior associated with the possible changes, such as the probabilities of transition and the threshold values. Some attributes are static (such as state, neighbourhood, probabilities of transition and threshold), while others are updated through the simulation (neighbours and geometry). The methods of this class update the dynamic attributes and execute the evolution of the geographic object.
3. Neighbour. In order to reduce the computation time, this class was implemented to store information of the neighbours of a geographic object directly with the object. The attributes of this class include the identifier of the neighbour, its state, the area within the neighbourhood, the distance between the objects, the influence

value, and the area to change from the object's state to the neighbour's state. Simple methods were implemented to handle (read and update) these attributes.

4. VectortoRaster. This class with the next class (RastertoVector) supports the procedure of geometric transformation. It executes the transformation of data from a standard vector format (shape file) to a standard matrix format (raster format), called rasterization. The rasterization is a simple process that consists of overlaying a regular grid on top of the vector file and to assign to each cell the value associated to the polygon that contains it. The algorithm used in this model is the scan-line algorithm, commonly applied in computer graphics to convert vector maps to raster images (Healey et al. 1998).
5. RastertoVector. This class executes the transformation of data from a matrix format to a vector format, called vectorization. The vectorization process is more complicated. It consists in extracting, from a raster image, sequences of vectors that represent polygons, lines or isolated points. The algorithm used in this model is a variation of the algorithm presented by Parker (1988) where the vectors are constructed in the border of each cell producing a stair effect in the polygons, but reducing the border and overlay problems between the adjacent polygons and preserving the integrity of the geographic space.

Description of the Graphic package

The classes in this package are:

1. Palette. It is a basic class that assigns a colour, expressed as a java.awt.Color, to a value or value interval.
2. FrameShape. It is a basic window based on the OpenMap library (OpenMap 2005) to display a shape file using a specific palette.
3. FrameGeometriesJTS and PanelJTS. These are simple classes based on Graphic User Interface (GUI) components of Java that display a list of geographic objects which can be instances of GeometryValue or GeographicObject classes.

Description of the Utilities package

The classes in this package are designed to support the parameterization of the VecGCA model and to analyse its results. These classes are:

1. Thresholds. Using two raster maps, this class calculates the transition probabilities and threshold values that define the resistance to change from a state *X* to a state *Y*, according to the procedure described in the section 2.3.2.
2. ResultAnalysis. From a sequence of dated shape files or text files in WKT (Well-Known Text) format, this class calculates for each possible state the coverage (area and proportion), the number of polygons and the mean, minimum and

maximum area of these polygons. The WKT format is defined in the OGC Standards (Open Geospatial Consortium, Int).

3. VisualAnalysis. This class supports the comparison of two lists of geographic objects and calculates the correspondence between them. This is similar to an overlay of two vector maps, but details of each object are presented, that is for each object the changes of state and area are calculated. For example, the area of an object in the first map, which state is forest, corresponds in the second map to 80% forest, 15% agriculture and 5% urban area.
4. RasterMatrix. It is an additional class to read a raster map from an ASCII file in a two-dimensional array.

Description of the Interface package

The classes composing this package are used to read the initial conditions of the model and store the state of the system (map corresponding to the geographic space) at any time step. These classes are:

1. GeometryValue. This class is designed to write the information contained in a shape file using the classes defined in the JTS library (JTS 2004). It has two attributes, one to describe the geometry of an object (geometry) and another associated to its state (value).

2. LoaderShapeFile. Based on the OpenMap library (OpenMap 2005), this class reads shape files and builds a list of objects of type GeometryValue which is used to define the initial conditions in the VecGCA model.
3. SaveShapeFile. It translates a list of GeometryValue objects to a shape file.
4. SaveJTS. This class was designed to store the geographic space of the model in text files using the WKT representation of geometries.
5. LoaderJTS. This is a complement of the above class; it reads text files that store the geographic space in WKT representation and builds a list of objects of type GeometryValue which is used to define the initial conditions of the model.

All these classes support the definition, simulation, visualization and result analysis of the VecGCA model, but the model's core is the VecGCA class that executes the evolution of the system under study. The following sections present the details of the simulation and the geometric transformation algorithms that execute that evolution.

2.2.1 Simulation algorithm

The simulation procedure controls the evolution of the geographic space through time. In VecGCA, space is implemented as a list of geographic objects. In this procedure, each element of the list of geographic objects is reviewed to determine what are the neighbours (*update_neighbourhood procedure*) and if there are neighbours that exert an influence higher than a threshold value. In such a case, the area to be changed is calculated and the *geometric transformation procedure* is executed on the geographic object that is reviewed. Finally, a procedure to check the topology of the whole geographic space is performed; this procedure removes possible errors introduced by the rasterization and vectorization procedure. Figure 2.4 presents a flow chart of this procedure.

The *update_neighbourhood* procedure built a buffer around a geographic object and checks which geographic objects are within this buffer (by intersection). When a geographic object is within the buffer, the influence value is calculated, and this information is added to the neighbours' list of the geographic object that is being reviewed. The detailed algorithm of this procedure is presented below.

> Let **g** be the geographic object to be reviewed. Let **p** be the polygon that represents the geometry of g. Let **buffer** be the polygon that defines the neighbourhood of g. Let **centre** be an auxiliary variable to store the centroid of **p**. For each geographic object of the geographic space that defines the vector-based cellular automata model do:
>
> 1. Intersect the geometry of this geographic object with **buffer**.
> 2. If the intersection is not empty then this geographic object is a neighbour of **g**; do:

2.1. Calculate the distance between the centroid of this neighbour and **centre**.

2.2. Calculate the intersection area.

2.3. Calculate the influence of this neighbour on **g** and the area to change according to the transition function of **g**.

2.4. Create a new Neighbour object with the following attributes: the **id** and state of the neighbouring object, the area calculated in 2.2, the distance between the neighbour and **g** calculated in 2.1, and the influence and area to change calculated in 2.3

2.5. Add this new Neighbour object to the neighbours' list of **g**.

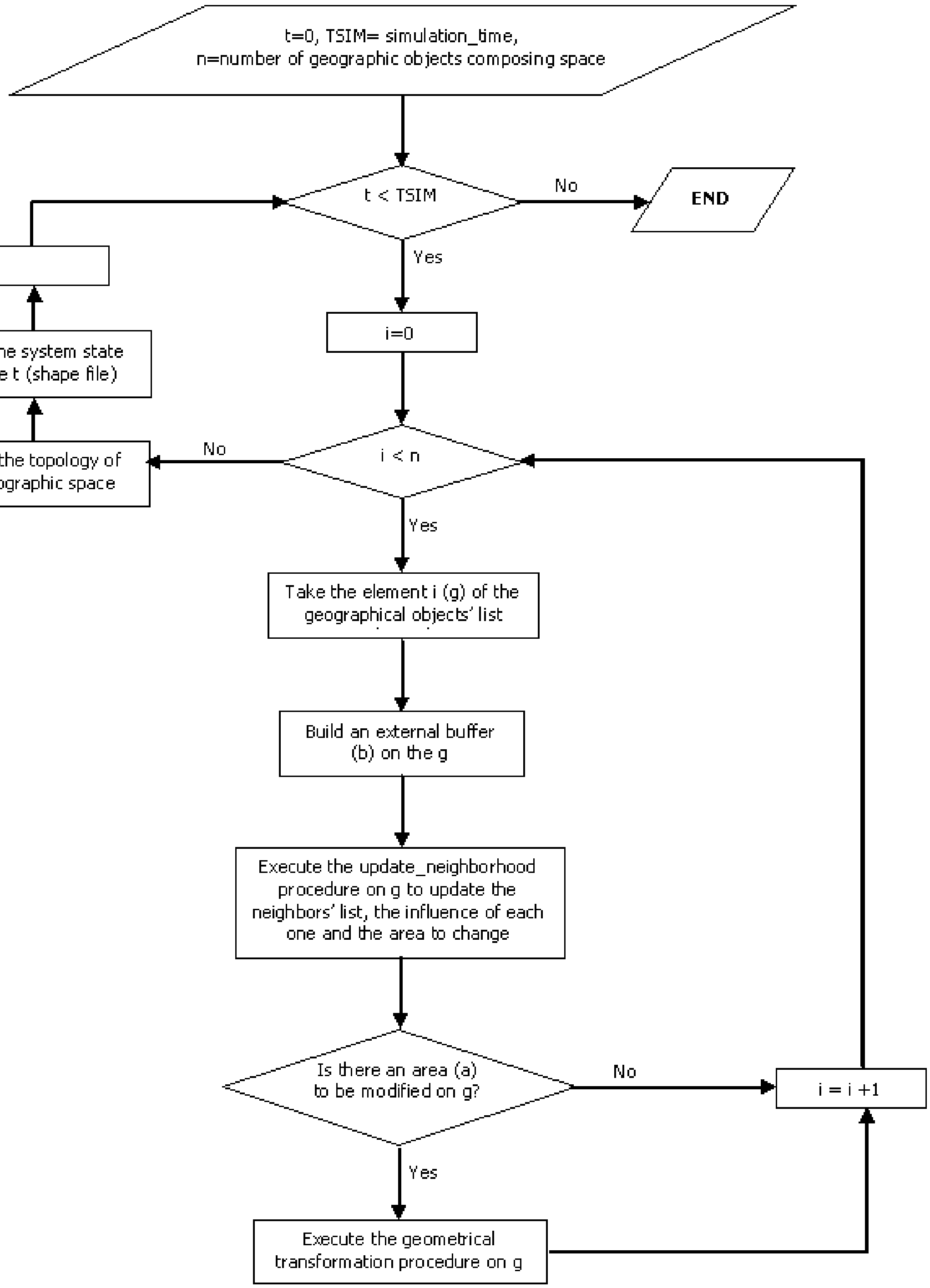


Figure 2.4. Simulation flow chart of VecGCA

2.2.2 Geometric transformation algorithm

The geometrical transformation procedure is responsible for the change of shape of the geographic objects. Its implementation includes a rasterization and vectorization process to control the quantity of area that changes state in the appropriated section of the polygon. The topological relationships between each polygon are calculated at each geometric transformation to preserve the integrity of the geographic space. Figure 2.5 presents a flow chart of the geometrical transformation procedure implemented in VecGCA model. This procedure encompasses the following steps:

1. Rasterize the geographic object into a matrix, which dimensions are defined by the minimum bounding box in the neighbourhood of the geographic object. Each cell's value corresponds to the identification number (ID) of each geographic object.
2. If some neighbours of the geographic object have an area calculated in the simulation procedure greater than 0, than the cells nearest to this neighbour are assigned the ID of the neighbour.
3. If some cells change state, then vectorize the cells corresponding to the geographic object and assign this new geometric representation to the geographic object.

4. If some neighbours of the geographic object have an area calculated in the simulation procedure greater than 0, then vectorize the cells corresponding to the ID of the neighbour, join this new polygon with the geometric representation of the neighbour, and assign this new geometric representation to the neighbour.

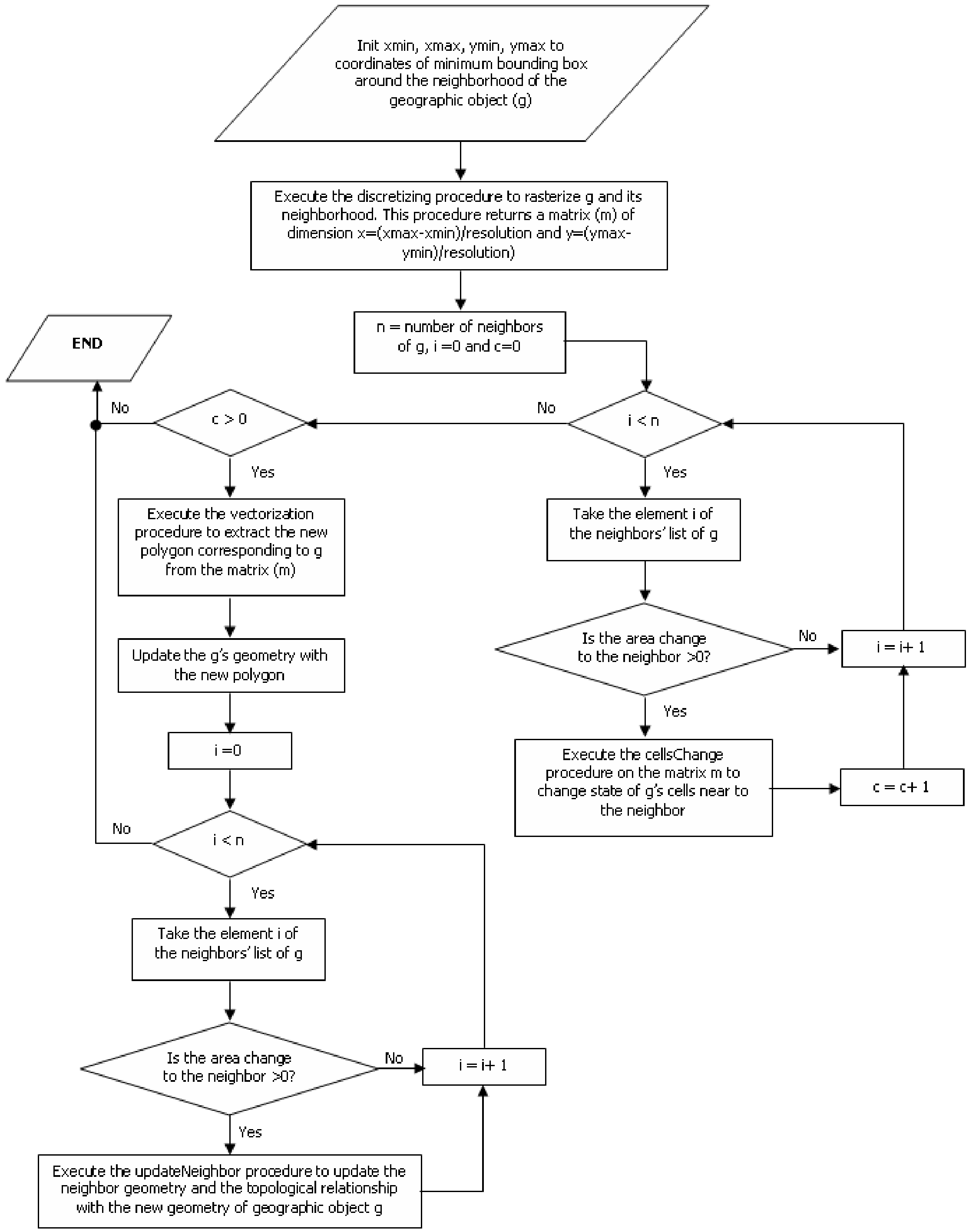


Figure 2.5. Flow chart of the geometric transformation procedure in VecGCA

2.3 Comparison of VecGCA and a raster-based CA model to simulate land-use changes

VecGCA was tested using real data to simulate the land-use changes in the Maskoutains, an agroforested region in southern Quebec, Canada. The results were compared with those obtained with a raster-based CA model applied to the same study area under the same conditions. This section presents an overview of land-use change modelling and describes the methodology used to test the model as a tool to simulated land-use changes and the results that were obtained.

2.3.1 Land-use change modelling

Land-use change models are useful tools for understanding the causes and consequences of land conversion, the interactions between socio-economic and biophysical forces that influence the rate and spatial pattern of land-use changes. Two categories of models can be identified for the study of land-use changes. The first group is the spatially explicit models at highly disaggregate scales, developed by geographers and natural scientists to study land-use changes by direct observation, using remote sensing data and GIS modelling (Jenerette and Wu, 2001; Wu, 2002; Almeida et al., 2003, Ménard and Marceau, 2007). The second group is the models, generally developed in the social sciences, to study the individual behaviour in human-environment interactions at the micro-scale (Irwin and Geoghegan, 2001; Parker et al., 2003; Moreno et al., 2007).

Verburg et al. (2004) distinguish six important features that must be considered to model land-use changes: (1) level of analysis; (2) cross-scale dynamics; (3) driving factors; (4) spatial interaction and neighbourhood effects; (5) temporal dynamics; and (6) level of integration.

The l*evel of analysis* defines the scale of analysis used to define the model (micro-scale or macro-scale as mentioned below). In addition, land use is the result of multiple processes that act over different scales (*cross-scale dynamics*). At each scale, different processes dominate land-use changes. Most land-use models are based on one scale or level exclusively, but others models are structured hierarchically to consider multiple levels into the land-use dynamics and to represent the cross-scale dynamics (White and Engelen, 2000; White, 2005).

A key element in the development of realistic models of land-use change is the identification of the most important drivers of change and how to best represent these drivers in the model. Land-use change is often modelled as a function of a selection of socio-economic and biophysical variables that act as *driving forces* of the land-use change. Driving forces are often considered exogenous to the land-use system to facilitate modelling, and they are modelled as external subsystems linked to the land-use model (*level of integration*). In addition, these drivers are scale dependent, that is at different scales of analysis different drivers have a dominant influence on the land-use systems (Veldkamp and Lambin, 2001).

Land use models are dynamic systems that reproduce the evolution of a land-use system through a time period (*temporal dynamics*). Generally, the land-use changes generated by the model are not predictable; they may depend on the initial conditions, and random events associated to the driving forces. However, the land-use patterns generated by the land-use models exhibit generally high spatial autocorrelation due to the *spatial interactions* between the land-use types themselves over a short or long distance, or through different scales.

CA models are a very common approach used to simulate land-use changes, because they are spatially explicit dynamic systems that can represent all the features mentioned previously. The early CA models were defined at one scale (Clarke and Gaydos, 1998; Jenerette and Wu, 2001), but advances in constrained CA models (White and Engelen, 2000; Straatman et al., 2004), coupled MAS-CA models (Parker et al., 2003; Moreno et al., 2007) and in multi-scale CA models (White, 2005) have allowed representing the cross-scale dynamics in land-use systems. In addition, CA are defined based on local interactions of cells, therefore they can represent the spatial interactions and neighbourhood effects present in a land- use systems. However, the scale sensitivity of the raster-based CA models is a disadvantage of this approach. We propose a new VecGCA model to overcome the scale sensitivity of the raster-based CA models, that retains all properties of the classical CA to represent the land-use dynamics.

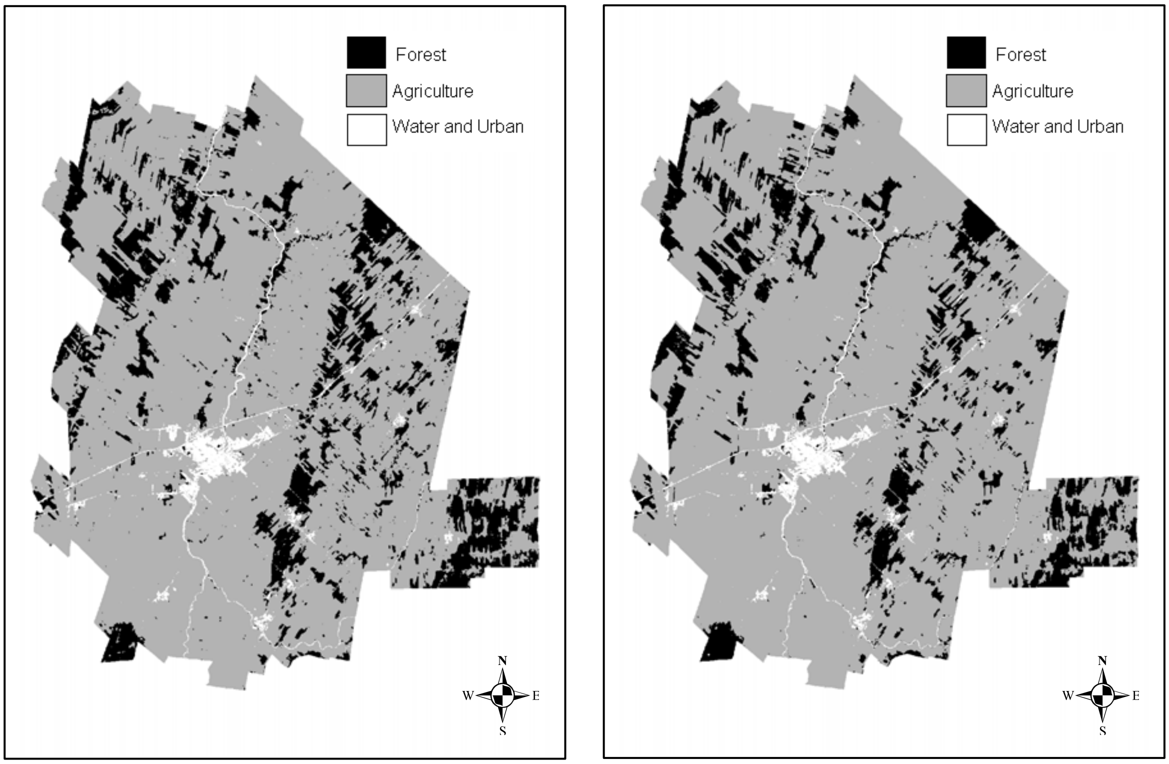
In the following sections, a simple land-use change model is presented to test the new approach. The VecGCA land-use change model is based on transition probabilities of land uses and it simulates the dynamics in the study area by assuming that these probabilities remained constant over time. This approach is similar to the early models of land-use changes which were simple grid-based Markov models (Ives et al. 1998). In order to compare the simulation outcomes with the results obtained using a traditional raster-based CA model, the implemented raster-based CA models are also simple models based in transition probabilities of land uses. The development of a more realistic land-use change model will be done when the new approach will have been tested.

2.3.2 Study area and dataset

The study area is the Maskoutains regional county municipality that covers an extent of 1312 km^2. In this region, two dominant land uses/land covers can be observed:

agriculture and forest. The fertility of the land and its proximity to the Montreal City market create a situation that is highly favourable for agriculture, but also generates high pressure on the forest remnants in the region. Between 1999 and 2002, the region has lost 23 km^2 of forested area, which corresponds to a decline of 10.5% (Soucy-Gonthier et al. 2003). The Maskoutains region was chosen for this study because of the availability of geographic data and the previous knowledge about the dynamics of land-use changes in this region (Ménard and Marceau 2007), which facilitate the implementation and testing of the VecGCA model.

The main data sources are two land-use maps of the Maskoutains region originating from the classification of Landsat Thematic Mapper (TM) images acquired in 1999 and 2002 (Figure 2.6) (Soucy-Gonthier et al. 2003). The images have an original spatial resolution of 30 m and the land-use classes are forest, agriculture, urban areas and water (classes 1, 2, 3 and 4). These maps were transformed in a vector format using the Raster to Polygon conversion tool in ArcGIS 9.0 (ESRI 2005).



(a) (b)

Figure 2.6. Land-use map of the Maskoutains region: (a) 1999, and (b) 2002

2.3.3 Definition of the VecGCA model

To apply the VecGCA model to a specific study area, the neighbourhood, the influence function, and the transition function that represents the dynamics of that study area must be determined. The neighbourhood is defined as an external buffer of 30 m around each geographic object in order to establish a comparison with the Moore neighbourhood in the raster-based CA model with a cell size of 30 m that corresponds to the original resolution of the raster land-use maps.

An exponential function as described in Equation 2.4 can be used to define the influence value, because that function is limited between 0 and 1 (as described in the section 2.1) and depends on a parameter α which can be redefined in function of the variables that control the influence value of a geographic object on another. For the Maskoutains model, α is redefined in function of the transitions probabilities, neighbours' area within the neighbourhood and the distance between the centroids of the objects, according to the following consideration:

- The influence value is directly proportional to the transition probability,
- The influence value is directly proportional to the neighbours' area within the neighbourhood, and
- The influence value is inversely proportional to the distance between the centroids of the objects.

For the model, this function is given by Equation 2.4.

$$\begin{aligned} g_{ab} &= 1 - e^{-\alpha_{ab}} \\ 0 \leq g_{ab} &\leq 1 \end{aligned} \quad (2.4)$$

where

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

α_{ab} is defined in Equation 2.5

$$\alpha_{ab} = P_{b \to a} * A(t)_a / d_{ab} \tag{2.5}$$

where

$P_{b \to a}$ is the probability to change from b's state to a's state,

$A(t)_a$ is the area of the neighbour a within the neighbourhood of the object b at time t, and

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

Transition probabilities are defined from the comparison of the two land-use maps of 1999 and 2002. They are calculated according to Equation 2.6.

$$P_{X \to Y} = \frac{A_{X \to Y}}{\sum_{i=1}^{4} A_{X \to i}} \tag{2.6}$$

where

$P_{X \to Y}$ is the transition probability from state X to state Y,

$A_{X \rightarrow Y}$ is the total area that changes from state X to state Y,

$A_{X \rightarrow i}$ is the total area that changes from state X to state i, and

i is each possible state (forest, agriculture, urban and water).

Table 2.1 presents the transition probabilities calculated for a temporal resolution of three years**.**

Table 2.1. Transition probabilities defined from the comparison of the two vector land-use maps of 1999 and 2002 for a temporal resolution of three years

t \ t + Δt	Forest	Agriculture	Urban	Water
Forest	0.78	0.22	0.00	0.00
Agriculture	0.02	0.98	0.00	0.00
Urban	0.00	0.00	1.0	0.00
Water	0.00	0.00	0.00	1.0

When a neighbour exerts an influence on a central object which is higher than its threshold value, that neighbour takes a portion of the surface of the central object, which is defined by the transition function. The transition function is given in Equation 2.7., which supposes that area is proportional to the neighbour's area within the neighbourhood and the neighbour's influence on the central object.

$$f_b = \begin{cases} A(t)_a * g_{ab} & \text{if } g_{ab} \geq \lambda_{ab} \\ 0 & \text{other case} \end{cases} \tag{2.7}$$

where

f_b is the transition function of object b,

$A(t)_a$ is the area of the neighbour a within the neighbourhood of the object b at time t, and

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

Threshold value can be defined as the probability that a geographic object does not change its state to state X although all its neighbours are in state X. Equation 2.8 provides the threshold value:

$$\lambda_{ab} = 1 - P_{\max} \tag{2.8}$$

where P_{max} is the probability that a geographic object b changes its state to the state of the geographic object a when all its neighbours are in the state of a.

Since the neighbourhood configurations for irregular polygons are infinite, a simplified situation for the calculation of the threshold values was applied, where all the polygons are considered as squares of same size, connected to each other as cells in the raster model. Then P_{max} is the probability that a geographic object changes its state from state X to state Y when its eight neighbours are in state Y. This probability was calculated from the comparison of the two raster land-use maps (1999 and 2002) and it is given by the number of cells in state X in 1999 that have changed to state Y in 2002, while having eight cells in state Y in its neighbourhood, divided by the total number of cells in state X with the same neighbourhood in 1999.

Table 2.2 presents the threshold values calculated for the model. This procedure is implemented in the class Thresholds of the package Utilities and can be used to determine the threshold values in any model from two raster images of different dates. The threshold values for the transitions between the same states have been assigned to 1, since they are not considered as changes of state.

Table 2.2. Threshold values indicating the minimum influence that a polygon must exert on another to produce a geometric transformation

t \ t + Δt	Forest	Agriculture	Urban	Water
Forest	1.00	0.11	1.00	1.00
Agriculture	0.37	1.00	1.00	1.00
Urban	1.00	1.00	1.00	1.00
Water	1.00	1.00	1.00	1.00

The original resolution (30 m) of the available land-use maps was chosen for the rasterization procedure, to ensure that all objects can be represented in the raster format.

2.3.4 Definition of the raster-based CA model

Two raster-based CA models were also implemented to compare results with those obtained using the VecGCA model. These models differ only in their spatial resolution. First, a resolution of 30 m was chosen to provide a direct comparison with the VecGCA model, in which land-use data at their original resolution of 30 m are used to establish the initial conditions of the model. Second, a resolution of 100 m was also used based on the results previously obtained in a scale sensitivity analysis conducted by Ménard and Marceau (2005), which indicates that 100 m is the best resolution to represent the dynamics of the study area.

Space was defined as a regular grid corresponding to a raster land-use map. Each cell can be in one of four states, namely forest, agriculture, urban or water, but only two changes of state have been considered in this region: forest to agriculture and agriculture to forest. The Moore neighbourhood was chosen to represent the influence of first-order adjacent cells on a cell. Probabilistic rules were calculated from the comparison between two land-use maps (1999 and 2002), according to the procedure described in Ménard and Marceau (2005), where a forested cell that has *n* agricultural cells in its neighbourhood has a probability of changing to agriculture equal to the number of forested cells with *n* agricultural neighbours that have changed to agriculture between 1999 and 2002, divided by the total number of forested cells with the same neighbourhood in 1999. Tables 2.3 and 2.4 present the transition probabilities calculated using the raster land-use maps at 30 m and 100 m spatial resolution, respectively.

Table 2.3. Transition probabilities for the raster-based CA model of 30 m (W=Water, F=Forest, A=Agriculture, U=Urban)

Transition	**Number of neighbours whose previous state is equal to the cell's next state**								
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
F → F	0.096	0.175	0.195	0.280	0.424	0.547	0.602	0.683	0.880
F → A	0.000	0.326	0.411	0.475	0.590	0.741	0.818	0.841	0.929
A → F	0.000	0.111	0.174	0.265	0.357	0.498	0.528	0.507	0.638
A → A	0.799	0.770	0.678	0.677	0.713	0.795	0.864	0.910	0.991
U → U	0.882	0.888	0.920	0.918	0.944	0.986	0.990	0.996	1.000
W → W	0.900	0.954	0.979	0.910	0.888	0.938	0.988	0.998	1.000

Transition probabilities which values are zero (0) are not included in the tables. The transition probability from forest to agriculture with 0 agricultural neighbours and from agriculture to forest with 0 forested neighbours has been assigned a value of 0, because they do not correspond to any significant ecological phenomena. Since a pseudo-random number generator was used to implement the probabilistic rules, ten replicas of each simulation were performed using the raster-based CA model and the mean results were considered in the comparison with the VecGCA model.

Table 2.4. Transition probabilities for the raster-based CA model of 100 m (W=Water, F=Forest, A=Agriculture, U=Urban)

Transition	**Number of neighbours whose previous state is equal to the cell's next state**								
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
F → F	0.196	0.342	0.478	0.541	0.650	0.762	0.804	0.868	0.928
F → A	0.000	0.142	0.208	0.260	0.368	0.481	0.555	0.693	0.832
A → F	0.000	0.039	0.078	0.121	0.214	0.323	0.360	0.403	0.661
A → A	0.577	0.712	0.743	0.735	0.825	0.909	0.939	0.969	0.995
U → U	0.923	0.952	0.951	0.979	0.990	0.991	0.997	0.997	1.000
W → W	0.980	0.964	0.978	0.951	0.959	1.000	1.000	0.000	0.000

2.3.5 Model simulations

Two simulation periods were considered in the study:

1. From 1999 to 2002 in order to compare the results of the VecGCA model and the raster-based CA models with the 2002 land-use map. The 1999 land-use maps (in raster and vector formats) were used to establish the initial conditions in the raster-based CA models and the VecGCA model. A temporal resolution of one year was chosen and the transition probabilities for this temporal resolution were calculated from the transition probabilities of three years using the exponential method

presented by Yeh and Li (Yeh and Li 2006) where the transition probability *P* calculated for a time step *t* is substituted by P^n for a time step *T* where $T = n*t$.

2. From 2002 to 2032 in order to observe the performance of the VecGCA when executed over a longer period of time (10 time units) and to compare its results with the results obtained with the raster-based CA models. The 2002 land-use maps (in raster and vector formats) were used to determine the initial conditions of each model. A temporal resolution of three years was used for the simulations.

Validation of the first simulation period was done by comparing the simulation outcomes of the VecGCA model with the 2002 vector land-use map, the 30 m raster-based CA model outcomes with the 2002 30 m raster land-use map, and the 100 m raster-based CA model outcomes with the 2002 100 m raster land-use map. The results obtained for the second simulation period have not been quantitatively validated since our purpose was to evaluate the performance of the VecGCA model in comparison to the raster CA models over a longer period of time.

In order to compare the simulation outcomes produced by the VecGCA model and the raster-based CA models, a landscape analysis using Fragstats 3.3., a computer software program designed to compute a variety of landscape metrics for categorical map patterns (McGarigal et al. 1995), was done on the raster-based CA results. The number of patches for each land use was calculated on the raster maps generated by the raster-based CA models and compared with the number of polygons produced by the VecGCA model.

2.3.6 Results

The first section presents the simulation results obtained from 1999 to 2002. The second section describes the possible states of the system in the following 30 years, corresponding to simulations conducted from 2002 to 2032.

Simulation results for the period 1999 to 2002

The results produced by the VecGCA model and the raster-based CA models were compared with the 2002 vector land-use map and the 2002 30 m and 100 m raster land-use maps, respectively, to assess the capacity of the models to effectively capture the dynamics of the study area (Table 2.5). The three models reveal a proportion of land use very similar to the corresponding reference map. The VecGCA model produced 14.92 % forested area for 2002 versus 14.83 % presents in the reference 2002 vector land-use map; the 30 m and 100 m raster-based CA produced 14.84 % and 14.86 % of forested area for 2002 versus, respectively, compared with 14.86 % and 14.86 % present in the reference 2002 30 m and 100 m raster land-use maps. However, the landscape configuration is quite different. With the 30 m raster-based CA, the number of forested and agricultural patches considerably increases from 1453 in 1999 to 2727 in 2002 and

Table 2.5. Statistics describing the simulation outcomes of the VecGCA model and the raster-based CA models, and comparison with the 2002 raster land-use map (F=Forest, A=Agriculture).

	Initial conditions Land-use map 1999			Land-use map 2002			Simulations outcomes for 2002		
	Vector format	Raster format		Vector format	Raster format		VecGCA	Raster-based CA	
		30 m	100 m		30 m	100 m		30 m	100 m
Proportion of F (%)	16.57	16.58	16.58	14.83	14.84	14.86	14.92	14.86	14.86
Proportion of A (%)	80.70	80.70	80.70	82.45	82.44	82.41	82.35	82.41	82.41
Number of patches/ polygons of F	1642	1453	915	1762	1335	707	1394	2727	871
Number of patches/ polygons of A	1865	902	218	2200	934	169	1650	1274	199

from 902 in 1999 to 1274 in 2002, respectively. This increase is due to the fragmentation of large forested patches into small forested patches produced by the change of state of forest cells to agriculture cells when at least one agriculture cell is present in the neighbourhood which produces additional new agricultural patches. These changes are possible due to the high transition probabilities calculated from the comparison between the two land-use maps of 30 m (1999 and 2002) (Table 2.3). These results are in accordance with a previous scale sensitivity investigation conducted by Ménard and Marceau (2005) indicating that the resolution of 30 m produces an unrealistic fragmentation of the territory.

With the two other models, the number of patches/polygons decreases with time producing a less fragmented landscape (Table 2.5). This can be explained by the disappearance of forested patches absorbed by large agricultural patches. In the 100 m raster-based CA model, the numbers of forested and agricultural patches decrease from 915 in 1999 to 871 in 2002 and from 218 in 1999 to 199 in 2002, respectively. This behavior is associated with the high transition probabilities from forest to agriculture when the number of agricultural neighbours is higher than 5. In VecGCA, the number of forested and agricultural patches (polygons) decreases from 1642 in 1999 to 1394 in 2002 and from 1865 in 1999 to 1650 in 2002, respectively. The disappearance of forested patches absorbed by large agricultural patches is explained by the high pressure that receives a forested object with an agricultural neighbour that covers its entire neighbourhood.

However, a difference between the results produced by the VecGCA model and the 100 m raster-based CA model can be observed when an overlay of the 2002 vector and 100 m raster land–use maps with the corresponding simulation outcomes is performed (Table 2.6). The forest and agricultural patches produced by VecGCA coincide with the real forested and agricultural patches in the study area in a slightly greater proportion than the patches generated by the 100 m raster-based CA model. These results can by explained

Table 2.6. Proportion of simulated area that coincides with the state of the system in 2002 for each land use

Land use	% coincident with the reference map	
	VecGCA	100 m raster-based CA
Forest	80.61	77.97
Agriculture	96.26	93.04
Others	98.54	97.86

by the capacity of VecGCA to reproduce the evolution of the objects by their change of shape, whereas the patches produced by the raster-based CA model are created by the agglomeration of individual cells changing state. The outcomes of VecGCA, obtained from the original spatial distribution of the land-use map, present a spatial distribution that is more similar to the state of the landscape in 2002 than the outcomes produced by the raster model although the cell size of 100 m has been identified as the most appropriate in a previous sensitivity analysis (Ménard and Marceau 2005).

A zoom on a small portion of the study area illustrates the detailed spatial distribution produced by VecGCA and the raster-based CA models (Fig. 2.7). The landscape generated by VecGCA is characterized by large patches of well-defined boundaries, in comparison with the diffuse boundaries and a high landscape fragmentation produced by both raster-based CA models.

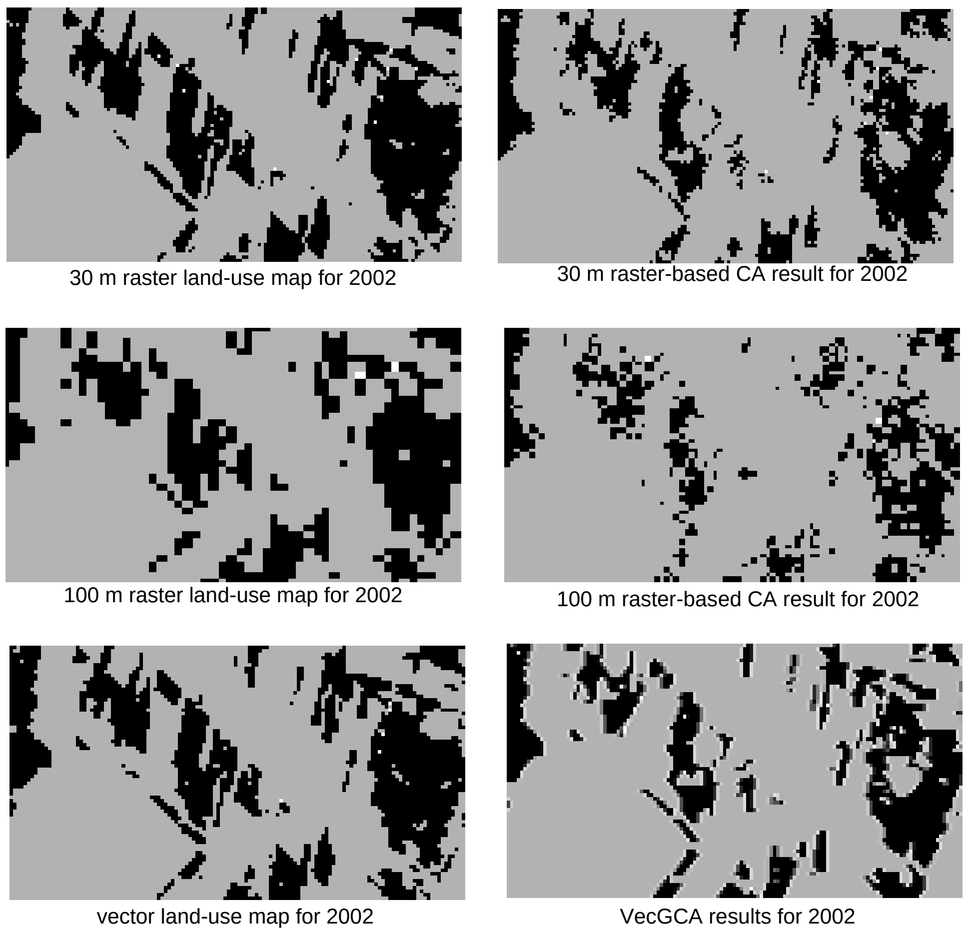


Figure 2.7. The 2002 land-use maps and the land-use spatial distribution generated by the VecGCA model and the raster-based CA models in 2002

Simulation results for the period 2002 to 2032

The simulation results for the period 2002-2032 reveal that the three models generate a similar trend, namely a decrease in forested areas and an increase in agricultural areas (Fig. 2.8), but in different proportions.

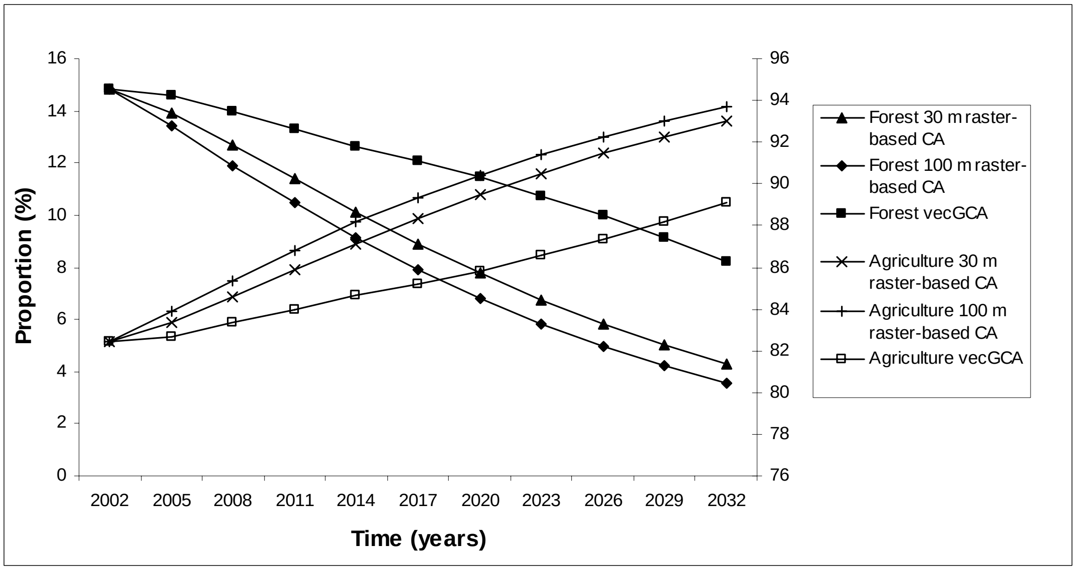


Figure 2.8. Proportion of forested and agricultural area calculated on the simulation outcomes of VecGCA and the 30 m and 100 m raster-based CA models

With the VecGCA model, the decrease in forested areas is lower in comparison to the decrease shown in both raster-based CA models; consequently the increase in agricultural area is also lower. In the VecGCA model, the proportion of forested area is reduced from 14.83 % in 2002 to 7.58% in 2032 and the proportion of agricultural area is increased from 82.45 % in 2002 to 89.69 % in 2032, whereas with the raster-based CA models the reduction in forested area is from 14.84% to 4.30% for the 30 m model and from 14.86% to 3.58% for the 100 m model, while the increase in agricultural area is from 82.44 % to 92.98 % and from 82.41 % to 93.69 % for the 30 m model and the 100 m model, respectively (Table 2.7). These results can be explained by the fact that with the VecGCA model, the decrease in forested area is determined by the change of state in only a portion

Table 2.7. Statistics describing the simulation outcomes of the VecGCA model and the raster-based CA models for 2032 (F= Forest, A=Agriculture)

	Initial conditions Land-use map 2002			Simulation outcomes for 2032		
	Vector format	Raster format		VecGCA	Raster-based CA	
		30 m	100 m		30 m	100 m
Proportion of F (%)	14.83	14.84	14.86	7.58	4.30	3.58
Proportion of A (%)	82.45	82.44	82.41	89.69	92.98	93.69
Number of patches/ polygons of F	1762	1335	707	1659	9753	474
Number of patches/ polygons of A	2200	934	169	1359	628	83

of the forested polygons produced by the influence exerted by the agricultural polygon neighbours at each time step. In comparison, in both raster-based CA models, the decrease in forested area is associated to the change of state of forested cells in the totality of their surface.

However, the landscape configuration produced by each model is different as revealed by the number of forested and agricultural patches/polygons (Table 2.7). With the 30 m raster-based CA model, the number of forested patches considerably increases from 1335 in 2002 to 9753 in 2032, while the number of agricultural patches decreases from 934 to 628 due to the agglomeration of agricultural patches. However, the 30 m raster-based CA model generates a considerably more fragmented landscape than the one produced by the

100 m raster-based CA and the VecGCA model. The fragmentation in the 30 m raster-based CA model is due to the division of large forested patches into small ones produced by the change of state of forest cells to agriculture cells when at least one agriculture cell is present in the neighbourhood. For the other two models, the reduction in the number of forested and agricultural patches/polygons is due to the disappearance of forested patches/polygons absorbed by large agricultural patches/polygons and the agglomeration or union of agricultural patches/polygons. In VecGCA, the number of forested and agricultural polygons decreases from 1762 in 2002 to 1659 in 2032 and from 2200 in 2002 to 1359 in 2032, respectively. A similar behaviour is provided by the 100 m raster-based CA model; the number of forested patches decreases from 707 in 2002 to 474 in 2032, while the number of agricultural patches decreases from 169 in 2002 to 83 in 2032.

The models display the same behavior for both simulation periods. The 30 m raster-based CA model produces a highly fragmented landscape that does not realistically represent the dynamics in the study area. These results are in agreement with those obtained in a previous study (Ménard and Marceau 2005) indicating that 30 m is not an adequate cell size for simulating the dynamics in the Maskoutains region and that the best cell size is 100 m. The 100 m raster-based CA and the VecGCA models both capture well the dynamics of the study area. However, there is no need to perform a cell size sensitivity analysis with VecGCA since the polygons correspond to the real distribution of land-use patches in the landscape.

2.4 Discussion

The results obtained reveal that VecGCA produces an adequate evolution of the geographic objects, generating realistic spatial patterns when compared to the reference land-use map. These results are independent of the cell size and no sensitivity analysis is required to determine neither the initial spatial distribution nor the cell size of the model. However, some limitations are still present in the model.

First, the rasterization used in the geometric transformation procedure introduces two problems: the selection of the cell size is arbitrary and affects the simulation outcomes. In addition, the rasterization produces a staircase effect on the polygons' border, generating errors in the delineation of the objects. A solution to overcome this problem is to replace the rasterization by a procedure that only uses vectors, where the portion removed from a geographic object is an irregular polygon whose borders conserve the initial definition of the objects.

An issue that is not addressed in the first version of VecGCA is the possible sensitivity to the neighbourhood definition. Several questions such as: Is VecGCA sensitive to the neighbourhood size? How to determine the appropriate neighbourhood size for a specific study area? Should the neighbourhood size be constant or variable around a geographic object? must be investigated. Finally, the appearance of new isolated polygons simulating the emergence of land-use patches is not included in VecGCA. Nevertheless, in this version of the model new polygons appear when a geographic object is divided into several objects due to the influence of its neighbours, or because a non-adjacent neighbour produces a geometric transformation.

The first version of VecGCA model overcomes the cell size sensitivity of the raster-based CA models; it defines the neighbourhood as an influence zone that represents neighbouring relationships more realistically than the Voronoi boundaries, and it allows the change of shape of geographic objects through time. The second step is to investigate its sensitivity to the neighbourhood size and if it is sensitive, to propose solutions to overcome this problem. In addition, the technical limitations introduced by the rasterization procedure should be removed to guarantee the good performance of the model. This is the subject of the following chapter.

CHAPTER 3

PERFORMANCE IMPROVEMENT OF THE GEOMETRIC TRANSFORMATION PROCEDURE AND SENSITIVITY ANALYSIS OF VecGCA TO THE NEIGHBOURHOOD SIZE

This chapter describes an improved version of VecGCA that overcomes the limitations present in the first version that were introduced by the rasterization process used in the geometric transformation procedure. In addition, a sensitivity analysis of VecGCA to the neighbourhood configuration is performed using two different study areas: Maskoutains region, Quebec, and Elbow river watershed, Alberta.

3.1 Update of VecGCA model

In the first implementation of the VecGCA model, a rasterization and vectorization process was executed to control the appropriate area that changes state in a specific section of the geographic object (Figure 2.2). The procedure consisted in rasterizing the geographic object, using a regular grid whose resolution was defined by the user, and eliminating the nearest cells to each respective neighbour to satisfy the area that changes state. The remaining cells that composed the geographical object were converted to the vector format again and the removed cells defined a new area that was vectorized and added to the corresponding neighbour. This procedure has two limitations: the resolution chosen to execute the rasterization is arbitrary and the simulation outcomes vary with the cell size. Also, the rasterization process produces a staircase effect on the polygons' border that introduces errors in the real definition of the objects. In addition, the VecGCA model is computationally intensive due to the handling of a large number of polygons that can compose a study area and the update of their topological relationships after each geometrical transformation during the simulation.

An improved implementation of the VecGCA geometrical transformation procedure is presented here to overcome the limitations introduced by the rasterization procedure and to reduce the computation time. This implementation involves a new definition of the geometrical transformation procedure in which the rasterization procedure has been replaced by the definition of an external buffer around the neighbours, which intersection with the geographic object defines the area to be removed from that geographic object and added to its neighbours. Also, some modifications of the simulation procedure were made to reduce the number of geometric operations and consequently to decrease the computation time required to conduct the simulations.

3.1.1 Simulation procedure

The simulation procedure presented in the section 2.2.1 was updated to reduce the computation time. At each time step, the updated simulation procedure calls three additional procedures:

1. Update neighbourhood procedure: it evaluates and updates the neighbourhood and neighbours of each geographic object.
2. Geometric transformation procedure: it executes the change of shape on each geographic object where the influence of its neighbours is higher than a threshold value that represents the resistance of a geographic object to change state for the state of its neighbour.
3. Simplify space procedure: it joins adjacent polygons having the same state and behavior, reducing the number of geographic objects that compose the geographic space.

Update neighbourhood procedure

As mentioned in the section 2.2 (implementation), each geographic object has two attributes that define the neighbourhood size (external buffer size) and the neighbours' list, respectively. In the neighbours' list, the geographic object stores information about all its neighbours: identification, state, distance between the centroid of the geographic object and the centroid of the neighbour object, area of the neighbour within the neighbourhood, neighbour's influence on the geographic object, and area of the object that must change for its neighbour's state. The procedure builds an external buffer around each geographic object and calculates which other objects are located inside this buffer. To check if a geographical object is located inside the buffer, a condition is evaluated before executing the intersection between the objects. This condition consists in calculating the coordinates of the minimum bounding box around the buffer and the coordinates of the minimum bounding box around the neighbour. If this evaluation indicates an intersection of the two minimum bounding boxes, then the neighbour is retained. Otherwise, it is discarded.

If a geographic object is found inside the buffer, the distance between the centroids, the intersection area of the neighbour object and the neighbourhood, the influence, and the area to change are calculated, and all this information is stored in the neighbours' list of the geographic object. In addition, the geographic object is stored as a neighbour of its neighbours, but only the identification, state and distance between centroids are kept. The other information about the intersection area, the influence and the area to change are updated when the neighbour is examined as a central geographic object.

Two conditions are evaluated before calculating the area of a geographic object to change for the state of its neighbour:

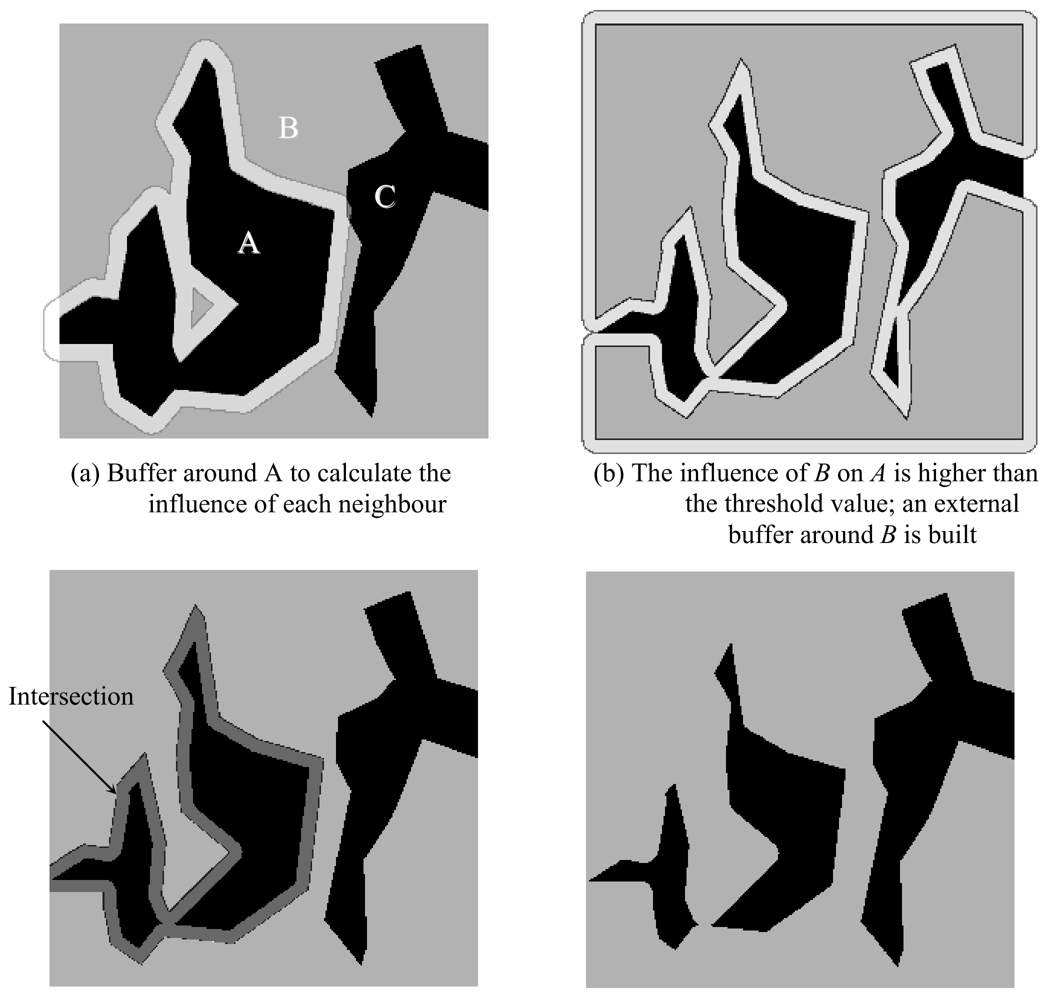
1. If two geographical objects A and B are neighbours and A exerts an influence on B, and B exerts an influence on A, only the highest influence between the two objects is considered as producing a geometric transformation;
2. If this influence is higher than a threshold value, the area to change is calculated according to the transition function; otherwise the area to change is assigned the value 0.

This updated implementation examines all geographic objects before executing any geometric transformation.

Geometric transformation procedure

The geometrical transformation procedure reduces the area of geographic objects (calculated by the transition function) from the region nearest to the corresponding neighbour. The reduced area creates a new polygon that is added to the corresponding neighbour.

To overcome the problems present in the first version of VecGCA, a new implementation is proposed, which consists in creating a buffer around the neighbour that exerts an influence higher than the threshold value, and intersects it with the geographic object (Figure 3.1).



(a) Buffer around A to calculate the influence of each neighbour

(b) The influence of *B* on *A* is higher than the threshold value; an external buffer around *B* is built

(c) The buffer around *B* is intersected with *A*

(d) The intersection area is removed from *A* and joined to *B*

Figure 3.1. Improved implementation of the geometrical transformation procedure

The intersection area is removed from the geographic object to create a new geographic object that is subsequently joined to the corresponding neighbour in the simplify space procedure (described below). The buffer size is automatically adjusted to guarantee that the intersection area corresponds to at least 95% of the area calculated by the transition function. The procedure is executed for each neighbour whose influence is higher than the threshold value, starting with the neighbour having the highest influence. This implementation is conceptually more elegant; it is expected that it will considerably reduce the computation time and remove the staircase effect that was present in the first version of the model.

Simplify space procedure

When all the geometric transformations are executed, the simplify space procedure is called. This procedure checks the whole geographic space and joins adjacent geographic objects with the same state and behavior, producing new geographic objects whose area is the sum of those adjacent polygons.

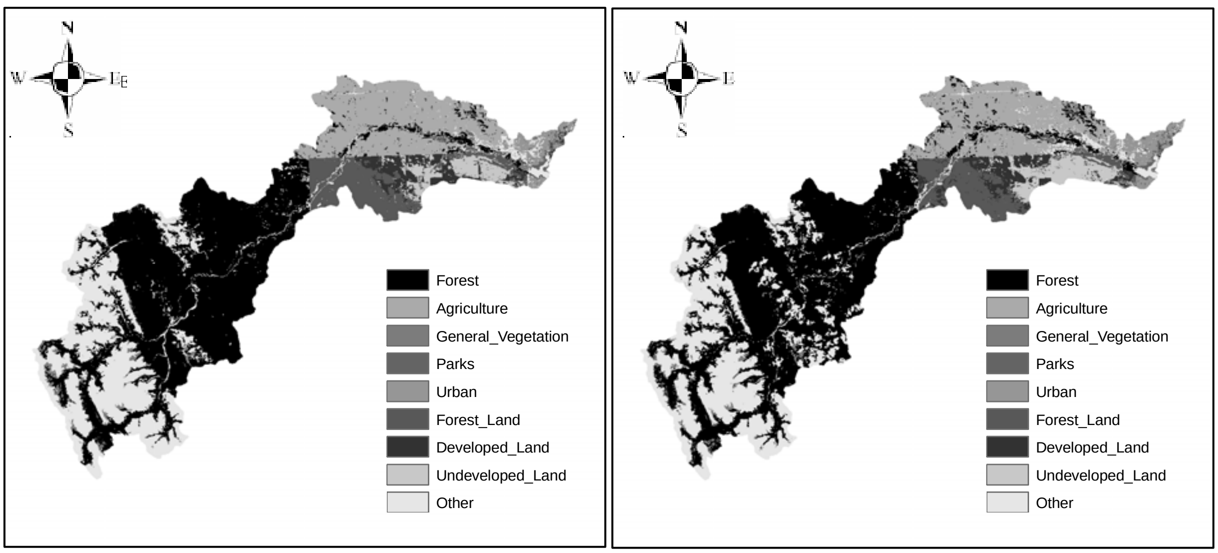
3.2 Sensitivity analysis of VecGCA to the neighbourhood size

VecGCA overcomes the cell size sensitivity of the raster-based CA models, but its sensitivity to the neighbourhood configuration has not been evaluated. This is important since the neighbourhood size is used to define the influence and the transition functions of the model.

Two land-use change models in two regions of different complexity (different polygon distributions, different aerial extensions and numbers of polygons, and different numbers of land-use classes), in southern Quebec and in southern Alberta, in Canada, were developed in order to test the improved implementation of the VecGCA geometric transformation procedure and to assess its performance. In addition, a sensitivity analysis to the neighbourhood configuration is conducted to determine the impact on the simulation outcomes of the VecGCA model. While the use of a vector-based approach overcomes the sensitivity to cell size, our hypothesis is that it does not address the possible sensitivity to neighbourhood configuration. This aspect needs to be evaluated before proper solutions can be investigated.

3.2.1 Study areas

The first study area is the Maskoutains region, described in the section 2.3.1. The second study area is the Elbow river watershed. This area comprises all the land area drained by the Elbow River and its tributaries, which covers approximately 1238 km^2. In this region, a greater variety of land uses/land covers can be observed: forest, agriculture, vegetated land (shrubs and other vegetation different from agricultural land), construction and open area, urban land, a portion of the Alberta's Rocky Mountains, a portion of the Tsuu Tina Nation reserve, and others. Two land-use/land-cover maps produced from Landsat Thematic Mapper images acquired in the summer of 1996 and 2001 are used in this study (Figure 3.2).



(a) (b)

Figure 3.2 Land-use maps of the Elbow river watershed: (a) 1996, and (b) 2001

In 1999, the landscape in the Maskoutains region can be defined as little fragmented; it was composed of 5247 polygons, with a mean area of 0.250 km^2 and a standard deviation of 14.24. 78.50% of the total area is represented by one polygon (agricultural area) that covers 1030.71 km^2. The landscape of the Elbow river watershed is more complex. In

1996, it was composed of 7195 polygons of smaller extent compared to the Maskoutains region (mean area of 0.172 km^2 and standard deviation of 6.67).

3.2.2 The land-use/land-cover VecGCA model

The model used to simulate the dynamics in both study areas is the same as described in the section 2.3.2. Space is defined as a collection of patches of different land uses/land covers, where each patch corresponds to a polygon of the vector land-use/land-cover map of the study area. The initial conditions were determined by the maps of 1999 and 1996 for the Maskoutains region and the Elbow river watershed, respectively.

The transition probabilities for the Elbow river watershed for a temporal resolution of five years were calculated from the comparison of the two land-use/land-cover maps of 1996 and 2001, according to the procedure described in the section 2.3.2.

3.2.3. Model simulation

To determine the performance of the VecGCA model, one simulation in each study area was run over ten time units and a neighbourhood size of 30 m. The computation time for the three procedures (update neighbourhood, geometrical transformation and simplify space) called from the simulation procedure were calculated. All simulations were performed on a DELL Dimension DXPO51, Intel ® Pentium ® Dual CPU (3.20 GHz and 3.19 GHz), 2.00 GB of RAM.

To test the sensitivity of the model to the neighbourhood configuration, four simulations for each study area were performed and their results were compared. Each simulation is associated to a different neighbourhood size: 30 m, which is the original resolution of the land-use/land-cover maps; 10 m, a small neighbourhood size which is 1/3 of the original resolution; and two larger neighbourhood sizes (60 m and 120 m), corresponding respectively to two and four times the original resolution of the land-use/land-cover maps. All the simulations were performed from 1999 to 2002 for the Maskoutains region and from 1996 to 2001 for the Elbow river watershed and compared to the land-use/land-cover maps of the two areas for the years 2002 and 2001, respectively. The temporal resolution was one year.

3.2.4 Results

The first section presents the performance assessment of the model when used to simulate land-use/land-cover changes in the two study areas. The second section describes the simulation outcomes of VecGCA for the Maskoutains region and the Elbow river watershed obtained with different neighbourhood sizes.

Performance improvement of the model

Two aspects were evaluated to determine the performance of the model: the adequate representation of the entities composing the landscape and the computation time.

Figure 3.3 presents a section of the 1999 land-use map of the Maskoutains region and the simulation outcomes obtained for 2001 using the first and the improved implementations of VecGCA. A first observation is that although both models start with the same initial conditions and produce a similar spatial distribution, the first implementation produces a staircase effect on the polygon’s borders due to the rasterization process used in the geometrical transformation procedure. This rasterization process also introduces some error in the boundary’s definition of the entities composing the study area due to the arbitrary selection of the cell size for the rasterization. In comparison, the improved implementation generates a spatial distribution of well-defined polygons that preserves the border definition as observable in the initial conditions, removing the staircase effect and the error introduced by the arbitrary selection of the cell size used in the rasterization process.

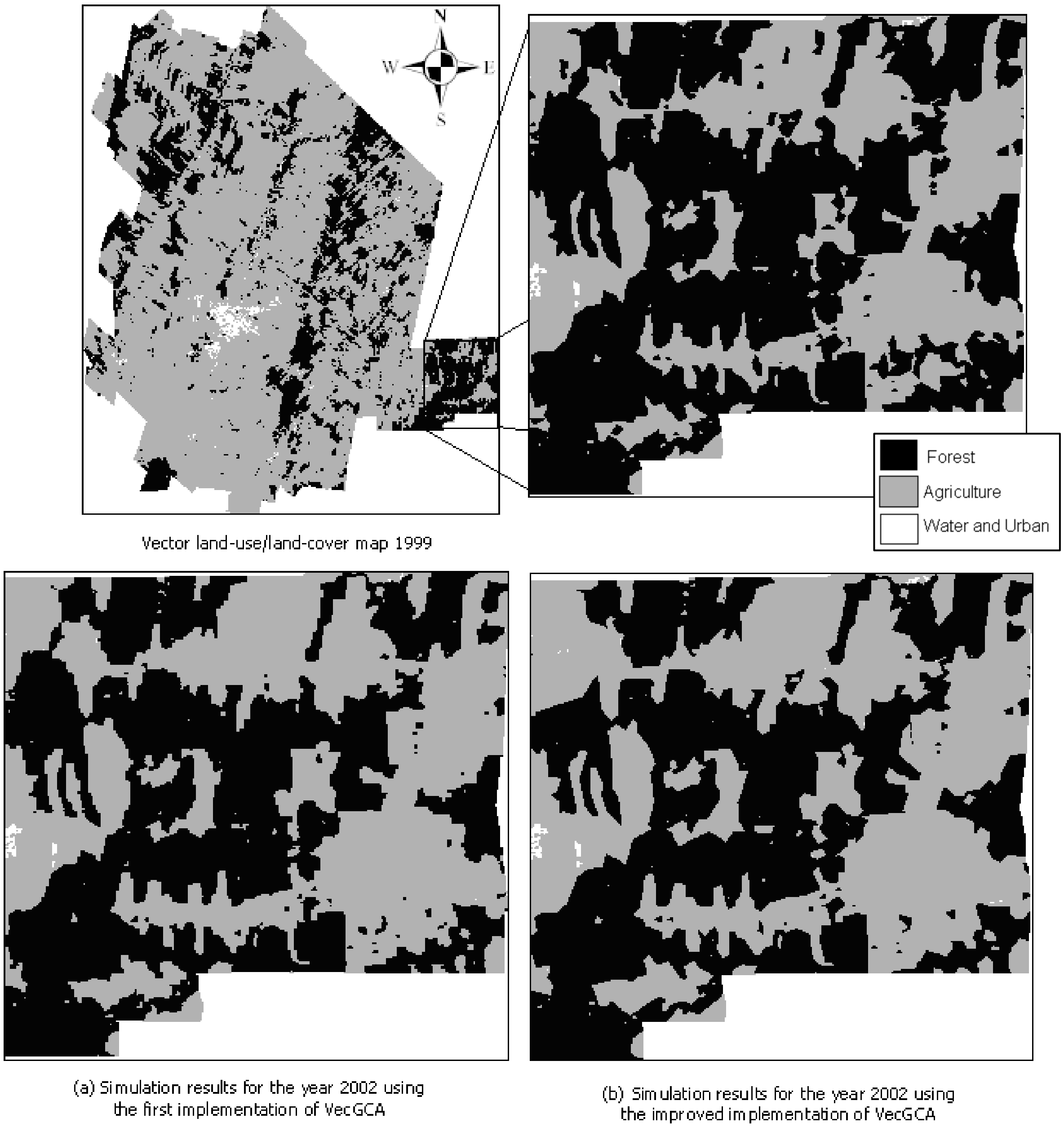


Figure 3.3. The 1999 vector land-use/land-cover map of the Maskoutains sub-region and the spatial distribution generated by VecGCA for the year 2002 using the first and the improved implementations of the model

In addition, a considerable reduction in the computation time between both implementations has been achieved, from 11.87 hours for one iteration to 13.14 hours for ten iterations in the Maskoutains region. This reduction of time can be explained by the optimization of the update neighbourhood procedure and the new implementation of the geometric transformation procedure that remove all operations of rasterization and vectorization.

When comparing the new implementation for the two study areas, the total computation time of the model (for ten iterations) is approximately the same, namely 13.14 hours for the Maskoutains region and 13.32 hours for the Elbow river watershed, with an average time of 1.31 hour per iteration in both models. However, the computation time for each procedure is different in each study area (Table 3.1). An analysis of these results indicates that the computation time of the VecGCA model depends on the number of possible changes of state and the fragmentation of the study area. A number of 36 possible land-use/land-cover changes can be found in the Elbow river watershed compared to only two in the Maskoutains region. Therefore there are more possible changes of shape to be executed in the Elbow river watershed and the average computation time for the geometrical transformation procedure is longer in this region than it is in the Maskoutains region (59.5 min compared to 21.0 min).

The update neighbourhood and simplify space procedures execute many geometrical operations of intersection and join among adjacent and near polygons. Therefore for regions composed of a large matrix containing numerous small patches the computation time associated to these procedures is expected to be generally high. This is the case for the Maskoutains region, where 78.50% of the total area is covered by one large polygon of agricultural area. Since the landscape in the Elbow river watershed is more fragmented, the computation time for these two procedures is shorter in comparison to the computation time for the Maskoutains region (10.9 and 9.5 min vs. 24.6 and 33.2 min) (Table 3.1).

Table 3.1. Average computation time of the procedures called in the new implementation of the model

Procedure	**Average computation time (minutes)**	
	Maskoutains region	**Elbow river watershed**
Update neighbourhood	24.6	10.9
Geometrical transformation	21.0	59.5
Simplify space	33.2	9.5

Sensitivity to the neighbourhood configuration

Simulations were performed for each study area with neighbourhood sizes of 10 m, 30 m, 60 m and 120 m. In the Maskoutains region, the results reveal that when using 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/land-cover map. When using the neighbourhood sizes of 60 m and 120 m, the difference between the simulated land-use/land-cover proportions for 2002 and the calculated proportions from the 2002 map is higher and might exceed 8% (Table 3.2).

Table 3.2. Proportion of land-use/land-cover (%) in the Maskoutains region using different neighbourhood sizes

		Simulation outcomes				2002 simulation outcome – 2002 land-use map
		1999	**2000**	**2001**	**2002**	
Forest	Neighbourhood 10 m	16.57	16.38	16.30	16.22	1.39
	Neighbourhood 30 m	16.57	16.03	15.44	14.59	-0.24
	Neighbourhood 60 m	16.57	16.02	14.90	12.16	-2.67
	Neighbourhood 120 m	16.57	12.40	9.43	6.37	-8.46
	Reference map	16.57	-	-	14.83	0
Agriculture	Neighbourhood 10 m	80.70	80.89	80.98	81.05	-1.4
	Neighbourhood 30 m	80.70	81.25	81.84	82.68	0.23
	Neighbourhood 60 m	80.70	81.25	82.38	85.11	2.66
	Neighbourhood 120 m	80.70	84.88	87.84	90.91	8.46
	Reference map	80.70	-	-	82.45	0

The neighbourhood size has a less pronounced impact on the simulation outcomes in the Elbow river watershed (Table 3.3). The largest difference (2.08 percentage points) is found for the agricultural land-use class using a neighbourhood size of 120 m. For all other classes, the simulated and calculated proportions differ by less than 1.5 percentages points when using different neighbourhood sizes. These results can be explained by the fact that the influence function (Equation 2.4) and the transition function (Equation 2.5) are directly proportional to the neighbours' area within the neighbourhood. The neighbours' area varies with the neighbourhood size and the landscape configuration. In the Maskoutains region, the majority of the objects have only one neighbour; they are small forested patches located inside a large matrix of agricultural land (Figure 3.4). The influence of the agriculture matrix on the small forested patches and the area that changes from forest to agriculture (calculated from the transition function) increase when the neighbourhood size increases.

Table 3.3. Proportion of land-use/land-cover (%) in the Elbow river watershed using different neighbourhood sizes

		1996	**1997**	**1998**	**1999**	**2000**	**2001**	**2001 simulation outcome – 2001 land-use map**
Forest	Neigh. 10 m	44.45	44.62	44.58	44.44	44.42	44.39	0.04
	Neigh. 30 m	44.45	44.49	44.36	44.15	44.11	43.46	-0.89
	Neigh. 60 m	44.45	44.97	44.84	44.72	43.62	43.58	-0.77
	Neigh. 120 m	44.45	45.53	45.35	45.08	44.86	43.53	-0.82
	Reference map	44.45	-	-	-	-	44.35	0
Agriculture	Neigh. 10 m	15.39	15.33	15.28	15.26	15.24	15.21	1.73
	Neigh. 30 m	15.39	15.41	15.30	15.40	15.36	15.35	1.87
	Neigh. 60 m	15.39	15.58	15.51	15.40	15.35	15.32	1.84
	Neigh. 120 m	15.39	15.74	15.77	15.60	15.56	15.56	2.08
	Reference map	15.39	-	-	-	-	13.48	0

Vegetation	Neigh. 10 m	1.98	1.85	1.82	1.82	1.80	1.79	0.11
	Neigh. 30 m	1.98	1.61	1.48	1.45	1.43	1.54	-0.14
	Neigh. 60 m	1.98	1.32	1.19	1.18	1.39	1.36	-0.32
	Neigh. 120 m	1.98	0.82	0.48	0.28	0.25	0.33	-1.35
	Reference map	1.98	-	-	-	-	1.68	0
Parks	Neigh. 10 m	0.87	0.81	0.78	0.75	0.73	0.74	-0.08
	Neigh. 30 m	0.87	0.74	0.67	0.62	0.61	0.60	-0.22
	Neigh. 60 m	0.87	0.72	0.67	0.66	0.64	0.56	-0.26
	Neigh. 120 m	0.87	0.71	0.66	0.62	0.62	0.61	-0.21
	Reference map	0.87	-	-	-	-	0.82	0
Urban	Neigh. 10 m	1.56	1.60	1.61	1.63	1.63	1.67	-0.63
	Neigh. 30 m	1.56	1.66	1.69	1.71	1.72	1.72	-0.58
	Neigh. 60 m	1.56	1.67	1.69	1.69	1.70	1.75	-0.55
	Neigh. 120 m	1.56	1.66	1.68	1.70	1.70	1.70	-0.6
	Reference map	1.56	-	-	-	-	2.30	0
Forest in Tsu Tina Nation reserve	Neigh. 10 m	6.80	6.78	6.75	6.74	6.72	6.73	0.86
	Neigh. 30 m	6.80	6.79	6.66	6.61	6.60	6.59	0.72
	Neigh. 60 m	6.80	6.79	6.71	6.64	6.63	6.62	0.75
	Neigh. 120 m	6.80	6.81	6.77	6.72	6.50	6.46	0.59
	Reference map	6.80	-	-	-	-	5.87	0
Developed land in Tsu Tina Nation reserve	Neigh. 10 m	3.04	3.03	3.01	2.99	2.99	2.97	-0.25
	Neigh. 30 m	3.04	3.01	3.07	3.07	3.06	3.05	-0.17
	Neigh. 60 m	3.04	3.03	2.95	2.97	2.96	2.97	-0.25
	Neigh. 120 m	3.04	3.00	2.94	2.94	2.78	2.64	-0.58
	Reference map	3.04	-	-	-	-	3.22	0

Undeveloped land in Tsu Tina Nation reserve	Neigh. 10 m	2.88	2.92	2.96	2.99	3.01	3.05	-0.47
	Neigh. 30 m	2.88	2.92	3.00	3.05	3.07	3.09	-0.43
	Neigh. 60 m	2.88	2.91	3.07	3.11	3.13	3.14	-0.38
	Neigh. 120 m	2.88	2.92	3.01	3.07	3.44	3.63	0.11
	Reference map	2.88	-	-	-	-	3.52	0

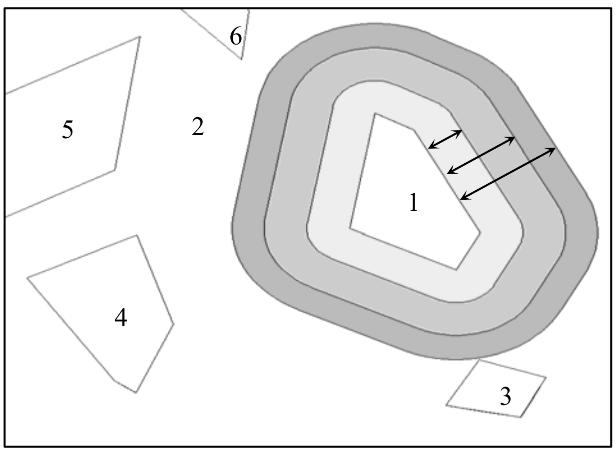


Figure 3.4. Schematic representation of the landscape configuration of the Maskoutains region where the objects have only one neighbour for different neighbourhood sizes

The landscape configuration for the Elbow river watershed is different. Each geographic object has several neighbours of different states where an increase of the neighbourhood size can produce an increase of the neighbours' area within the neighbourhood as well as an increase in the number of neighbours (Figure 3.5). The increase of the neighbours' area is less important than the one produced in a landscape composed of a large matrix containing numerous small objects, such as in the Maskoutains region. Consequently, the increase of influence and the area to change from the object' state to the neighbour's state is often not significant when the neighbourhood size increases. When the number of neighbours increases, the influence and the area to change for the neighbours present in the neighbourhood do not increase significantly due to the fact that these neighbours are distant geographic objects separated by other objects. Therefore, in this landscape configuration the simulation outcomes are less sensitive to the neighbourhood size.

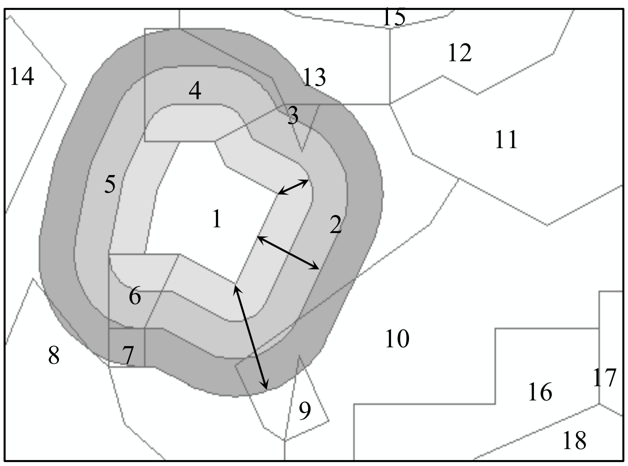


Figure 3.5. Schematic representation of the Elbow river landscape configuration where the objects have several neighbours; when the neighbourhood size increases the number of neighbours and the neighbours' area within the neighbourhood also increase

Additionally, in both landscape configurations, coarser neighbourhood sizes produce a landscape that is less fragmented because small geographic objects (forested patches) tend to disappear quickly, absorbed by the larger geographic objects of agricultural land (Figures 3.6 and 3.7).

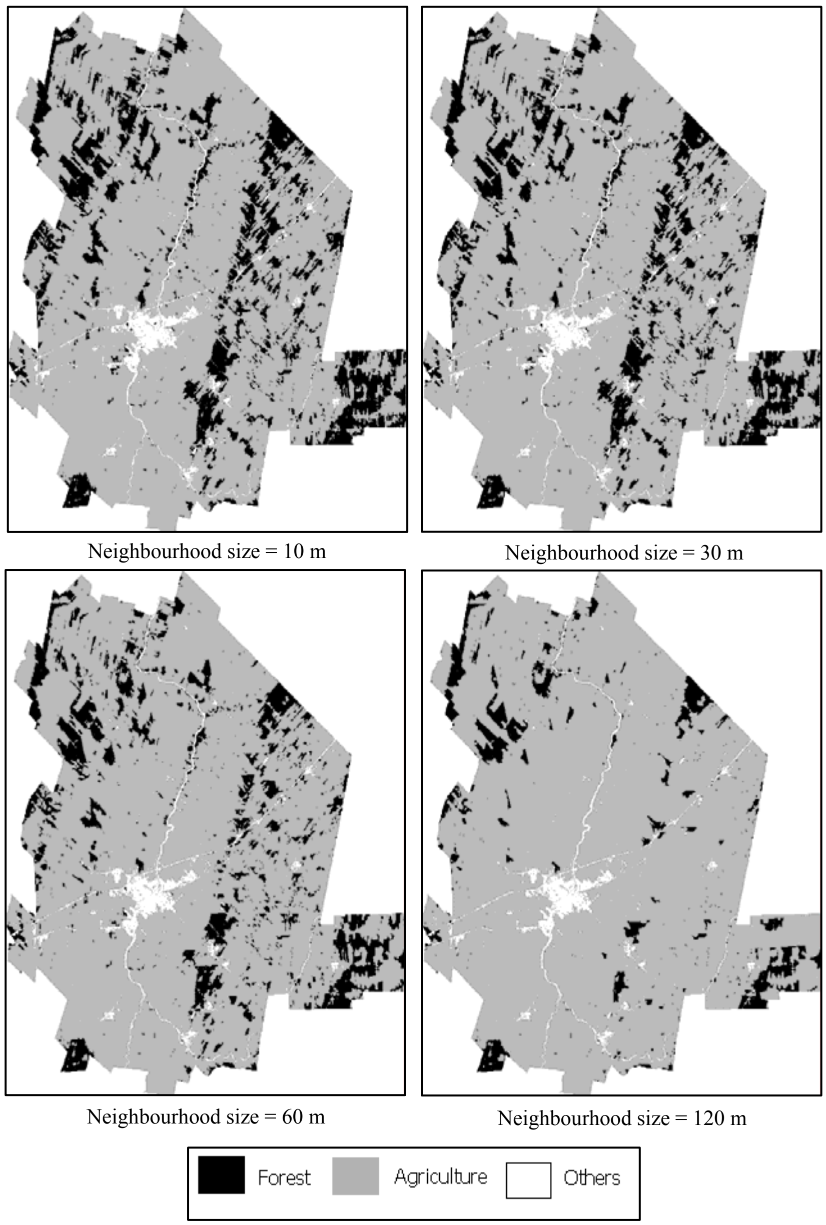


Figure 3.6. Simulation outcomes for the Maskoutains region for 2002 using different neighbourhood sizes

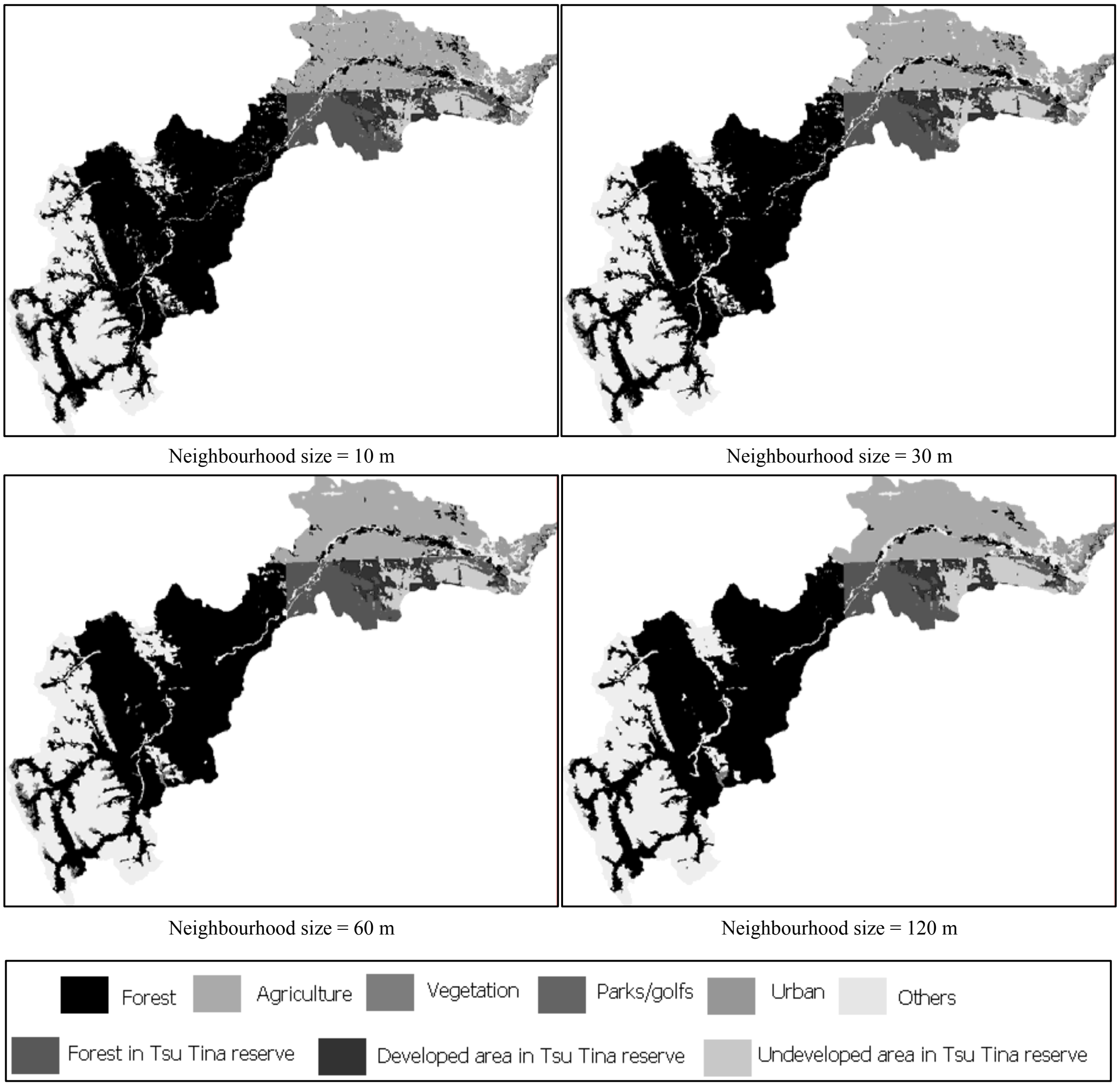


Figure 3.7. Simulation outcomes for the Elbow river watershed for 2001 using different neighbourhood sizes

3.3. Discussion

The results show that the improved version of VecGCA considerably reduces the computation time; it also removes the problems introduced by the rasterization process used in the geometric transformation procedure, that is the staircase effect in the polygon's border and the arbitrary selection of the resolution used in the rasterization. However, the computation time remains long when compared to the simulation time for a raster-based CA model. For example 13.14 hours for ten iterations are required by the Maskoutains region VecGCA model versus approximately two hours for the same simulation using a 100 m raster-based CA model.

Nevertheless, if we consider the time needed for the calibration and sensitivity analysis to cell size of a raster-based CA model, the computation time of VecGCA remains reasonable. For example, Clark and Gaydos (1998) reported that the calibration of SLEUTH to study the urban growth in San Francisco, California, required hundreds of hours of CPU time. In a hypothetical example where the time required to calibrate a simple raster-based CA model is one hour and the simulation time is two hours for ten iterations, if a sensitivity analysis necessitates testing 25 scenarios (5 cell sizes and 5 neighbourhood configurations), the total computation time will be 75 hours for that model.

Using VecGCA, conducting a sensitivity analysis to cell size is not necessary. The calibration process includes testing the influence and transition functions to guarantee that they well capture the dynamics in the study area. This is done by executing the model for a few iterations and comparing the results with the available dataset for the study area. In this project, to calibrate VecGCA for the Maskoutains region, simulations were performed from 1999 to 2002 using a time step of three years, and the results were compared with the 2002 land-uses map; the time required for the calibration of this region was approximately three hours and the total computation time was approximately 17 hours. Similar times were required to calibrate and run the Elbow river watershed VecGCA model. The calibration was done from 1996 to 2001 with a temporal resolution of five years and the results were compared with the 2001 land-use map.

Another aspect evaluated in this chapter is the sensitivity of VecGCA to the neighbourhood configuration. The results revealed that the model is sensitive to the neighbourhood size and this sensitivity depends on the landscape configuration of the study area. The problem is to define how to control or remove this sensitivity. Two possible solutions are envisioned to address this problem:

1. The definition of the influence and transition functions independently of the neighbours' area within the neighbourhood. In this case, the neighbourhood is used

only to determine what are the neighbours of a central object. The increase or decrease of the neighbourhood size can increase or decrease the number of neighbours, but it does not modify the influence value of a neighbour or its area to change calculated in the transition function.

2. A dynamic neighbourhood adapted to each geographic object where the neighbours are defined by no-geometric properties. In this neighbourhood, there are no limitations of distance; the neighbourhood is the whole geographic space.

Our hypothesis is that the second option is the best solution, because it removes the definition of fixed distance and considers all possible distances in only one neighbourhood definition. In the next chapter, a dynamic neighbourhood is introduced in the VecGCA model in order to remove its sensitivity to the neighbourhood configuration.

CHAPTER 4

DYNAMIC NEIGHBOURHOOD IN VecGCA

This chapter describes the characteristics of a new neighbourhood definition proposed to overcome the neighbourhood size sensitivity present in the previous version of VecGCA. The new neighbourhood involves the redefinition of the influence and transition functions of VecGCA. A test of the model to simulate land-use changes in two different study areas and the comparison with the previous version of VecGCA are presented.

4.1 Dynamic neighbourhood definition and update of VecGCA

The dynamic neighbourhood proposed in this research is a neighbourhood that changes through time; there is no distance or fixed area that delineates it and it is specific to each geographic object. The neighbourhood includes the whole geographic space, and the neighbourhood relationships between two objects are defined according to the properties of each geographic object. Objects *a* and *b* are neighbours if they are separated by 0, 1 or more objects whose states are favourable to the change of state from *a* to *b*. A *n x m* binary matrix describes if a state *X* is favourable to the transition from the state *Y* to *Z*, where *n* is the number of possible states of a geographic object and *m* is the number of possible transitions in the model. In this matrix, the 1 values indicate that a state *X* is favourable to a transition and the 0 values indicate the opposite.

For example, let us suppose a geographic space as defined in Figure 4.1, composed of six geographic objects that represent patches of different land uses/land covers (U = undeveloped land, D = developed land, P = park, C = commercial land and W = water). Let us suppose that the possible transitions are U to D, U to C, U to P, P to D, and P to C. Let us suppose that the matrix *M* represents the favourable states to the transitions in the model.

$$M = \begin{array}{c} \\ \mathrm{U} \rightarrow \mathrm{D} \\ \mathrm{U} \rightarrow \mathrm{C} \\ \mathrm{U} \rightarrow \mathrm{P} \\ \mathrm{P} \rightarrow \mathrm{D} \\ \mathrm{P} \rightarrow \mathrm{C} \end{array} \begin{array}{c} \begin{array}{ccccc} \mathrm{U} & \mathrm{D} & \mathrm{C} & \mathrm{P} & \mathrm{W} \end{array} \\ \begin{bmatrix} 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \end{bmatrix} \end{array}$$

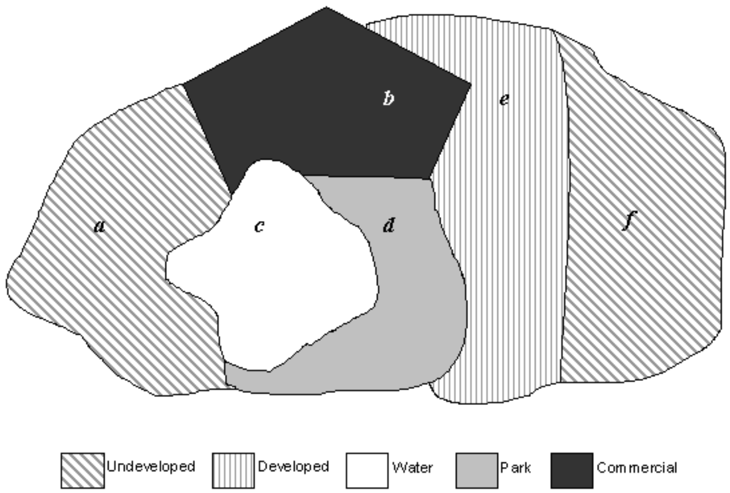


Figure 4.1. Geographic space composed of six geographic objects. The geographic object *a* has four neighbours: the adjacent objects *b*, c and *d*, and the non-adjacent object *e*.

This matrix indicates for example, that commercial land is favourable to the transition from undeveloped land to developed land, from undeveloped land to commercial land and from park to developed land. Using this matrix, we can say that the neighbours of object *a* in Figure 4.1 are the adjacent objects *b*, *c*, *d* and the non-adjacent object *e*. *e* is neighbour of *a* for two reasons: first because *e* and *a* are separated by *b* that is a commercial land and this state is favourable to the transition from undeveloped to developed land; second, because *e* and *a* are separated by the objects *c* and *d* that are in the states water and park, respectively, and these states are favourable to the transition from undeveloped to developed land. However, we cannot say that *a* is neighbour of *e*, because the transition from developed to undeveloped land is not possible. This matrix is obtained from the analysis of historical spatial data that reveals when a change of state of a geographical object has occurred due to the influence of its non-adjacent neighbours and what are the states of these intermediate objects. The procedure to calculate this matrix is described in the methodology section.

In the previous version of the VecGCA model, each neighbour exerts an influence on the central object producing its change of shape if this influence is higher than a threshold value (λ) that represents the resistance of the geographic object to change state for the state of its neighbour. This influence value is constant on the whole surface of the central object. The transition function quantifies the area of the central object that changes its state for the neighbour's state.

With the dynamic neighbourhood definition, the influence value is variable on the surface of the central object. The influence value increases when the neighbour is closer to the central object; the maximum value (g_{max}) is obtained in the object's border and decreases inside the object. Additionally, two considerations remain from the definition presented in the sections 2.1 and 2.3.3: the influence function must be limited between 0 and 1, and the influence function must be defined in function of the variables that determine the pressure of a geographic object on another.

According to the results obtained in the previous version of the model, an exponential function (Equation 2.4) can represent the influence function into the model. However, that function must be redefined in order to include the new considerations of a dynamic neighbourhood. A combined function is proposed to define the influence function, where the influence outside the geographic object is represented as the exponential function used in the previous version of the model, and an inverse exponential function defines the influence value inside the geographic object (Equation 4.1). Figure 4.2 presents the graph of the new proposed influence function. The parameter α is defined as a function that depends on the factors that determine the influence of a neighbour to the central object: the transition probability from the neighbour's state and the central object's state, the common border between the neighbour and the central object (if they are adjacent) or the common border between the neighbour and the object that connects it to the central object, and the minimum distance between the neighbour and the central object.

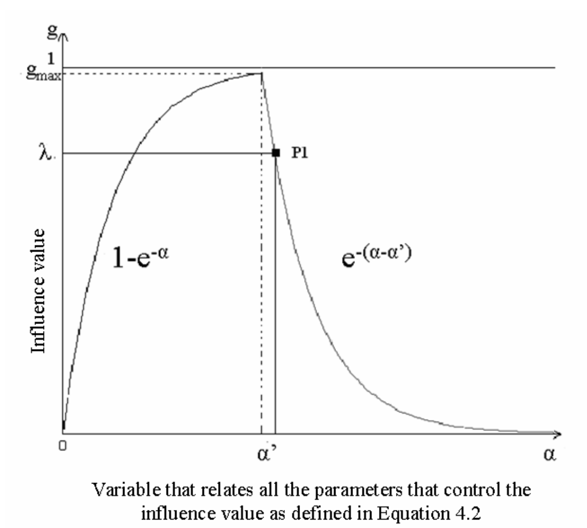


Figure 4.2. Influence function used to implement the dynamic neighbourhood

$$g_{ab} = \begin{cases} 1 - e^{-\alpha_{ab}} & \text{if} \quad 0 \le \alpha \le \alpha' \\ e^{-(\alpha_{ab} - \alpha_{ab}')} & \text{if } \alpha > \alpha' \end{cases} \tag{4.1}$$

where

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

α_{ab} is defined in Equation 4.2 and

α_{ab}' is the value α_{ab} on the border.

$$\alpha_{ab} = P_{b \to a}{}^{1/2} \left(\frac{A_a}{A_b} + \frac{CB}{B_b} + e^{-d\,\min} \right) \tag{4.2}$$

where

$P_{b \to a}$ is the transition probability from the *b*'s state to the *a*'s state,

A_a is *a*'s area,

A_b is *b*'s area,

CB is the common border between *a* and *b*,

B_b is *b*'s perimeter, and

d_{min} is the minimum distance between *a* and *b.*

If *a* and *b* are not adjacent neighbours, *CB* is the common border between *a* and another object adjacent to *a* that was used in the analysis of the favourable states to the transition from *a* to *b*, and B_b is replaced by the perimeter of this other object.

As A_a / A_b can be very large if a is larger than the central object, a factor is introduced to regulate this value between 0 and 1. Equation 4.2 is rewritten as Equation 4.3.

$$\alpha_{ab} = P_{b \to a}{}^{1/2} \left(\frac{\frac{A_a}{A_b}}{\frac{A_{\max}}{A_{\min}}} + \frac{CB}{B_b} + e^{-d\min} \right) \tag{4.3}$$

$$0 \le \alpha \le 3$$

where

A_{max} is the largest object's area within the whole geographic space, and

A_{min} is the smallest object's area.

If the influence on the object's border is higher than λ, then the geometrical transformation procedure is performed. The area that changes is not specified in the transition function as in the previous version. Instead, the transition function determines exactly the buffer size that is used in the geometrical transformation procedure to take a portion of the central object and add it to the corresponding neighbour. This buffer size is calculated from the point where the influence value inside the central object is equal to λ (corresponding to P1 in Figure 4.2). Therefore, the transition function is derived from the influence function. The transition function calculates the value of d_{min} for which the influence value is equal to the threshold value (λ) when α_{ab} is higher than α_{ab}', that is the influence inside the object. From Equation 4.1, α_{ab} can be defined by Equation 4.4, and by replacing (4.3) in (4.4)

$$\alpha_{ab} = \alpha_{ab}' - Ln(\lambda) \tag{4.4}$$

$$P_{b \to a}^{1/2} \left(\frac{\frac{A_a}{A_b}}{\frac{A_{\max}}{A_{\min}}} + \frac{CB}{B_b} + e^{-d\min} \right) = \alpha_{ab}' - Ln(\lambda) \tag{4.5}$$

d_{min} can be found from Equation 4.5 and defines the transition function (Equation 4.6).

$$f_{ab} = -Ln\left[\frac{1}{P_{b \to a}^{1/2}} \left(\alpha_{ab}' - Ln(\lambda) \right) - \frac{\frac{A_a}{A_b}}{\frac{A_{\max}}{A_{\min}}} - \frac{CB}{B_b} \right] \tag{4.6}$$

where

> f_{ab} is the transition function that determines the size of the buffer that is built around *a* to take a portion of *b*.

To clarify the transition function concept, Figure 4.3 presents a hypothetical example where the transition function of a geographic object is calculated. Let us suppose a geographic space composed of four geographic objects *a*, *b*, c and *d*. Let us suppose that *b*, *c* and *d* exert an influence on *a* that is higher than the threshold values. Therefore the transition function is calculated for *bc*, *ca* and *da* to determine the buffer size that must be built around *c*, *c* and *d* to take a portion of *a*. For *b*, the buffer size is defined by f_{ba}, calculated from the Equation 4.6, and represents the distance from any point on the border of *a*, because *a* and *b* are adjacent, to a point in its interior where $g_{ba} = \lambda_{ba}$. For *c* and *d*, the buffer size is defined by f_{ca} and f_{da}, respectively. They are also calculated from Equation 4.6 and represent the distances from the closest point of *c* to *a* to a point in the interior of *a* where $g_{ca} = \lambda_{ca}$, and from the closest point of *d* to *a* to a point in the interior of *a* where $g_{da} = \lambda_{da}$.

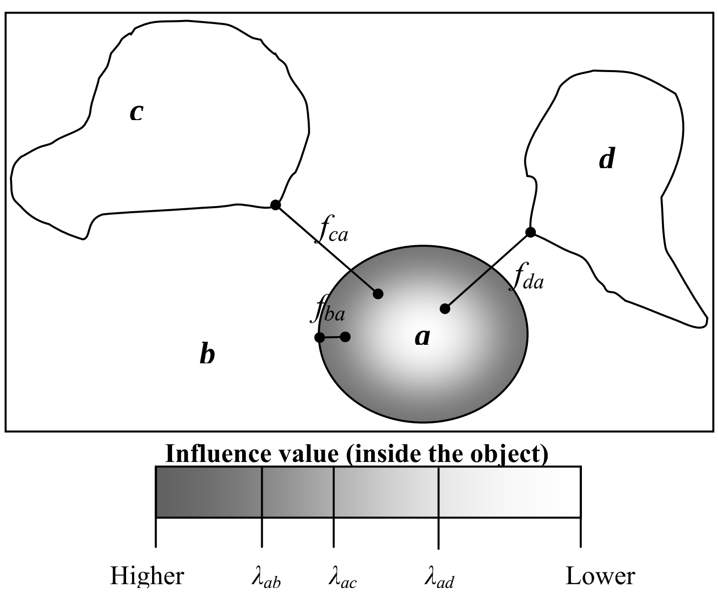


Figure 4.3. Schematic representation of the distance calculated from the transition function that defines the buffer size to be built around each neighbour to take a portion of a central object (geometric transformation procedure described in the section 3.1.1).

4.2 Land-use change VecGCA models using a dynamic neighbourhood

To test the dynamic neighbourhood and to determine if it overcomes the sensitivity to the neighbourhood size that is present in the previous version of VecGCA, two land-use VecGCA models have been built for two regions of varying landscape configuration in Canada. The results were compared with the ones obtained using the previous version of VecGCA.

4.2.1 Study areas

The first study area is the Maskoutains region described in the section 2.3.1. The second study area is a sub-region of the Elbow river watershed, located in Southwest Alberta, Canada, which covers approximately 731 km^2. The subregion was selected from the study area described in the section 3.2.1, where a portion corresponding to the Alberta's Rocky Mountains was excluded because significant changes were not observed when the available data was analyzed. Three land-use maps generated from Landsat Thematic Mapper images acquired in the summer of 1996, 2001 and 2006 were available for that region. A reclassification from the land uses described in the section 3.2.1 was done to focus on the main classes: forest, agriculture, urban, water and the Tsuu Tina Nation Land. The dynamics inside the Tsuu Tina Nation Land has not been studied; therefore there are no visible changes in this area.

4.2.2 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 influence function and the transition function are given in Equations 4.1 and 4.6, respectively.

The transition probabilities and threshold values are obtained from the comparison of two land-use maps of different dates and are calculated as described in the section 3.2.2. The binary matrix that describes if a state X is favourable to the transition from the state Y to Z is obtained from the comparison of two historical vector land-use maps. This procedure checks when an object A changes, in a portion or in the totality of its surface, from the state Y to the state Z without having adjacent objects in the Z state. The procedure is looking for the closest object in the state Z; the objects that separate the object A from this closest object are considered intermediate objects, and the states of these intermediate objects are considered favourable states to the transition from Y to Z. Tables 4.1 and 4.2 present the matrix corresponding to the Maskoutains region and the eastern subregion of the Elbow river watershed, respectively.

Table 4.1. Matrix of favourable states for land-use transitions in the Maskoutains region

Transitions	Land uses			
	Forest	Agriculture	Urban	Water
F → A	0	0	0	1
A → F	0	0	0	1

Table 4.2. Matrix of favourable states for land-use transitions in the Elbow river watershed

Transitions	Land uses				
	Forest	Agriculture	Urban	Water	Reserve
F → A	0	0	1	1	0
F → U	0	1	0	1	0
A → F	0	0	1	1	0
A → U	1	0	0	1	0
U → F	0	1	0	1	0
U → A	1	0	0	0	0

4.2.3 Model simulations

Five simulations on each study area were performed to compare the results of the dynamic neighbourhood with the results obtained using the previous version of VecGCA (for four different neighbourhood sizes: 10 m, 30 m, 60 m and 120 m) and the reference land-use/land-cover maps of the two areas. The simulations were run from 1999 to 2002 for the Maskoutains region and the results were compared with the 2002 land-use/land-cover map. For the Elbow river watershed, the simulations were performed from 1996 to

2006, and the results obtained were compared with the 2001 and 2006 land-use/land-cover maps. The temporal resolution of the simulations is one year.

4.2.4 Results

When using the previous version of VecGCA in the Maskoutains region, the simulated proportion of forested and agricultural land for 2002 varies up to 10 percentage points (Table 2.4) when the neighbourhood size varies from 10 m to 120 m. For example, the proportion of forested area is 16.22% using a neighbourhood size of 10 m, in comparison to 6.37% when using 120 m as the neighbourhood size. A comparison of these results with the proportion and distribution of land uses present in the 2002 land-use map suggests that 30 m is a good neighbourhood size to simulate the dynamics in this area. A spatial overlay of the 2002 land-use map and the simulation results for 2002 reveals that when using a neighbourhood size of 10 m, 97.49 % of agricultural area generated by VecGCA coincides with the agricultural area present in the 2002 land-use map, in comparison with 89.71% when a neighbourhood size of 120 m is used (Table 4.3). For the forested area, the obtained results are opposite; the coincident proportion is smallest when the neighbourhood size is 10 m (Table 4.3). These results can be explained by the fact that when the neighbourhood size increases, small forested patches disappear due to the high influence of the agricultural area.

Table 4.3. Proportion of land uses for 2002 produced by VecGCA and percentage of coincidence of the simulation outcomes and the 2002 land-use map for the Maskoutains region using the previous version of VecGCA

		Buffer neighbourhood				2002 land-use map
		10 m	30 m	60 m	120 m	
Land-use proportion (%)	Forest	16.22	14.59	12.16	6.37	14.83
	Agriculture	81.05	82.68	85.11	90.91	82.45
% coincident with the reference map	Forest	79.02	80.61	81.46	86.45	-
	Agriculture	97.49	96.26	94.19	89.71	-

For the Elbow river watershed, the simulation outcomes were compared with the proportion of land use and spatial distribution of patches calculated from two land-use maps corresponding to 2001 and 2006. In both cases, the results obtained are similar; the proportions of agricultural and urban areas slightly increase with the neighbourhood size while it is the opposite for the proportion of forested area (Tables 4.4. and 4.5).

The proportion of forested land for 2001 using a neighbourhood size of 10 m is 44.65% in comparison to 42.54% using 120 m as the neighbourhood size (Table 4.4). For 2006, the proportion of forested area is 44.58% and 41.39% using a neighbourhood size of 10 m and 120 m respectively (Table 4.5). As mentioned is the previous chapter, these results indicate that for the Elbow river watershed the previous version of VecGCA is less sensitive to the variation of the neighbourhood size than it is in the Maskoutains region. The sensitivity varies with the landscape configuration because the influence and the transition functions are directly proportional to the neighbours' area within the neighbourhood and this area varies with the neighbourhood size and the landscape configuration.

Table 4.4. Proportion of land uses for 2001 produced by VecGCA and percentage of coincidence of the simulation outcomes and the 2001 land-use map for the Elbow river watershed using the previous version of VecGCA

		Buffer neighbourhood				**2001 land-use map**
		10 m	**30 m**	**60 m**	**120 m**	
Land-use proportion (%)	Forest	44.65	44.02	43.10	42.54	46.49
	Agriculture	25.96	26.24	26.90	26.93	23.35
	Urban	5.17	5.51	5.78	6.30	5.40
% coincident with the reference map	Forest	95.84	96.17	96.61	96.86	-
	Agriculture	86.35	85.61	84.02	83.06	-
	Urban	93.73	89.24	86.30	79.61	-

For both years 2001 and 2006, the proportion of forested, agricultural and urban area varies less than 5 percentage points when the neighbourhood size increases from 10 m to 120 m, but the best spatial distribution of patches is produced with a neighbourhood size of 10 m (Tables 4.4 and 4.5). These results suggest that 10 m is a good selection to use as neighbourhood size to simulate the dynamics of that study area.

Table 4.5. Proportion of land uses for 2006 produced by VecGCA and percentage of coincidence of the simulation outcomes and the 2006 land-use map for the Elbow river watershed using the previous version of VecGCA

		Buffer neighbourhood				**2006 land-use map**
		10 m	**30 m**	**60 m**	**120 m**	
Land-use proportion (%)	Forest	44.58	43.67	42.28	41.39	45.01
	Agriculture	25.99	26.27	27.27	27.19	24.98
	Urban	5.21	5.83	6.23	7.19	6.18
% coincident with the reference map	Forest	94.58	95.20	96.09	96.49	-
	Agriculture	88.11	87.28	85.05	80.61	-
	Urban	93.84	85.99	81.90	72.48	-

Using the dynamic neighbourhood, the results obtained for both regions reveal a good performance of the model independently of the landscape configuration. For the Maskoutains region, the proportion of forested and agricultural land differs by less than 1 percentage point of the proportion calculated from the 2002 land-use map (Table 4.6). Additionally, a spatial overlay of the simulation outcomes and the 2002 land-use map shows that the spatial distribution of patches produced by the dynamic neighbourhood corresponds to 83.60 % and 96.48 % of the spatial distribution of forested and agricultural patches, respectively that is present in the 2002 land-use map (Table 4.6).

Table 4.6. Proportion of land uses for 2002 produced by VecGCA and percentage of coincidence of the simulation outcomes and the 2002 land-use map for the Maskoutains region using the dynamic neighbourhood

		Dynamic neighbourhood	2002 land-use map
Land-use proportion (%)	Forest	14.27	14.83
	Agriculture	83.00	82.45
% coincident with the reference map	Forest	83.60	-
	Agriculture	96.48	-

For the Elbow river watershed, the simulation results obtained are very similar to the landscape configuration represented on the 2001 land-use map. The proportion of forested land for 2001 corresponds to 44.25% in comparison to 46.49% of forested land calculated from the 2001 land-use map (Table 4.7). In general, the proportion of land uses generated by VecGCA varies by less than 3 percentage points when compared to the 2001 land-use map. Additionally, the results reveal a high correspondence of the landscape generated by VecGCA using a dynamic neighbourhood and the landscape present in the 2001 land-use map. A proportion of 96.15 %, 86.17 % and 88.18 % respectively corresponds to the forested, agricultural and urban patches present in the 2001 land-use map (Table 4.7). The same analysis performed using the 2006 land-use map (Table 4.8) leads to similar results which suggests that the model captures very well the dynamics in the region.

Table 4.7. Proportion of land uses for 2001 produced by VecGCA and percentage of coincidence of the simulation outcomes and the 2001 land-use map for the Elbow river watershed using the dynamic neighbourhood

		Dynamic neighbourhood	2001 land-use map
Land-use proportion (%)	Forest	44.25	46.49
	Agriculture	25.87	23.35
	Urban	5.66	5.40
% coincident with the reference map	Forest	96.15	-
	Agriculture	86.17	-
	Urban	88.18	-

Table 4.8. Proportion of land uses for 2006 produced by VecGCA and percentage of coincidence of the simulation outcomes and the 2006 land-use map for the Elbow river watershed using the dynamic neighbourhood

		Dynamic neighbourhood	2006 land-use map
Land-use proportion (%)	Forest	44.22	45.01
	Agriculture	25.54	24.98
	Urban	6.02	6.18
% coincident with the reference map	Forest	94.85	-
	Agriculture	88.22	-
	Urban	85.10	-

4.3 Discussion

The results obtained with the implementation of a dynamic neighbourhood in VecGCA demonstrate that the model can adequately represent the dynamics in two study areas. In addition, the neighbourhood definition removes the neighbourhood size sensitivity of VecGCA because the buffer of influence associated with each geographic object has been eliminated. The neighbourhood's area is now the whole geographic space. Therefore a geographic object could be a neighbour of all other geographic objects that compose space. For example, in a geographic space composed of 100 geographic objects, a geographic object could have from zero to ninety-nine neighbours. A dynamic neighbourhood allows representing all possible neighbourhood sizes in a unique neighbourhood configuration. The neighbours of a geographic space can be adjacent or separated by a minimum distance of 10 m, 50 m, 1 km or any other distance where the limit is the extension of the geographic space.

In terms of computation time, the dynamic neighbourhood increases the number of geometric operations executed in the update neighbourhood procedure. In this procedure, the whole geographic space must be reviewed for each geographic object to determine its neighbours. In addition, the number of calls to the geometrical transformation procedure also increases, because the number of neighbours for each geographic object that can produce a change of shape could be high. For the Maskoutains region, the computation time was approximately 48 hours, including six hours of calibration (as described in Section 3.3) and 42 hours of simulation time (for three iterations from 1999 to 2002). For the Elbow river watershed model, the calibration time was approximately 8 hours (as described in Section 3.3) and 52 hours of simulation time (for ten iterations from 1996 to 2006). However, using VecGCA with a dynamic neighbourhood eliminates the computation time associated to the sensitivity analysis that should be conducted to determine the best combination of cell size and neighbourhood configuration, which is a considerable advantage.

CHAPTER 5

CONCLUSION

The objective of this research was to propose a new vector-based cellular automata model that overcomes the scale sensitivity of the classic raster-based cellular automata models and the limitations of the previous implementations of vector-based CA models. An incremental development of VecGCA model was presented. Three versions of the model were tested with real data to simulate land-use/land-cover changes in two regions of different landscape configuration in Canada and satisfactory results were reached.

The first version of VecGCA introduced the new definitions of space, neighbourhood and transition function to overcome the cell size sensitivity and to allow the change of shape of geographic objects. In this version, a procedure that encompasses a rasterization and vectorization procedure was implemented to execute the geometric transformation of geographic objects. The model was tested to simulate land-use changes in an agroforested area in southern Quebec, the Maskoutains region. The results revealed that VecGCA produces an adequate evolution of the geometry of the objects, producing realistic patterns similar to the reference land-use map. Its initial spatial distribution corresponds to the real patches of the study area. In comparison, when using a raster-based CA model, a sensitivity analysis must be conducted to determine the cell size that best represents the dynamics of the study area and to generate the initial distribution associated to this cell size. Nevertheless, the first version of VecGCA had some limitations introduced by the rasterization procedure used in the geometric transformation procedure: the use of an arbitrary cell size, and the staircase effect in the border of the object. This resulted in the loss of precision in the definition of the geographic objects in the simulation outcomes as well as the disappearance of whole objects that were too small to be represented by the chosen cell size.

A second version of the VecGCA was implemented to resolve these technical problems introduced by the rasterization process. The rasterization procedure was removed and replaced by an external buffer built around each neighbour to remove the area calculated in the transition function from a geographic object and join it to the neighbour that exerts an influence on that object. This implementation generates a more realistic representation of the polygons composing the landscape, and considerably reduces the computation time.

A sensitivity analysis to the neighbourhood size was done using the second version of VecGCA model to simulate the land-use changes in two regions of different spatial complexity. The results demonstrated that the model remains sensitive to the neighbourhood configuration and that the sensitivity depends on the landscape configuration. A dynamic neighbourhood was proposed to overcome this problem.

Finally, a third version of the model was developed to include the dynamic neighbourhood definition. In this definition, the neighbourhood relationships among objects are described semantically, the buffer of influence is removed, and the neighbourhood is not associated to a fixed distance. An object *A* is neighbour of another object *B* if they are adjacent or they are separated by other objects which states are favourable to the change of state from *A* to *B*. The principal advantage of this new neighbourhood definition is that it is independent of a fixed influence zone and it uses the whole geographic space to evaluate which geographic objects exert an influence on others to generate a geometric transformation or change of shape. The results revealed that the dynamic neighbourhood implemented in VecGCA produces spatial patterns very similar to the reference land-use maps for two study areas of different spatial complexity, which suggest that it is independent of the landscape configuration.

The final version of VecGCA model overcomes the scale sensitivity of the raster-based CA models by allowing the representation of space as a collection of geographic objects where each object corresponds to a real entity of irregular shape and size (e.g. a forest, a city, a lake), which behaviour is independent of scale, and by including a new neighbourhood definition that encompasses all possible neighbourhood configurations in a unique dynamic neighbourhood. In addition, the implementation of the evolution of the geographic objects through geometric transformations (changes in shape and size) offers a major improvement compared to the previous developed vector-based CA model.

5.1 Recommendations for future work

The first step for future work is to improve the implementation of VecGCA to reduce the computation time and ensure that VecGCA becomes an attractive and useful tool to simulate land-use/land-cover changes or other spatio-temporal phenomena that imply geometric transformations of objects. Two options are evaluated:

1. Optimization of the source code. Check the source code to reduce the number of loops, calls to recursive procedures, repeated calculations of areas, intersections, differences, etc.
2. Use a spatial database management system that handles the geometry of the geographic objects. In the actual implementation of VecGCA, the geographic

> objects list is handled in RAM memory and all geometry operations are performed using the available classes in JTS library. However, using a spatial database to store the geographic objects with a spatial index on their geometry attributes should reduce the computation time involved in the geometric operations (intersection, difference and union).

VecGCA was tested to simulate the land-use/land-cover changes in two regions of varying landscape configuration in Canada. These models were defined based on transition probabilities calculated from historical data, and factors such as distance to main roads or global constraints were not considered. Future work will be conducted to calibrate VecGCA including additional parameters in the influence and transition functions (Equations 4.1, 4.2 and 4.6). A methodology will be introduced to determine the key factors that define the dynamics in the study area and how these factors can be included in the influence and the transition functions.

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APPENDIX A

PUBLICATIONS

The results of this research have been published or submitted in three scientific journals, two book chapters, and three proceedings of international conferences.

SCIENTIFIC PAPERS

Moreno, N., Ménard, A., and Marceau, D. J. (2007). VecGCA: a vector-based geographic cellular automata model allowing geometrical transformations of objects. *Environment and Planning B: Planning and Design,* vol 34, in press.

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