Université de Montréal

Modélisation par automate cellulaire de scénarios d'aménagement forestier dans une région rurale du sud du Québec

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Cette thèse intitulée :

Modélisation par automate cellulaire de scénarios d'aménagement forestier dans une région rurale du sud du Québec

Par
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RÉSUMÉ DE LA THÈSE

La municipalité régionale de comté (MRC) des Maskoutains (Québec, Canada) est un territoire majoritairement agricole au prise avec un sérieux problème de déforestation. Les boisés résiduels de cette région se fragmentent et disparaissent sous l'effet de l'intensification des pratiques agricoles. Un automate cellulaire (AC) a été élaboré pour simuler les dynamiques territoriales futures de ce paysage. Les AC sont des modèles de simulation dans lesquels l'espace est composé de cellules qui évoluent dans le temps suivant l'application de règles spécifiant comment les états des cellules réagissent aux différentes configurations de voisinage. Lorsqu'un AC représente un territoire géographique, il est caractérisé par une échelle spatiale spécifique. Il a été démontré que l'échelle spatiale a une influence considérable sur les résultats d'analyse statistique et de modélisation statique. Or, les décisions concernant l'échelle spatiale des AC sont souvent prises de façon arbitraire. Cette étude a donc comme double objectif d'effectuer une analyse de sensibilité des AC à l'échelle spatiale et de tester l'influence de différents scénarios d'aménagement dans le but de protéger les superficies forestières résiduelles.

Pour tester la sensibilité à l'échelle spatiale, des combinaisons de plusieurs tailles de cellule et configurations de voisinage ont été utilisées pour élaborer différents AC. Des règles de transition probabilistes ont été dérivées de la comparaison de deux cartes d'utilisation du sol provenant de la classification d'images satellitaires. L'analyse de sensibilité montre que l'échelle spatiale a un impact significatif sur les dynamiques simulées. Les domaines d'échelle spatiale présents dans les résultats révèlent la non-linéarité des relations qui lient les composantes de l'échelle spatiale des AC aux résultats de simulation. Sur les bases de cette analyse de sensibilité, un AC a été élaboré et des scénarios d'aménagement forestier ont été conçus et testés (réduction de la déforestation, ligniculture, protection de la connectivité forestière). Ces simulations révèlent qu'aucun des scénarios ne parvient à protéger les niveaux actuels de superficies forestières. Cependant, certains scénarios réussissent à réduire significativement, à court et à moyen terme, les pertes de superficies et à reporter la fragmentation et l'isolation des parcelles de forêt.

Mots-clés : automate cellulaire, échelle spatiale, scénarios d'aménagement, MRC des Maskoutains, modélisation, paysage agroforestier

THESIS ABSTRACT

The Maskoutains regional county municipality (RCM) in Southern Quebec, Canada, is a dominant agricultural territory characterized by intense deforestation caused by agriculture intensification. A cellular automata (CA) model was elaborated to simulate the future territorial dynamics of this agro-forested landscape. CA are simulation models in which space is an array of cells that evolve through time with the application of transition rules dictating how the different cell states react to state configurations present in a specified neighborhood. A specific spatial scale characterizes CA models when they are used to simulate a geographic territory. Scale has been shown to significantly influence statistical analysis and modeling results. However, decisions related to scale components in CA modeling are often made arbitrarily, and their impact on the simulation results is still poorly understood. The objective of this study is twofold: 1) perform a scale sensitivity analysis of CA, and 2) test the influence of different land-use scenarios implemented to protect the remaining forested areas.

To test the sensitivity to spatial scale, CA were elaborated using a combination of multiple cell sizes and neighborhood configurations. Probabilistic transition rules were computed from the comparison of two land-use maps derived from Landsat-TM images. Results of the sensitivity analysis reveal that spatial scale has a considerable impact on simulation outcomes both in terms of land-cover areas and spatial structure. The spatial scale domains that are present in the results show the non-linear relationships that link the spatial scale components to the simulation results. Based on these findings, a CA was elaborated to study the impact of various forest management scenarios (reduced deforestation, ligniculture, forest connectivity protection). Results indicate that none of the scenarios succeed in maintaining the actual levels of forest area. However, certain scenarios significantly reduce the loss of forest areas in the short to mid-term, and delay the fragmentation, reduction, and isolation of forest patches.

Keywords : cellular automata, spatial scale, management scenarios, Maskoutains RCM, modeling, agroforested landscape

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Tu es la bille dans mon univers de cellules carrées

Tu es la folie dans mon monde de raison

Tu es le plus beau des systèmes complexes

Tu m'offres la plus précieuse des alliances

Merci Julie!!!

CHAPITRE 1. INTRODUCTION GÉNÉRALE

1.1 Problématique de déforestation dans la MRC des Maskoutains

Les environnements ruraux dominés par des matrices agricoles sont normalement parsemés de parcelles de forêt résiduelles qui jouent plusieurs rôles importants. Ces rôles incluent la préservation de l'hétérogénéité spatiale, esthétique et fonctionnelle des paysages ruraux (Domon, 1994), le maintien de la biodiversité par la protection d'une vaste gamme d'habitats (Wilcove, 1985) et de corridors essentiels à la connectivité du paysage (Lynch and Whitcomb, 1978; Robinson et al., 1995; Burke and Nol, 1998), la protection contre l'érosion éolienne et la réduction de la pollution agricole (Gangbazo and Bazin, 2000; Patoine and Simoneau, 2002). Malgré leur importance reconnue, l'état des forêts résiduelles en milieu agricole se dégrade et leur avenir semble précaire dans plusieurs régions de la planète. Les changements majeurs que connaissent certains paysages agroforestiers ont donc engendré un déclin en terme de superficie et une fragmentation prononcée des forêts (Westmacott and Worthington, 1984; Malecki and Sullivan, 1987).

Ces transformations sont nettement visibles dans certaines régions agroforestières du sud du Québec, au Canada (Domon, 1994; Bélanger and Grenier, 1998). Depuis la seconde moitié du 19e siècle, l'agriculture québécoise avait été principalement centrée sur la production laitière. Cependant, dans les années 1970, une série d'événements majeurs inter-reliés incluant des améliorations notables dans la productivité des cultures, la stagnation du marché laitier et une demande accrue pour le maïs-grain (Domon et al., 1993; Bélanger, 1999) ont poussé le gouvernement provincial à encourager la production de maïs-grain. Or, cette production plus spécialisée et industrielle a entraîné une homogénéisation des conditions biophysiques, une intensification agricole de l'utilisation du sol et le retrait de la majorité des éléments propres au milieu rural (Domon, 1994). Conséquemment, il est estimé que les régions du sud de la province ont perdu entre 15% et 17% de leur superficies forestières de 1971 à 1986 (Desponts, 1995) et cette tendance s'est poursuivie dans plusieurs secteurs pour atteindre aujourd'hui des niveaux qui menacent leur intégrité écologique et esthétique.

La municipalité régionale de comté (MRC) des Maskoutains est un bon exemple de l'intensité de la déforestation qui caractérise certaines régions. Cette MRC de la région de la Montérégie couvre un territoire de 1312 km^2 situé à l'est de Montréal. Centrée sur la ville de St-Hyacinthe, cette MRC est considérée comme la capitale et le centre névralgique de l'agriculture québécoise. Ses terres productives, des conditions climatiques favorables et sa proximité aux marchés de Montréal se conjuguent pour expliquer que près de 97% de son territoire soit zoné agricole (Gouvernement du Québec, 2001). Plusieurs études confirment l'intense déforestation qui sévit dans cette région. Les proportions de territoires forestiers ont chuté, de 1984 à 2002, de 20% (262 km^2) à 15% (200 km^2) (Li and Beauchesne, 2003; Savoie et al., 2002; Soucy-Gonthier et al., 2002). La principale raison expliquant la poursuite du déclin forestier depuis les années 1980 est le développement et la croissance soutenue de l'industrie porcine maskoutaine. Cette industrie présente une croissance importante au Québec mais il est à noter que 29% de la production porcine provinciale s'effectue dans la région de la Montérégie-Est (Gouvernement du Québec, 2003). Cette situation contribue à la déforestation puisque plusieurs producteurs détruisent leur boisés pour pouvoir épandre du lisier de porc (Delage, 2004), et certains producteurs céréaliers trouvent avantageux d'éliminer leurs boisés en réponse à la forte demande pour des terres agricoles que cela engendre (Bonin, 2002; Savoie et al., 2002).

L'intensification de l'agriculture dans la MRC des Maskoutains compromet la biodiversité et l'intégrité environnementale du territoire. L'extrapolation linéaire des tendances à la baisse des superficies forestières observées dans les dernières décennies dans cette région suggère qu'il ne restera plus de forêts dans 30 ans (Delage, 2004). Cette situation inquiète les intervenants de ces milieux qui cherchent à répondre à la question suivante : Est-ce que des stratégies de protection des forêts peuvent réussir à modifier cette tendance?

1.2 Modélisation par automate cellulaire

L'avenir des forêts résiduelles en milieu agricole représente un cas particulier de l'étude des changements d'utilisation du sol. Récemment, la recherche sur les changements d'utilisation du sol s'est faite de plus en plus avec l'aide de modèles. La modélisation, et tout particulièrement la modélisation spatialement explicite et intégrée, représente une méthode efficace pour explorer des trajectoires temporelles alternatives des territoires et pour tester la compréhension des processus clés du paysage (Lambin et al., 2000). Un type de modèle qui est de plus en plus utilisé dans ce genre d'étude est les automates cellulaires (AC). Les AC sont des modèles dynamiques dans lesquels des propriétés globales émergent à partir des interactions spatiales et locales des entités de base (Wu and Webster, 2000 ; Ligtenberg et al., 2001). Ils simulent un espace composé de cellules qui évoluent dans le temps suivant l'application de règles spécifiant comment les états de ces cellules réagissent aux différentes configurations de voisinage. Le formalisme de base des AC, tel que défini par Wolfram en 1984, spécifiait que les cellules devaient être carrées et uniformes, les itérations régulières, l'ensemble d'états possibles discret et relativement petit, le voisinage de premier ordre (von Neumann et Moore) et les règles de transition déterministes et simples.

Les caractéristiques des AC utilisés en géographie sont toutefois très différentes de celles de ce formalisme d'origine. Plusieurs transformations ont été requises pour l'adapter aux particularités de l'espace géographique (Couclelis, 1997 ; Torrens and O'Sullivan, 2001). Parmi les principales transformations, on peut noter l'utilisation de règles de transition stochastiques et complexes, l'usage de voisinages étendus, le traitement différentiel des états et l'imposition de contraintes externes spécifiant les quantités de changement d'états. Ces automates cellulaires géographiques ont été abondamment utilisés dans la dernière décennie pour modéliser les changements d'utilisation du sol, principalement en milieu urbain (Batty and Xie, 1994; Clarke et al., 1997; White et al., 1997; Clarke and Gaydos, 1998; Wu and Webster, 1998; Wu, 2002; de Almeida et al., 2003; Barredo et al., 2003). Les études centrées sur les dynamiques des paysages ruraux sont plus rares. L'études des patrons résidentiels en milieu rural ontarien (Deadman et al., 1993) et dans les Rocheuses américaines (Theobald and Hobbs, 1998), ainsi que l'analyse de la déforestation en forêt amazonienne (Soares-Filho et al., 2002) en sont des exemples. Toutes ces utilisations des AC ont démontré qu'ils pouvaient saisir efficacement la nature hautement décentralisée, spatiale, locale et multi-critère des territoires géographiques.

1.3 Le problème d'échelle spatiale dans les automates cellulaires géographiques

Dans les multiples décisions qui doivent être prises dans l'élaboration d'un AC, celles liées à l'échelle spatiale comptent parmi les plus importantes. L'échelle représente généralement la fenêtre de perception à travers laquelle la réalité est observée (Marceau, 1999). Quatre définitions de l'échelle spatiale peuvent être identifiées dans la littérature. L'échelle cartographique réfère au ratio d'une distance sur une carte à la distance correspondante au sol. L'échelle d'observation ou géographique est liée à l'étendue de la région à l'étude. L'échelle opérationnelle fait référence à l'échelle à laquelle certains processus opèrent dans l'environnement. Finalement, l'échelle de mesure, communément appelée résolution spatiale, réfère à la plus petite partie identifiable d'un objet (Cao and Lam, 1997).

Dans un AC appliqué à un territoire géographique, l'échelle spatiale est définie par trois composantes : l'étendue spatiale, la taille de cellule et la configuration du voisinage. L'étendue spatiale réfère à la superficie totale de la région modélisée. Cette étendue est normalement fixée dans une des toutes premières étapes de l'élaboration de l'AC, lorsque la problématique est définie et la région d'étude est choisie. La taille de cellule spécifie la superficie couverte par chaque cellule de la matrice. La configuration du voisinage quant à elle détermine la distribution et le nombre de voisins qui seront considérés pour l'application des règles de transition. Une revue de la littérature révèle que les tailles de cellule varient de moins de 100 m X 100 m à près de 1 km X 1 km alors que les configurations de voisinage varient des traditionnels von Neumann (4 cellules) et Moore (8 cellules) à des configurations circulaires pouvant compter jusqu'à 196 cellules. La taille des cellules et le voisinage utilisés sont traditionnellement déterminés par un mélange de disponibilité des données, de ressources informatiques, d'intuition, d'essais et erreurs et quelquefois, par des connaissances sur la taille des unités spatiales de base et leur influence. Ces paramètres d'AC sont donc choisis de manière relativement arbitraire et sont interchangeables et l'impact de leurs variations sur les simulations d'AC est mal connu. Les chercheurs dans le domaine s'entendent sur le fait que des études systématiques concernant l'effet d'échelle dans les AC sont manquantes et nécessaires (Theobald and Hobbs, 1998; Wu, 1998; Jenerette and Wu, 2001).

La communauté scientifique est confrontée depuis longtemps au problème de l'impact des variations de l'échelle spatiale sur les résultats d'analyse et de modélisation. Premièrement, il a été démontré que le nombre et la taille des unités spatiales affectent les résultats de coefficients de corrélation (Yule and Kendall, 1950) et d'analyse de régression (Clark and Avery, 1976). Puis, il a été établi que l'utilisation d'unités spatiales alternatives pour la cueillette de données influence l'estimation des paramètres de modèles de localisation/allocation (Goodchild, 1979), de modèles d'interaction spatiale (Putman and Chung, 1989) et en statistique multivariée (Fotheringham and Wong, 1991). De plus, l'influence de l'échelle spatiale a été formellement définie par la formulation du problème des unités spatiales modifiables, mieux connu sous le nom de MAUP (Openshaw, 1984). Le MAUP spécifie qu'il existe un grand nombre de façons de diviser une région en unités spatiales ne se chevauchant pas. Si les unités spatiales sont arbitrairement définies alors tout travail d'analyse ou de modélisation basé sur celles-ci n'est valide que pour celles-ci. La présence du MAUP a été observée en classification d'images de télédétection (Marceau et al., 1994), et en écologie du paysage (Jelinski and Wu, 1996; Qi and Wu, 1996). Finalement, l'effet spécifique de variations de configuration de voisinage a été observé dans des simulations d'AC théoriques. Packard et Wolfram (1985) ont démontré que la taille du voisinage avait un effet sur la vitesse de propagation des changements dans l'espace. Li et al. (1990) ont trouvé que lorsque des voisinages plus étendus sont utilisés, les états des cellules deviennent plus sensibles aux cellules éloignées. Cette interdépendance augmente les probabilités d'observer des simulations d'AC aux dynamiques aléatoires. Récemment, Bollinger et al. (2003) ont trouvé que leur AC historique générait des patrons plus réalistes lorsque des voisinages de taille moyenne étaient utilisés alors que Chen et Mynett (2003) ont démontré que différents voisinages affectaient les patrons spatiaux et la stabilité systémique de leur modèle proie-prédateur.

1.4 Objectifs et organisation de la thèse

Le but de cette thèse est de développer un automate cellulaire géographique appliqué aux changements d'utilisation du sol dans la MRC des Maskoutains. Plus spécifiquement, deux objectifs sont successivement poursuivis : 1) évaluer la sensibilité de simulations d'AC à des variations d'échelle spatiale et 2) tester l'influence de différents scénarios d'aménagement forestier sur l'avenir des superficies forestières de cette MRC. Dans le cadre de l'analyse de sensibilité, différentes tailles de cellule et configurations du voisinage sont utilisées, créant ainsi un vaste spectre de scénarios d'échelle spatiale. Dans un contexte où les modèles sont de plus en plus élaborés pour prédire le comportement de systèmes complexes naturels ou anthropiques, il s'avère crucial d'acquérir des connaissances de manière systématique sur la sensibilité des composantes des modèles. D'autant plus que l'influence de l'échelle spatiale a déjà été démontrée dans d'autres domaines de la géographie. Pour ce qui est du test des scénarios d'aménagement, des simulations représentant des réductions de déforestation, l'introduction de la ligniculture dans la région, la protection de la connectivité forestière et le statu quo sont exécutées. L'originalité de cet objectif de recherche réside dans l'étude, par AC, du processus de déforestation qui a cours dans cette région et la modélisation explicite de trajectoires hypothétiques dans le futur. L'analyse de ces trajectoires permettra d'évaluer le potentiel des stratégies d'aménagement testées pour la préservation des superficies forestières dans un paysage en phase avancée d'homogénéisation.

L'ensemble de cette thèse se présente comme suit. Le chapitre 2 poursuit l'introduction au domaine d'étude en présentant un portrait global des AC en géographie à travers l'analyse du débat portant sur l'impact des transformations des AC sur la complexité des patrons qu'ils génèrent. En plus d'introduire certains des principaux concepts de cette thèse, ce chapitre expose la position des auteurs dans ce débat par l'entremise d'une discussion sur la nature dualiste de la contribution scientifique des AC. Le chapitre 3 est consacré à la poursuite du premier objectif qui est l'analyse de sensibilité à l'échelle spatiale alors que le chapitre 4 présente les recherches effectuées en ce qui a trait au second objectif portant sur la simulation de scénarios d'aménagement forestier dans la MRC des Maskoutains. Le chapitre 5 a pour but de positionner cette thèse dans l'ensemble des études de modélisation de l'espace géographique par AC, de présenter un bilan des contributions à la géographie de ce type d'utilisation des AC et de faire état des grandes tendances qui animent présentement ce domaine de recherche. Finalement, une synthèse des principales conclusions et contributions de cette thèse est présenté au chapitre 6.

Il est à noter que les quatre prochains chapitres font et feront l'objet de publications scientifiques dans des revues avec comité de pairs. Le chapitre 2 a été publié sur le site web de l'*Institut d'Analyse Géographique* de France (www.iag.asso.fr) sur invitation. Le chapitre 3 est sous presse à la revue *Environment and Planning B: Planning and Design*. Finalement, les chapitres 4 et 5 ont été respectivement soumis pour publication aux revues *Landscape and Urban Planning* et *Progress in Human Geography*.

CHAPITRE 2. AUTOMATES CELLULAIRES ET COMPLEXITÉ : PERSPECTIVES GÉOGRAPHIQUES[1]

2.1 Introduction

Au cours des dernières années, un débat a surgi au sein de la communauté scientifique concernant les automates cellulaires géographiques (ACG). La question centrale de ce débat peut être formulée de la manière suivante : les ACG faisant l'objet de nombreuses modifications par rapport au formalisme des automates cellulaires (AC) tel qu'abondamment décrit par Wolfram (1984, 2002) conservent-ils la propriété de générer l'émergence de structures complexes? Les applications des ACG étant nombreuses et variées, quel est l'apport scientifique de ce type de modèle autant pour les géographes que pour les chercheurs de diverses disciplines préoccupés par l'étude des systèmes complexes?

L'objectif du présent article est d'apporter un éclairage sur cette question en mettant en évidence l'importance et la complémentarité des différentes contributions fournies par les ACG. L'idée centrale défendue dans cet article est que les ACG sont développés afin de répondre à deux objectifs principaux : celui de comprendre la dynamique spatio-temporelle d'un système naturel ou anthropique à partir d'hypothèses exprimées dans les règles de transition et celui de prédire le plus réalistement possible l'évolution d'un tel système, souvent dans un but de planification et de gestion.

Afin de répondre à la question soulevée, cet article fournit d'abord une description des AC ainsi que des modifications qui leur sont apportées lors de leur application dans un contexte géographique. Ensuite, des définitions de la complexité et de la science des systèmes complexes sont exposées en soulignant le fait que les AC et les ACG sont des modèles particuliers pouvant dans certaines conditions favoriser l'émergence de structures complexes. L'article s'achève sur une discussion présentant la double

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[1] Ménard, A., É. Filotas et D. J. Marceau (2004) Automates cellulaires et complexité : perspectives géographiques. Institut d'Analyse Géographique, Publication électronique : www.iag.asso.fr

contribution scientifique des ACG qui permet aux géographes de contribuer, sur un plan fondamental, au raffinement de la théorie des systèmes complexes et, dans une perspective plus appliquée, d'apporter des éléments de réponse sur l'évolution d'un territoire pouvant en faciliter une meilleure gestion.

2.2 Les automates cellulaires

Un automate cellulaire (AC) est un modèle qui simplifie une réalité à un groupe d'automates (entité pouvant traiter de l'information et exécuter des actions) d'aspect cellulaire (Hogeweg 1988, Phipps 1992). Il se compose de cinq éléments. L'espace est représenté par une *matrice*, soit un arrangement régulier de cellules (automates), qui peut être linéaire (unidimensionnel), surfacique (bidimensionnel) ou volumétrique (tridimensionnel). Chaque cellule contient une valeur d'attribut extraite d'un *ensemble discret d'états possibles*. Toutes les cellules évoluent selon une dimension temporelle discrète, c'est-à-dire par *itérations*. À chaque itération, des *règles de transition* sont appliquées à toutes les cellules. Ces règles spécifient comment les différents états des cellules réagiront aux configurations d'états se trouvant dans le *voisinage* immédiat de chaque cellule.

Dans sa forme classique et originale, les cinq caractéristiques des AC possèdent les propriétés strictes suivantes. Tout d'abord, la matrice utilisée est considérée comme infinie, uniforme et constituée de cellules carrées. Les états des cellules proviennent d'un ensemble discret de valeurs qui ont toutes le même poids et sont normalement peu nombreuses. Le voisinage est local, c'est-à-dire défini pour ne comprendre que les voisins contigus de premier ordre (voisinage de Von Neumann ou de Moore). De plus, chaque voisin possède un poids identique dans l'application des règles de transition. Ces dernières sont déterministes et appliquées à toutes les cellules de manière uniforme et synchronisée. Elles sont aussi statiques, c'est-à-dire qu'elles ne peuvent être modifiées en cours de simulation. Finalement, les itérations sont régulières et ne sont ponctuées que par l'exécution des règles de transition.

L'origine des AC remonte à la fin des années 1940. Les premiers investigateurs sont Ulam et von Neumann (von Neumann 1963). Jusqu'aux années 1970, les AC sont étudiés par des chercheurs qui s'intéressent à la théorie de l'information et des mathématiques. C'est entre autre avec l'accessibilité croissante aux ordinateurs et surtout grâce à la parution du fameux « Game of Life » de Conway en 1971 (Gardner 1971) que la popularité des AC se répand (Hogeweg 1988). En 1984, le physicien Wolfram découvre que certaines simulations d'AC ont la propriété de permettre l'émergence de structures dites complexes. Dès lors, de multiples disciplines s'adonnent à l'étude et à l'utilisation des AC, notamment la biologie, la physique, la chimie et l'économie. La géographie, elle aussi, n'échappe pas à cette vague de popularité envers ce nouvel outil de modélisation.

2.3 Les automates cellulaires géographiques

Pour les géographes intéressés à modéliser des processus spatiaux, les AC présentent divers avantages. Tout d'abord ce sont des modèles qui traitent de l'espace de manière explicite et à un niveau de détail considérable. Cette propriété les rend ainsi compatibles avec la majorité des bases de données spatiales, entre autres celles gérées par les SIG matriciels. Aussi, les AC sont dynamiques. Les processus spatiaux peuvent donc y être représentés de façon directe. Ils sont de plus hautement adaptables et peuvent ainsi être utilisés pour décrire un nombre varié de situations et de processus. Il est aussi aisé de faire le lien entre les processus, encapsulés dans les règles de décision, et les patrons qu'ils génèrent. Mais par-dessus tout, ils sont surtout très simples à comprendre et à implémenter comparativement aux modèles analytiques traditionnels.

Tobler, en 1979, dans un article intitulé *Cellular Geography*, est le premier à lier les AC et la géographie. En fait, il a présenté cinq modèles de base permettant d'expliquer l'évolution d'une partie de territoire, représentée par une cellule géographique. L'un de ces modèles est la formalisation géographique des AC. Cependant, ce n'est que vers la fin des années 1980 que l'on voit apparaître dans les revues scientifiques des résultats de recherche utilisant les AC en géographie. Phipps (1989, 1992) a utilisé les AC pour étudier théoriquement la formation de parcelles générées par des processus écologiques et anthropiques (notamment l'expansion urbaine). Couclelis (1985, 1988) les a adoptés pour explorer la complexité et démontrer comment les processus géographiques globaux peuvent émerger d'intéractions locales simples. C'est à partir des années 1990 que les AC, dits géographiques (ACG), sont largement décrits dans les revues scientifiques. Ces ACG sont utilisés pour étudier des phénomènes tels que la ségrégation, l'expansion, la croissance et le développement urbain, la poly-centralité des villes, la circulation et la congestion routière, l'urbanisation à l'échelle régionale, les dynamiques de changement d'utilisation du sol ou l'histoire de l'urbanisation (Torrens et O'Sullivan 2001).

Malgré leurs attraits évidents, il s'avère que la structure authentique des AC présente d'importantes limites à la simulation de phénomènes réels en géographie. Au fil des ans, les géographes ont donc apporté de multiples modifications au formalisme de base des AC. Dans un premier temps, la structure régulière et infinie de l'espace est substituée par une matrice de dimension finie et quelquefois composée de cellules de taille et de forme variable. Cette délimitation de l'espace entraîne des problèmes de traitement des effets de bordure en simulation. Deuxièment, le voisinage est fréquemment élargi pour englober jusqu'à plus d'une centaine de cellules. Lorsque c'est le cas, les états des cellules de ces voisinages doivent être pondérés par la distance à la cellule traitée pour respecter les principes de l'autocorrélation spatiale. Enfin, les règles de transition ont été considérablement transformées. Elles sont maintenant presque exclusivement probabilistes pour prendre en considération la variabilité inhérente des systèmes écologiques ou anthropiques. Elles sont souvent sélectives, c'est-à-dire qu'elles ne s'appliquent pas de façon identique à toutes les cellules. Ainsi, chaque cellule se voit assignée un niveau de recevabilité d'un état qui peut dépendre des caractéristiques bio-physiques, locationnelles ou relationnelles du territoire qu'elle représente. Finalement, dans certains ACG, les dynamiques sont « contraintes » par des sous-modèles externes, de nature économique ou socio-démographique par exemple, qui peuvent spécifier le nombre de cellules devant changer à chaque itération.

Devant ces nombreuses modifications apportées par les géographes au formalisme des AC afin de représenter plus fidèlement la réalité géographique lors de la modélisation, la question posée par certains chercheurs (Couclelis 1985, Phipps 1992, Torrens et O'Sullivan 2000a) au cours des dernières années est la suivante : les ACG conservent-ils la capacité de reproduire des comportements complexes?

2.4 La complexité et la science des systèmes complexes

La science de la complexité est apparue au cours de la dernière moitié du 20e siècle grâce aux initiatives d'une vaste gamme de chercheurs provenant de disciplines variées. Durant cette période, plusieurs chercheurs insatisfaits ont en effet remarqué que la science traditionnelle, réductionniste et déterministe, ne permettait pas de décrire et de comprendre l'ensemble des phénomènes naturels et anthropiques rencontrés dans leur recherche. Parmi ces scientifiques, mentionnons le cybernéticien Ashby dont les études portaient sur les propriétés du cerveau humain, les informaticiens Turing et Kolmogorov et leur quête d'une machine universelle et aussi Von Neumann et Hofstadter pour leur travaux sur la vie et l'intelligence artificielle (Turing 1950, Ashby 1956). Ce changement de paradigme toucha aussi les disciplines scientifiques plus appliquées. Par exemple, l'économiste Arthur remit en question le dogme de « l'homo economicus » au profit d'une vision du marché économique où les acteurs ne possèdent pas la totalité de l'information et peuvent parfois faire des choix irrationnels. Le météorologiste Lorenz observa aussi l'extrême sensibilité des mouvements atmosphériques aux conditions initiales (Lorenz 1963).

La théorie contemporaine de la complexité se veut une synthèse des développements récents dans les domaines de la physique non-linéraire et de l'étude moderne des systèmes dynamiques (Parrott et Kok, 2000). Elle implique maintenant un ensemble actif de chercheurs dans les domaines aussi divers que les mathématiques, la physique, l'informatique, la biologie, l'écologie, la philosophie, l'économie et la géographie. Ces scientifiques se consacrent à l'étude des propriétés complexes, non-linéaires et parfois chaotiques qui émanent des systèmes dynamiques. Dans la perspective de réunir et d'approfondir les connaissances provenant de ces disciplines éparses, plusieurs centres de recherche portant sur les systèmes complexes ont vu le jour durant les dernières décennies, dont le célèbre Santa Fe Institute (www.santafe.edu). Les partisans de cette nouvelle science espèrent pouvoir trouver en elle un cadre explicatif général permettant de comprendre l'ensemble des systèmes dynamiques auxquels ces divers champs d'étude sont confrontés. Cette promesse anime et séduit la communauté scientifique concernée.

2.4.1 Les propriétés des systèmes complexes

La théorie de la complexité propose une vue holistique des systèmes. Contrairement au réductionnisme, l'analyse holistique tente de comprendre la mécanique des systèmes en mettant l'emphase sur les entités qui les composent et surtout sur les relations qui existent entre celles-ci. Chacune des entités a un rôle singulier à jouer et contribue au fonctionnement global du système. Le système forme un tout cohérent dont la dynamique est intimement liée à la dynamique de ses entités et ne peut être comprise sans y référer. Les entités d'un système complexe sont structurées en une hiérarchie de différents niveaux d'organisation, lesquels entretiennent entre eux des rapports spécifiques. La dynamique du système à un niveau inférieur de la hiérarchie a un impact direct sur les niveaux supérieurs. La science des systèmes complexes se distingue des méthodes traditionnelles d'analyse par le fait qu'elle étudie non seulement les interactions entre les entités d'une même échelle de la structure hiérarchique, mais aussi les interactions entre les différentes échelles. Elle permet donc de comprendre certains phénomènes dont le fonctionnement dépend des relations entre les entités existant à une échelle inférieure et qui jusqu'alors ne pouvaient être expliqués par la seule analyse de la dynamique se déroulant à l'échelle globale du système.

Suivant ce schéma de pensée, un système complexe peut être défini comme un tout cohérent dont les éléments et leurs interactions génèrent des structures nouvelles et surprenantes qui ne peuvent pas être définies *a priori* (Batty et Torrens 2001). La complexité du système provient des propriétés suivantes : la quantité et la diversité des éléments qui le composent, la non-linéarité, l'émergence, l'auto-organisation et l'imprévisibilité. Ces caractéristiques sont expliquées en détail dans les paragraphes qui suivent.

Tout d'abord, les systèmes complexes comptent un nombre important de composantes hétérogènes identifiables sur différentes échelles d'espace. Deuxièment, les relations entre ces entités sont très souvent non-linéaires. C'est-à-dire qu'elles ne peuvent s'exprimer par un simple facteur de proportionnalité. Ainsi, la faible variation d'une entité *A* peut produire une variation extrême de l'entité *B* à laquelle elle est liée. L'évolution du système se traduit ainsi par une très forte sensibilité aux conditions initiales. Une légère perturbation de l'état initial du système peut le faire diverger hors de sa trajectoire habituelle.

La propriété d'émergence réfère à l'apparition inattendue de patrons spatiaux et temporels dans la dynamique et la structure du système (Parrott 2002). L'émergence est une fonction de la synergie d'un système. En effet, le comportement global d'un système complexe ne peut être compris par la simple somme des comportements individuels des entités qui le composent. L'auto-organisation quant à elle, est le mécanisme responsable de l'émergence. Elle est le processus par lequel l'effet collectif des interactions locales entre les entités du système, bien qu'apparemment désorganisé, forme une structure et un comportement ordonnés émanant au niveau global (Parrott 2002). L'auto-organisation peut aussi être expliquée comme une collaboration entre les entités du système qui modifient leur structure interne dans le but d'améliorer la viabilité et l'efficacité des relations que ce dernier entretient avec son environnement (Manson 2001).

Finalement, la multitude et la disparité des entités du système en combinaison avec les propriétés d'auto-organisation, d'émergence et de non-linéarité, produisent un comportement global qui ne peut être anticipé. Ce système modifie ses échanges d'énergie et adapte ses interactions avec son milieu environnant. Les relations entre ses composantes sont donc en constante évolution; de nouvelles entités sont créées et d'autres se transforment. Ceci produit des changements inattendus dans la dynamique du système qui échappe à tout équilibre et stabilité. Il a été remarqué par plusieurs chercheurs que ces systèmes, malgré leur comportement évolutif, demeurent toujours cohérents (Holland 1996). Ils se situent à la frontière du chaos (Langton 1986). La nature imprévisible des systèmes complexes est la raison pour laquelle leur évolution ne peut être prédite ni contrôlée comme l'aurait voulu la science traditionnelle déterministe.

2.4.2 Définitions de la complexité

La complexité n'est pas une propriété facilement quantifiable. Comment affirmer, par exemple, qu'un système soit plus complexe qu'un autre? Les spécialistes de la théorie de la complexité sont engagés dans des recherches qui tentent de définir une mesure de la complexité qui soit réaliste, efficace et qui puisse s'adapter facilement à divers domaines d'étude.

Il est possible d'entrevoir trois formes différentes de complexité synthétisant l'ensemble des conceptions utilisées. Premièrement, la complexité algorithmique (Manson 2001) ou structurelle (Wu et Marceau 2002), qui origine des travaux de Chaitin (1992) sur la théorie de l'information, réfère à l'algorithme le plus court permettant de reproduire le comportement d'un système. Cette perception de la complexité met l'emphase sur la diversité des éléments composant le système. Deuxièmement, la complexité déterministe ou fonctionnelle est associée à la nature non-linéraire des systèmes complexes et à leur sensibilité aux conditions initiales. Cette conception s'appuie grandement sur les théories du chaos et de la catastrophe. Finalement, la complexité agrégée ou auto-organisatrice est associée aux propriétés émergentes des systèmes complexes. Elle est une mesure des conséquences des interactions locales et rétroactives entre les entités du système sur sa dynamique globale.

Il n'existe pas à ce jour de définition de la complexité qui rallie l'ensemble des chercheurs oeuvrant dans ce domaine. Ceci n'est pas une conséquence de la jeunesse de ce champ d'étude mais est principalement dû à la multidisciplinarité de celui-ci. Chaque domaine scientifique étudie les systèmes complexes avec ses outils et ses prérogatives de sorte que des définitions propres à plusieurs disciplines variées ont été formulées.

2.4.3 La modélisation des systèmes complexes

La théorie de la complexité est particulièrement appropriée pour analyser la majorité des phénomènes naturels ou anthropiques étudiés en géographie. Le développement de nouvelles théories connexes portant par exemple sur l'auto-organisation critique, les systèmes complexes adaptatifs, les fractales et les AC ont permis d'accroître notre compréhension de la complexité écologique (Wu et Marceau 2002). De plus, l'avénement de nouvelles méthodes de programmation, principalement l'approche orienté-objet, ainsi que l'augmentation de la puissance des ordinateurs permettent de construire des modèles de systèmes complexes réalistes et efficaces. Les méthodes de modélisation des systèmes complexes en géographie peuvent être divisées en trois catégories : les modèles centrés sur l'individu, les modèles centrés sur les agents et les AC (Parrott et Kok 2002). Dans une perspective de représentation d'un écosystème, le modèle centré sur l'individu permet d'illustrer un ensemble de nombreux organismes en interaction au sein de leur environnement. Le modèle centré sur l'agent permet de modéliser des individus qui ont la capacité d'acquérir des connaissances sur leur environnement et d'adapter leur comportement en fonction de cet apprentissage. La modélisation de systèmes géographiques humains s'exécute ainsi par le biais d'agents. Comme expliqué précédemment, les AC permettent quant à eux de représenter l'évolution d'un territoire en modélisant l'espace explicitement par une matrice. Ces modèles, bien que présentant des caractéristiques différentes, possèdent la propriété commune de mettre l'accent sur les individus ainsi que sur leurs interactions locales à partir desquelles émergent des structures globales du système étudié. Cette propriété commune est essentielle à la création de comportements complexes mais n'en garantit pas la présence, la complexité étant rarement observée dans les résultats de modélisation.

Ainsi, même si les AC font partie des modèles possédant les caractéristiques nécessaires pour générer des comportements et des patrons empreints de complexité, ce ne sont pas tous les AC ni toutes les simulations qui en génèrent. Les travaux de Wolfram ont en effet montré, à l'aide d'AC uni-dimensionnels et binaires, que seulement 4% des règles de transition généraient des patrons complexes. De plus, quiconque a déjà joué avec le « Game of Life » de Conway s'est aperçu que selon les conditions initiales de cet AC les résultats pouvaient être très différents, de complexes à très simples. Certaines simulations créent des patrons fractaux d'une richesse inouïe alors que d'autres prennent fin abruptement après seulement quelques itérations ou restent figées à perpétuité. De plus, ce qui rajoute à cette situation de rareté est l'ambiguïté qui persiste quant à la quantification de la complexité. Il n'existe toujours pas de méthodes statistiques ou mathématiques standardisées pour déterminer si une dynamique temporelle ou spatiale est complexe.

2.5 Contributions scientifiques des automates cellulaires géographiques

Les AC sont maintenant abondamment utilisés comme outil de modélisation de l'espace géographique. La popularité de la théorie des systèmes complexes et les multiples travaux ayant démontré que les AC pouvaient générer des patrons complexes ont fortement contribué à leur adoption par les géographes. Cependant, cette transition d'un outil de modélisation général à un modèle de l'espace géographique a été ponctuée de nombreuses transformations qui ont, à leur tour, engendré d'importants questionnements. Les

ACG peuvent-ils toujours générer des patrons complexes? Ont-ils une utilité au-delà de la complexité? C'est en dressant un portrait des contributions scientifiques des ACG que des réponses peuvent être apportées à ces questions.

La modélisation est la simplification d'une réalité, géographique ou non, dans le but de la comprendre ou de prédire. Une façon d'interpréter l'apport scientifique des ACG au cours des dernières années est de distinguer les différentes contributions qu'ils ont générées selon le but visé. D'abord, il existe des ACG qui sont conçus pour comprendre les processus, souvent simples et locaux, à l'origine des patrons observés, souvent complexes et globaux, à la surface de la terre. Ces modèles exploratoires tentent d'expliquer les patrons ou la dynamique spatiale d'un phénomène géographique à partir d'hypothèses théoriques formalisées dans leurs règles de transition (Phipps 1989; 1992, Semboloni 1997, Wu et Webster 2000). La règle de parcimonie s'applique donc fréquemment dans l'élaboration de ces ACG. Ainsi, les modèles doivent être simples pour permettre d'établir adéquatement le lien qui existe entre patron et processus. Les transformations apportées aux AC pour les rendre plus aptes à modéliser l'espace géographique sont donc moins présentes dans ce genre de modèles, pour ainsi tirer profit des qualités intrinsèques aux AC.

Un autre objectif visé par les ACG est la prédiction. Dans ce cas, ces modèles sont développés pour informer sur l'avenir d'un territoire, pour extrapoler dans le futur les dynamiques spatiales d'une région, souvent en lien avec différents scénarios d'intervention (Deadman *et al.* 1993, Engelen *et al.* 1995, White *et al.* 1997, Clarke et Gaydos 1998, White et Engelen 2000, Soares-Filho *et al.* 2002). Ils doivent représenter le plus fidèlement possible le territoire modélisé puisque, la plupart du temps, des impératifs d'aménagement et de gestion en dépendent. Devant s'adapter à une situation réelle bien particulière, ces modèles font généralement appel à plusieurs des transformations mentionnées précédemment. Ils ont donc une structure et un fonctionnement différents et sont plus compliqués que les AC formels.

Cette dichotomie dans la contribution des ACG élaborés ces dernières années est en partie à l'origine du débat sur la nature même des ACG et de leurs liens avec la complexité. Ainsi, alors que l'utilisation des ACG exploratoires est justifiée par le potentiel qu'ils possèdent pour générer des comportements complexes et émergents, les ACG prédictifs puisent toute leur valeur dans leur utilité pratique. Ces derniers s'accordent mal avec la théorie des systèmes complexes et cela pour trois raisons. Premièrement, la complexité étant si peu fréquemment rencontrée dans les simulations d'AC, il n'est peut-être pas pertinent de s'y attarder et ainsi de compromettre le réalisme de l'ACG pour tenter d'en produire. Deuxièmement, ceux-ci sont souvent contraints par des sous-modèles analytiques et cette situation peut empêcher l'émergence de comportements complexes propres aux AC. Troisièmement, si cette émergence se manifeste, elle risque d'être perçue comme une anomalie de simulation. En effet, l'émergence de comportements complexes génère inévitablement des simulations ponctuées d'événements et de patrons imprévisibles et surprenants. Or, de telles simulations sont difficilement interprétables et peuvent ne pas concorder avec la vision anticipée du territoire modélisé. La motivation des chercheurs impliqués dans ce genre d'exercice de modélisation est de produire des ACG opérationnels dont les comportements sont plausibles (Torrens et O'Sullivan 2000a). La complexité ne se situe pas au centre des préoccupations de ces modélisateurs. En effet, ce sont leurs capacités à faciliter la planification et la gestion du territoire et à permettre le développement de nouvelles politiques qui sont priorisées (Torrens et O'Sullivan 2000b).

L'avenir des ACG passe donc par un agenda de recherche équilibré entre recherche exploratoire et appliquée, entre les ACG modifiés et ceux qui sont davantage reliés au formalisme traditionnel des AC. Alors que les premiers contribuent rapidement à la découverte de renseignements pratiques et souvent valorisés sur les territoires géographiques, il demeure important de poursuivre au même rythme la recherche plus fondamentale portant sur les AC en géographie. Ce genre de recherche, en plus d'être un outil efficace et prometteur pour investiguer des hypothèses et théories concernant les dynamiques spatiales de territoires anthropisés et naturels, permettent aux géographes de contribuer, à terme, au développement multi-disciplinaire de la théorie des systèmes complexes (Torrens et O'Sullivan 2000a, 2000b, 2001). En effet, si les géographes désirent que les ACG contribuent à cette théorie, et qu'il soit possible de faire des rapprochements entre ces modèles et ceux de disciplines connexes, telles la biologie, la physique et l'informatique, il est alors important de conserver le plus possible la forme originelle des AC dans les ACG. En somme, les chercheurs élaborant des ACG doivent être conscients de l'héritage des AC et être soucieux de contribuer un jour à la théorie unificatrice qu'est celle de la complexité.

PARAGRAPHE DE LIAISON A

Le chapitre 2 a présenté un portrait global des automates cellulaires (AC) en géographie à travers l'analyse du débat portant sur l'impact des transformations des AC sur la complexité des patrons qu'ils génèrent. En plus d'introduire certains des principaux concepts de cette thèse (complexité, automate cellulaire, transformations géographiques), ce chapitre a exposé la position des auteurs dans ce débat par l'entremise d'une discussion sur la nature dualiste de la contribution scientifique des AC (compréhension des relations processus-patrons vs prédiction).

En s'appuyant sur les bases théoriques et techniques présentées au chapitre 2, le chapitre 3 amorce les recherches menant à l'exécution de simulations par AC de la région des Maskoutains. En effet, l'élaboration d'un AC pour une région donnée implique de choisir une taille de cellule et une configuration de voisinage opérationnelles. Or, quel est l'impact de modifier ces deux paramètres sur les résultats de simulation? Le chapitre suivant présente donc une analyse de sensibilité des AC aux variations d'échelle spatiale (tailles de cellule et configurations du voisinage). Cette analyse sert de base à l'élaboration de l'AC final qui est utilisé pour tester l'impact de différentes stratégies d'aménagement forestier dans cette région.

CHAPITRE 3. EXPLORATION OF SPATIAL SCALE SENSITIVITY IN GEOGRAPHIC CELLULAR AUTOMATA[2]

3.1 Abstract

Cellular automata (CA) are individual-based models where states, time and space are discrete. Spatio-temporal dynamics emerge from the simple and local interactions of the cells. When using CA in a geographic context, non-trivial questions have to be answered concerning the choice of spatial scale, namely cell size and neighbourhood configuration. However, the spatial scale decisions involved in the elaboration of geographic cellular automata (GCA) are often made arbitrarily or in relation to data availability. The objective of this study is to evaluate the sensitivity of GCA to spatial scale. A stochastic GCA was built to model land-cover change in the Maskoutains region (Quebec, Canada). The transition rules were empirically derived from two Landsat-TM (30 m resolution) images taken in 1999 and 2002 that have been resampled to four resolutions (100, 200, 500 and 1000 m). Six different neighbourhood configurations were considered (Moore, Von Neumann and circular approximations of 2, 3, 4 and 5 cell radii). Simulations were performed for each of the 30 spatial scale scenarios. Results show that spatial scale has a considerable impact on simulation dynamics both in terms of land-cover areas and spatial structure. The spatial scale domains present in the results reveal the non-linear relationships that link the spatial scale components to the simulation results.

Keywords: geographic cellular automata, spatial scale, sensitivity analysis, MAUP, land-cover change.

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3.2 Introduction

In the process of modeling the real physical world, a large number of models have been elaborated and used. Cellular automata (CA) are individual-based models designed to simulate systems in which the global properties emerge from the spatial local interactions of the system basic entities (Wu and Webster, 2000; Lightenberg et al, 2001). They are composed of five basic components. Space is modeled with a matrix, which is a regular arrangement of cells that can either be linear, planar or volumetric. Each cell of the matrix possesses a state, which comes from a discrete ensemble of possible states. All cells evolve in time through simulation characterized by discrete time steps. At each time step, deterministic transition rules are applied uniformly to all cells. These rules dictate how the different cell states will react to state configurations present in a specified neighbourhood of each cell. This formulation refers to the classical definition of CA, which has been loosened by practice. These five components distinguish CA from other individual-based, bottom-up modeling approaches, like connectionist models (Smith III, 1976; Kauffman, 1993; Wuensche, 1999, 2002) or multi-agents models (Brown and O'Leary, 1995; Ferber, 1995). Additional information on CA can be found in Wolfram (1984, 1988, 2002).

Geographers or other scientists interested in modeling the geographic space rapidly realized the potential of CA. The reasons of CA popularity in geography are multiple (Torrens, 2000). First, CA are particularly adept at dealing with spatial phenomena. Traditional modeling techniques tend to abstract from spatial details while CA make implicit use of the spatial complexity (White et al. 1997). Also, traditional models (location-allocation models, econometric models) generally use a relative view of space (Couclelis 1997). CA on the other hand, handle proximal space, which combines both the relative and the absolute views of space through the concept of neighbourhood. Site and situation are therefore linked in CA. Second, geographers are already familiar with the cell representation of CA because of its similarities with the spatial characteristics of remote sensing images and raster GIS (Geographical Information Systems) (Wagner, 1997; Batty et al, 1999; Manson, 2000). Third, the process being modeled is entirely encapsulated in the transition rules allowing the link between the patterns and the underlying process. Finally, there is an increasing need for a high level of spatial details in applications related to decision-making processes and CA satisfy this need.

The original formalism of CA is simple, but can be perceived as too limited when applied in a geographic perspective (Couclelis, 1997; Torrens and O'Sullivan, 2000; O'Sullivan, 2001a). Many alterations have been made over the years to adapt CA to the geographic space. The major transformations to CA relate primarily to the transition rules and the neighbourhood configuration. Almost all Geographic Cellular Automata (GCA) have adopted stochastic transition rules in order to capture the intrinsic variability of human-related phenomenon. Also, the transition rules are not always applied uniformly to all cells. This is done to reflect the situations where the process being modeled does not apply to all states but only to specified parts of the landscape (for example, in a GCA of urban expansion, it makes sense not to apply the rules to cells representing lakes and national parks).

As for the neighbourhood used, even if the traditional Von Neumann neighbourhood (four cardinal neighbours; also known as queen's case) and Moore neighbourhood (eight first-order neighbours; also known as rook's case) are still applied, the tendency is clearly leaning towards extended neighbourhoods, sometimes encompassing well over one hundred cells. The justification behind these larger neighbourhoods lies in the geographic influence of land-use states and local actors. This transformation of CA formalism has an impact on transition rule application since it now has to deal with spatial autocorrelation. Therefore, transition rules almost always incorporate a distance-based weighting procedure. Finally, because the majority of GCA is now focusing more on concrete predictability and geographic plausibility rather than on theoretical process modeling, the transition rules are increasingly empirically derived. To acquire such transition rules diverse methods have been employed, like multi-criteria analysis (Wu and Webster, 1998), genetic algorithms (Jenerette and Wu, 2001), principal component analysis (Li and Yeh, 2002a), neural networks (Li and Yeh, 2002b) and linear extrapolation (Lay, 2000; Jenerette and Wu, 2001). Application domains of GCA include, among others, urban expansion (White and Engelen, 1993, 1994; Wu and Webster, 2000), land use/cover change (Deadman et al, 1993; Batty and Xie, 1994; White and Engelen, 1994; Engelen et al, 1995; Clarke et al, 1997; White et al, 1997; Clarke and Gaydos, 1998; White and Engelen, 2000; White et al, 2000; Soares-Filho et al, 2002), theoretical spatial dynamic modeling (Semboloni, 1997; Webster and Wu, 2001) and ecology (Colansanti and Grime, 1993; Flamm and Turner, 1994; Lett et al, 1999).

In the many decisions that must be taken when elaborating a GCA, those related to spatial scale are certainly amongst the most important. Scale generally represents the window of perception through which reality is observed (Marceau, 1999). At least four meanings of spatial scale can be identified in the literature. The cartographic scale refers to the proportion of a distance on a paper map to the corresponding distance on the ground. The geographic or observational scale refers to the size or spatial extent of a study. The operational scale relates to the scale at which certain processes operate in the environment. Finally, the measurement or spatial resolution scale refers to the smallest distinguishable parts of an object (Cao and Lam, 1997). In a GCA, spatial scale is defined by three components: the spatial extent, the cell size, and the neighbourhood configuration. Spatial extent is an important GCA spatial scale component and refers to the dimension of the area that is modeled. Cell size specifies what area of the landscape each cell is going to cover. Neighbourhood configuration determines the distribution and number of neighbours that will have an impact on each cell's evolution. Table 3.1 presents the cell sizes and neighbourhood configurations used in GCA found in recent studies. This list of GCA applications is not exhaustive, but is representative of the research domain. Cell sizes vary from 100 m X 100 m and less to almost 1 km X 1 km. Neighbourhood configurations are mainly shaped as circular approximations and range in size from the Moore neighbourhood (one cell radius) to a 196 cells neighbourhood (eight cell radius). What determines the values that these two components take is a mixture of data availability, intuition, computing and resource considerations, trial and error, and sometimes information concerning spatial unit sizes or influences.

Table 3.1 Cell size and neighbourhood configuration used in geographical applications of cellular automata

Authors	Year	Cell size	Neighborhood shape	Nb. neighbours	Region
Arai & Akiyama	2003	92 m x 113 m	Rectangular (5x5)	24	Peri-urban region of Tokyo (Japan)
Barredo et al.	2003	100 m	Circular (8 cells radius)	172	Dublin (Ireland)
Batty & Xie	1994	220 m	Moore	8	Savannah region, Georgia (USA)
Clarke & Gaydos	1998	210 m	Moore	8	Baltimore-Washington region (USA)
Clarke et al.	1997	300 m	Moore	8	San Francisco bay, California (USA)
De Almeida et al.	2003	100 m	Moore	8	Bauru region (Brazil)
Deadman et al.	1993	100 m	Moore or Von Neumann	4 or 8	Wellington County, Ontario (Canada)
Jenerette & Wu	2001	250 m	Moore	8	Phoenix, Arizona (USA)
Li & Yeh	2000	50 m	Circular (2 cells radius)	20	Region in the south of China
Theobald & Hobbs	1998	804 m	Variable	4 or 8 or 20	Summit County, Colorado (USA)
Vandergue et al.	2000	Sensus sectors	First-order connectivity	-	Bogota (Peru)
White & Engelen	1993	500 m	Circular (6 cells radius)	112	Atlanta, Cincinnati, Milwaukee and Houston (USA)
White & Engelen	1994	250 m	Circular (6 cells radius)	112	Caraibeen island
White & Engelen	2000	500 m	Circular (8 cells radius)	196	Netherlands
White et al.	1997	250 m	Circular (6 cells radius)	112	Cincinnati, Ohio (USA)
White et al.	2000	250 m	Circular (8 cells radius)	196	Saint-Lucia Island
Wu	1998	28.5 m	Square (5x5)	24	Guangzhou city (China)

Table 3.1 Cell size and neighbourhood configuration used in geographical applications of cellular automata

Scientists have been confronted for a long time to the impact of spatial scale variations on analysis results. First, the number and size of areal units have been shown to greatly affect correlation coefficients (Yule and Kendall, 1950) and regression analysis results (Clark and Avery, 1976). Then, it was demonstrated that using alternative areal units to gather data affects parameter estimation in location-allocation modelling (Goodchild, 1979), spatial interaction modeling (Putman and Chung, 1989) and multivariate statistical analysis (Fotheringham and Wong, 1991). Next, Openshaw (1984) systematically defined the spatial scale influence by formulating the Modifiable Areal Unit Problem (MAUP). The MAUP states that an enormous number of different ways exist by which a region can be divided into non-overlapping areal units for the purpose of spatial analysis. If areal units are arbitrarily determined, then the value of any work based upon them may not possess any validity independent of the units that are used. The presence of the MAUP was later confirmed in remote sensing classification (Marceau et al, 1994) and landscape ecology (Jelinski and Wu, 1996; Qi and Wu, 1996). Finally, the specific effects of different neighbourhood configurations have been observed in theoretical CA simulations. Packard and Wolfram (1985) identified early that neighbourhood size modulates how quickly changes propagate through space. Li et al. (1990) found that when more neighbors are involved in updating each cell, cell values become increasingly sensitive to cells at larger distances and this increased interdependence among cells makes random dynamics more likely. Recently, Bolliger et al. (2003) found that their CA of historical landscape self-organized to a realistic critical state if neighbourhoods of intermediate size (radius = 3 cells) were used, and Chen and Mynett (2003) observed that different neighbourhoods (Moore and extended Moore) affected the spatial patterns and the system stability of their prey-predator model.

3.2.1 Objective

The objective of this study is to evaluate the sensitivity of GCA simulations to variations in spatial scale. More specifically, this sensitivity will be investigated in regards to the cell size and the neighbourhood configuration. A sensitivity analysis assesses the contribution of model imput factors to the uncertainty in the model response (Crosetto et al., 2000). In a context where models are increasingly built to study and eventually predict the behaviour of complex natural and human systems, it is crucial to acquire the best possible knowledge on the sensitivity of model components. Moreover, this sensitivity evaluation also finds its relevance in the words of Fotheringham (1989) and Jelinski and Wu (1996) who mentioned that one of the potential solutions to the MAUP is to perform sensitivity analysis and search for fluctuations in variables and relationships with scale. Furthermore, scientists agree that there is a need for more systematic study of spatial scale sensitivity in GCA (Theobald and Hobbs, 1998; Wu, 1998; Jenerette and Wu, 2001).

3.3. Methodology

3.3.1 Study area and dataset

The study area chosen for this study is the Maskoutains regional county municipality (MRC), a highly cultivated area of the Montérégie administrative region located in south-western Quebec, Canada. The Maskoutains region covers 1312 km^2 and is centered on the city of Saint-Hyacinthe. This region is historically one of the cradles of Quebec agriculture because of its highly productive lands (St-Lawrence Lowlands) and its proximity to the Montreal area markets.

Even though the majority of its territory is cultivated, agriculture's pressure on the forested remnants is still high. In 1999, the Maskoutains region was covered by 218 km^2 (16,64% of the region) of forest, and in 2002 of only 195 km^2 (14,88%). This represents a decline of 10,54% of forested area (Soucy-Gonthier et al, 2003). These numbers raise important ecological and societal questions, which are not the focus of this study. However, theoretically and computationally speaking, this opposition between forest and agriculture offers a simple yet interesting landscape dynamics for a GCA application.

The dataset used is comprised of two land-cover maps of the Maskoutains region, one for 1999 and another for 2002, derived from two Landsat-TM remote sensing images (Soucy-Gonthier et al, 2003). The original spatial resolution of these images is 30 m and the land-cover classes are forest, non-forested vegetation (which can be simplified by agriculture) and the rest (urban areas, roads, water, ...). After radiometric, atmospheric and geometric corrections were executed and field verification performed, the final land-cover maps created had an overall reliability of 88,5% (84,2% for the Maskoutains 1999 subset and 97,4% for the 2002 subset). These classified maps were combined with a simplified map of soil capability for agriculture (Gouvernement du Canada, 1972). This was accomplished because a visual analysis of early simulations substantiates that the addition of this map greatly contributes to the plausibility of the simulations and because evidences suggest that land covers are correlated with superficial deposits in this region (Pan et al, 1999). The combination of the land-cover map with a binary version (high potential vs moderate-to-low potential) of the soil capability for agriculture map results into a new land-cover map composed of four classes, which are forest and agriculture on both high potential and moderate-to-low potential soils. The urban expansion phenomenon was not considered because 97% of the region territory is protected for agriculture (Gouvernement du Québec, 2000). Our GCA is therefore solely based on the opposition between forest and agriculture land covers.

3.3.2 Spatial scale sensitivity scenarios

To evaluate the spatial scale sensitivity of GCA simulations, it is necessary to establish diverse spatial scale scenarios. Five cell sizes were selected: 30 m (original resolution), 100 m, 200 m, 500 m and 1000 m. These cell sizes cover the extent of the cell size spectrum commonly used in GCA applications. The datasets at the four non-original resolutions were acquired by nearest neighbour re-sampling. This re-sampling method uses the value of the closest input cell for the output cell value. Other standard methods such as bilinear and cubic re-sampling methods were not used since they produce new cell values from four and 16 neighbours respectively. In addition to preserving the original land-cover values, nearest-neighbour re-sampling also maintained the different proportions of land-cover areas. Six neighbourhood configurations were chosen based on what is commonly used in the literature: Moore, Von Neumann, C2 (circular approximation of two cell radius), C3, C4 and C5. The number of neighbours of each neighbourhood configuration is respectively 8, 4, 12, 28, 48 and 80. These choices create 30 different scenarios (5 cell sizes X 6 neighbourhood configurations) used to test the sensitivity of GCA simulations to spatial scale (Figure 3.1). Spatial extent was not modified because the purpose of our research is to study the land-cover dynamics of the Maskoutains region. In the remainder of the text, mention will be made of cell size and neighbourhood configuration groups. These groups correspond respectively to the columns and rows of Figure 3.1 and incorporate all scenarios where one spatial scale component is maintained constant while the other one is changing (ex.: the 30 m group comprises the six scenarios with a cell size of 30 m (Figure 3.1, Column #1), and the Moore group includes the five scenarios with a Moore neighbourhood (Figure 3.1, Row #2). Since the transition rules are probabilistic, ten replicates were executed for each scenario in order to introduce an element of randomness, or noise, into the simulations. Finally, since the original classified maps were three years apart, each time step represents three years. A temporal extent of 48 years (16 time steps) was selected for the simulations because it provides enough data for analysis purposes and because the temporal extent of the simulations should not be considerably longer than the temporal extent of the data used to derive the transition rules.

CELL SIZE

NEIGHBOURHOOD CONFIGURATION

SCENARIOS	30 m	100 m	200 m	500 m	1000 m
Von Neumann (4)	10	10	10	10	10
Moore (8)	10	10	10	10	10
C2 (12)	10	10	10	10	10
C3 (28)	10	10	10	10	10
C4 (48)	10	10	10	10	10
C5 (80)	10	10	10	10	10

Number of replicates

* The number in parenthesis indicates the number of cells in each neighbourhood configuration

Figure 3.1 Simulation framework for the 30 spatial scale scenarios

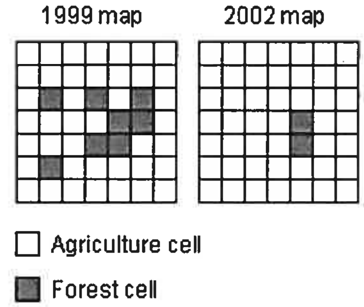
3.3.3 Elaboration of the transition rules

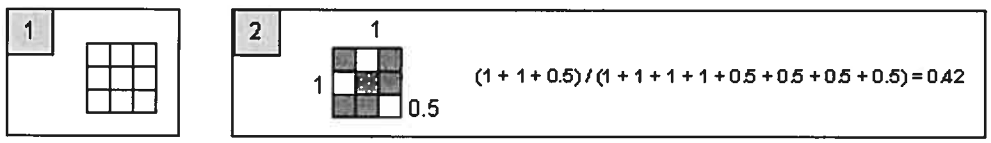
The main component of any GCA is the transition rules (Torrens, 2000). As said before, they are formulated differently in every GCA study. To better isolate the spatial scale sensitivity and prevent arbitrariness in GCA characteristics, the transition rules were kept as simple and empirical as possible. The method used to create the probabilities is inspired by the linear interpolation method used by Jenerette and Wu (2001) and Lay (2000). This method derives transition rules from an overlay of two maps acquired at different times, usually years. This overlay determines the cells that have changed between maps. In the urban growth context in which Jenerette and Wu (2001) used it, the probability that a non-urban cell with n urban neighbours would become urbanized is computed by dividing the number of all cells with n urban neighbours at time t-1 that became urbanized at time t by the total number of non-urban cells with n urban neighbours at time t-1. In their model, urban and non-urban land-covers were opposed.

In the context of our study, agriculture and forest land-covers are opposed. The agriculture cells present in the neighbourhood of a forest cell increase this cell's chances of being transformed to agriculture. Therefore, a forest cell that has X agriculture cells in its neighbourhood (Moore neighbourhood for example) will have a probability of changing to agriculture equal to the number of forest cells with X agriculture neighbours that changed to agriculture between 1999 and 2002 divided by the total number of forest cells with the same neighbourhood in 1999. However, to adapt this method to our situation, which has to deal with different neighbourhood configurations (and number of neighbours) and with the fact that extended neighbourhoods have cells at varying distances from the focus cell, we performed the following modifications. Refer to Figure 3.2 for a graphical explanation of the elaboration of the transition rule probabilities.

Procedures:

1. Selection of a neighbourhood configuration : Moore
2. Determination of the agriculture pressure in the neighbourhood of the forest cells of the 1999 map (example for one forest cell)
   - Allocation of weights (refer to Figure 3) to the agriculture cells present in its neighbourhood
   - Computation of the pressure to change coefficient (Sum of weights / Maximum sum of weights for the Moore neighbourhood)
3. Computation of the transition rule probabilities





3

Coeff. of the 1999 forest cells that changed status: [1.00] [0.92] [0.75] [0.58] [0.75] [1.00]

Coeff. of the 1999 forest cells that did not change status: [0.42] [0.58]

Classes of the transition rule probabilities

	[0]	]0 - 0.25]	]0.25 - 0.5]	]0.5 - 0.75]	]0.75 - 1[	[1]
Forest cells that changed	0	0	0	3	1	2
All forest cells	0	0	1	4	1	2
TRANSITION RULE PROBABILITES	0.00	0.00	0.00	0.75	1.00	1.00

Figure 3.2 Illustration of the procedures for the elaboration of the transition rule probabilities (example given for the transition from forest to agriculture)

First, a weighting procedure was introduced to give more importance to closer cells. The eighty cells that compose the different neighbourhood configurations were associated to a distance class (Figure 3.3) of values ranging from 1 to 13. All cells of a distance class are at equal distance from the focus cell. Consequently, when evaluating the pressure to change characterizing the neighbourhood of a cell of a particular state, each cell of the opposing state is given a weight corresponding to the inverse of its distance class. The sum of the weights, divided by the maximum weight sum of the corresponding neighbourhood configuration, is then attributed to the focus cell. This coefficient ranges from 0 (no opposing state cells in the neighbourhood) to 1 (complete opposition in the neighbourhood). That way, neighbourhood situations of different neighbourhood configurations are brought to the same range of values. The following situation is given as an example. A forest cell has a Moore neighbourhood composed of five forest cells and three agriculture cells. The three cells of the opposing state are located to the north, the east and the southwest of the focus cell. The north and east cells each receive a weight of 1 (1 / 1) and the southwest cell has a weight of 0.5 (1 / 2). The sum of the weights of this particular neighbourhood arrangement equals 2.5. Because the maximum sum of weights of the Moore neighbourhood is 6 ((4 X 1) + (4 X 0.5)), that forest cell therefore has a value of 0.42 (2.5 / 6), symbolizing the pressure of agriculture in its environment.

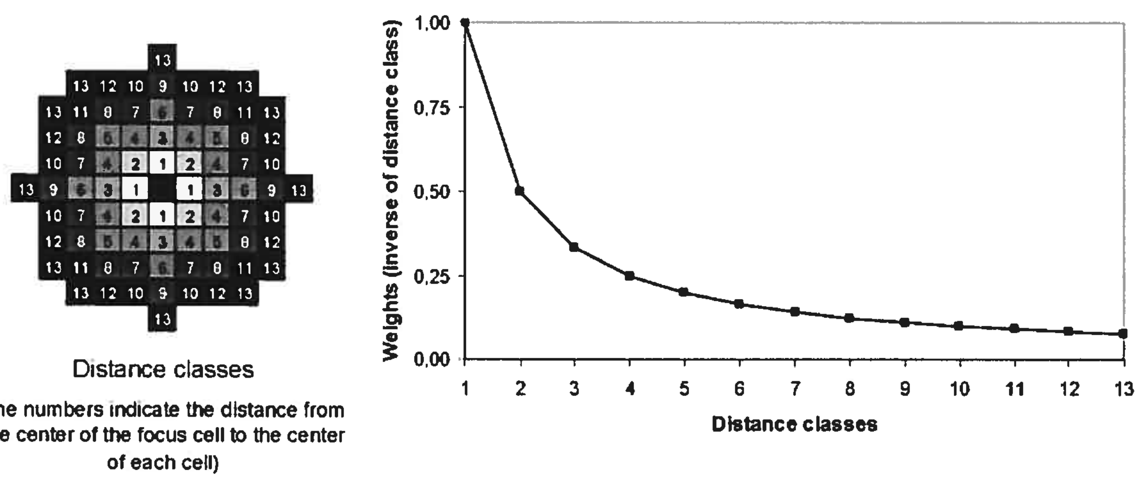


Figure 3.3 Distance classes around a focus cell and associated weights (the shades of grey represent the limits of the different neighbourhood configurations)

The second modification was designed to cope with multiple neighbourhood configurations. When dealing with a single neighbourhood configuration, the number of neighbours of the opposing state present in the neighbourhood corresponds to a discrete ensemble of possible neighbourhood arrangements. In those cases, the number of transition rules characterizing the change from one state to another will be equal to the number of possible neighbours (four in the Von Neumann neighbourhood, eight in the Moore, etc). In the present study, the neighbourhood arrangements are not characterized by the number of neighbours but by a coefficient value, the rationale of which was just explained. The number of different coefficient values is not constant and can get very high since it increases as neighbourhood configurations progressively include more neighbours (the number of different neighbourhood arrangement equals s^n, s corresponding to the number of states and n to the number of neighbours). In order to reasonably limit the number of transition rules and make it constant for all neighbourhood configurations, the coefficient values previously obtained were grouped into six classes to generate the transition rule probabilities: [0],]0-0.25],]0.25-0.50],]0.50-0.75],]0.75-1[and [1]. This number of classes allows for a good representation of the coefficient values while maintaining reasonable class frequencies. Using the same logic as before, the transition rules were then computed by dividing the frequencies of each coefficient classes of the cells of a particular state that changed between maps by the frequencies of each coefficient classes of all the cells of that state. Therefore, for every spatial scale scenario and for each of the four possible transitions (forest to agriculture on good soils and on moderate-to-low potential soils, agriculture to forest on good soils and on moderate-to-low potential soils), six transition rule probabilities were created (Table 3.2). The number of cells that will change state at each time step is a reflection of the rate of change and the neighbourhood situations present in the two land-cover maps used to compute the transition rule probabilities.

Table 3.2 Empirically-derived transition rule probabilities for all scenarios (prob. have been multiplied by 100 for visual simplicity)

	Coefficient	30 m						100 m						200 m						500 m						1000 m					
	classes	M	VN	C2	C3	C4	C5	M	VN	C2	C3	C4	C5	M	VN	C2	C3	C4	C5	M	VN	C2	C3	C4	C5	M	VN	C2	C3	C4	C5
	0	2	2	1	1	1	1	1	1	1	0	0	0	1	1	1	0	0	0	1	2	1	0	0	0	1	2	0	0	0	0
Agriculture	] 0 - 0.25 [	13	2	12	7	6	4	4	1	4	3	2	2	3	1	3	2	2	2	4	2	3	2	2	2	5	2	4	3	3	3
to	[0.25 - 0.5 [	23	22	29	26	24	21	10	9	13	12	11	10	7	6	10	9	9	9	6	4	8	9	9	9	2	5	3	4	4	5
Forest	[0.5 - 0.75 [	42	33	46	45	44	41	24	18	29	27	26	23	17	13	19	19	18	17	12	9	12	7	7	8	12	1	20	10	0	0
on HPAS	[0.75 - 1 [	51	48	56	60	59	58	41	35	45	48	47	47	26	21	37	39	43	40	3	16	0	0	0	0	0	20	0	10	0	0
	1	63	55	56	60	59	58	56	44	45	48	47	47	69	35	37	39	43	40	0	0	0	0	0	0	0	0	0	10	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0
Agriculture	] 0 - 0.25 [	8	0	7	5	4	3	4	0	3	2	2	1	2	0	2	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0
to	[0.25 - 0.5 [	16	14	23	21	22	20	8	6	13	13	14	13	5	3	8	8	9	9	2	1	4	2	0	0	0	0	0	0	0	0
Forest	[0.5 - 0.75 [	38	28	41	38	39	41	28	16	28	31	26	27	13	8	19	29	0	9	0	6	4	2	0	0	0	0	0	0	0	0
on MLPAS	[0.75 - 1 [	20	37	28	42	46	49	50	39	40	17	25	25	33	30	19	29	0	9	0	6	4	2	0	0	0	0	0	0	0	0
	1	50	7	28	42	46	49	0	20	40	17	25	25	33	30	19	29	0	9	0	6	4	2	0	0	0	0	0	0	0	0
	0	12	14	10	8	7	6	7	9	6	5	6	4	7	9	7	3	0	0	2	9	0	0	0	0	0	0	0	0	0	0
Forest	] 0 - 0.25 [	33	14	30	22	19	16	15	9	14	11	10	9	12	9	11	10	10	10	13	9	12	9	6	4	13	0	13	10	11	14
to	[0.25 - 0.5 [	44	42	48	45	42	38	24	22	27	24	22	19	17	16	20	17	16	14	12	11	14	15	16	18	16	19	20	20	21	20
Agriculture	[0.5 - 0.75 [	62	55	71	66	64	59	42	36	44	40	39	35	31	27	36	31	30	27	27	21	27	24	22	20	21	22	20	17	16	13
on HPAS	[0.75 - 1 [	83	77	84	86	85	81	58	51	67	64	62	58	45	39	48	48	48	44	31	32	37	34	34	31	24	24	24	26	25	28
	1	84	78	84	86	85	81	80	72	67	64	62	58	55	51	48	48	48	44	44	37	37	34	34	31	24	21	24	26	25	28
	0	20	26	16	10	8	9	10	11	9	0	0	0	0	17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Forest	] 0 - 0.25 [	43	26	37	28	22	18	14	11	15	13	15	18	22	17	21	17	0	0	0	0	0	0	0	0	0	0	0	0	0	0
to	[0.25 - 0.5 [	52	50	55	50	47	40	28	26	27	23	21	19	17	19	18	19	17	28	0	0	0	0	0	0	0	0	0	0	0	0
Agriculture	[0.5 - 0.75 [	71	66	79	73	71	65	43	42	48	39	34	29	34	33	39	31	31	27	35	25	35	33	36	40	0	0	20	0	0	0
on MLPAS	[0.75 - 1 [	90	84	92	92	92	91	65	56	77	75	74	63	55	50	63	63	61	50	35	39	42	42	40	38	40	33	33	33	36	38
	1	92	86	92	92	92	91	90	82	77	75	74	63	75	72	63	63	61	50	50	46	42	42	40	38	33	33	33	33	36	38

HPAS : high potential agricultural soils
MLPAS: moderate to low potential agricultural soils
M: Moore neighbourhood
VN: Non Neumann neighbourhood
C2 to C5: Circular neighbourhood of radius 2 to 5 cells

Table 3.2 Empirically-derived transition rule probabilities for all scenarios (prob. multiplied by 100 for visual simplicity)

Ten replicates were performed for each scenario, for a total of 300 simulations. Since every simulation has 16 time steps, a total of 4800 time steps were computed and the same amount of maps were saved. Because the dynamics modeled represents the binary opposition between forest and agriculture lands, only one land-cover was used as an indicator of the system state. To accurately describe the forest areas on each of the 4800 maps, two indicators were chosen: forest area and number of patches.

To ensure that the differences observed between the 30 spatial scale scenarios are entirely created by the differences in transition rule probabilities associated to spatial scale between each scenario, we performed other simulations for each scenario using a fixed set of transition rule probabilities. Instead of selecting a completely arbitrary fixed set of transition rule probabilities, they were generated by computing the average of the 30 transition rule probability sets. Only five replicates were performed for each scenario because low variability between replicates had been noticed in simulation results. We hypothesize that the results from these simulations will exhibit as much variability but less coherence than the main simulations because this set of transition rule probabilities is not adapted to each spatial scale.

On the basis of the results obtained with the initial set of spatial scale scenarios, additional simulations were performed to refine the exploration of spatial scale sensitivity. The same methodology developed to create the 30 original scenarios was used to create six new spatial scale scenarios. Cell sizes of 40 m, 50 m, 60 m, 70 m, 80 m and 90 m were chosen for the finer analysis. The Moore neighbourhood configuration was selected for these scenarios because the differences between the 30 m and 100 m cell sizes were neighbourhood-independent and because it is a common used neighbourhood. Again, ten replicates per scenarios were performed and the forest area and number of patches at each time step were extracted.

3.4 Results and discussion

The results are first presented in three sections that successively describe with increasing details the analysis of spatial scale sensitivity. First, the main objective is addressed: Are GCA sensitive to spatial scale? Second, spatial scale is decomposed into its two components, cell size and neighbourhood configuration, for a more detailed assessment of their respective impact on GCA simulations. Third, the individual response of each spatial scale scenario in relation to the two spatial scale components is investigated. Moreover, the results from the fixed transition rules simulations are analysed for comparison with the results obtained from the main, empirically derived and changing, transition probabilities. Finally, in light of the results obtained with the 30 scenarios, results from additional simulations performed in order to refine the exploration of spatial scale sensitivity and investigate the effects of small spatial scale variations are presented.

3.4.1 Are GCA sensitive to spatial scale?

In order to synthesise the dynamics expressed by each scenario, the mean forest areas and number of patches were computed at each time step. In all cases, the means accurately represent the scenarios since no extreme or outlying result was observed, standard deviations are small, and the value distributions at each time step, for each scenario and for each of the two indicators, are normal (Normality verified with standard nonparametric Kolmogorov-Smirnov goodnest-of-fit Tests at alpha = 0,05).

Figure 3.4 presents the mean forest area for each of the scenarios through time. A first observation is that all the mean forest areas show a negative slope and that their dynamics seems to be stable towards the end of the simulations. This stabilization can be explained by an equilibrium between two phenomena. First, the majority of the forest areas that disappear through time are located in cultivated environments. Therefore, as time advances, the remaining forest areas are increasingly located in forested environments, which are environments with lower probabilities of change to agriculture. Second, there are always small probabilities of agriculture conversion to forest in highly cultivated locations. These small quantities of new forest areas cancel out the small quantities of new agriculture areas gained in highly forested environments.

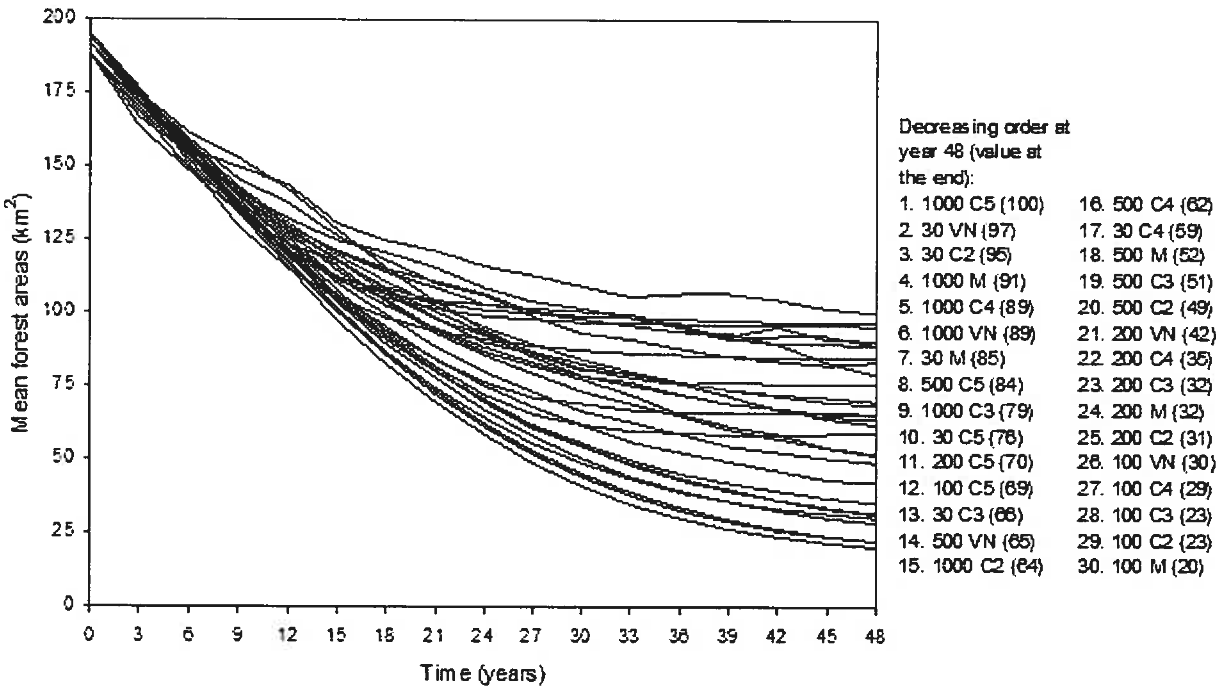


Figure 3.4 Mean forest area through time for all scenarios

The overall behaviour of the scenarios is one of divergence. At the start of the simulation, the forest areas means for all scenarios are very similar and range from 188 km^2 to 195 km^2. This was expected since the initial conditions of land cover were derived from the resampled 2002 remote sensing imagery where proportions of land cover has been respected. As the simulations progress, the scenarios slowly start to diverge and ultimately exhibit, after 16 time steps or 48 years, a wide spectrum of forest area means, varying between 25 km^2 and 100 km^2. Therefore, depending on the spatial scale scenario, the region can lose from 47% to 89% of its forest cover. Also, the order of the scenarios at the end of the simulations suggests that cell sizes may have a structuring impact on the results.

Figure 3.5 presents the mean standardized number of patches for each of the scenarios through time. The raw number of patches was transformed (scaled to the initial value) because of the different orders of magnitude that separated the scenarios of different cell sizes. Logically, the number of patches in an image is inversely proportional to the cell size used. Therefore, the number of patches at each time step was divided by the number of patches at the start of the simulations (e.g.: a value of two at a specific time step indicates that there is twice the number of patches of time step zero and a value below one indicates a decline in the number of patches). Figure 3.5 distinctly shows that the 30 m group generates a lot more patches than all the other scenarios. The scenarios of this group reveal a large increase in patches in the first 18 years and stabilize at values ranging from 30 to 40 in the remainder of the simulations. This means that the scenarios of this group create more than 30 times the number of patches present in the initial maps. The 24 other scenarios exhibit more modest responses in number of patches with values that remain between 0.5 and 3.5 throughout the simulations.

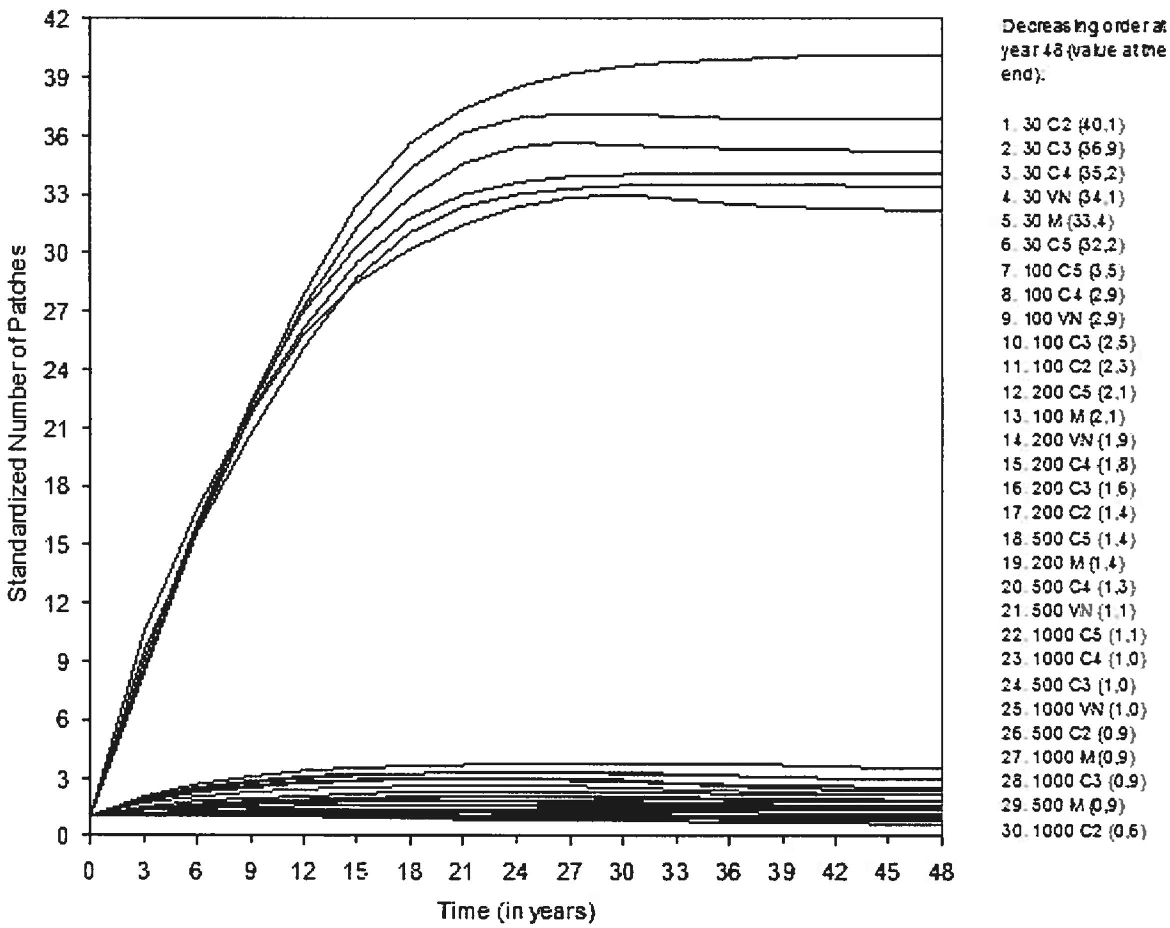


Figure 3.5 Mean standardized number of patches through time for all scenarios

From these results, it is clear that GCA simulation dynamics are sensitive to spatial scale. Different scenarios give rise to different results in terms of forest area and number of patches, and that somewhat rapidly during the simulations. But which spatial scale component has the highest influence: cell size or neighbourhood configuration?

3.4.2 The influence of each spatial scale component

In order to assess which spatial scale component has the highest influence, it is imperative to isolate them from each other. To achieve this goal, the 300 simulations were first divided into five groups of 60 simulations, based on the cell size. The mean forest area and the mean standardized number of patches of these groups were computed at each time step. Then, the same 300 simulations were divided into six groups of 50 simulations based, this time, on the neighbourhood configuration. Again, the mean values of both indicators in these groups were computed. Figure 3.6 presents the mean forest area and the mean standardized number of patches through time for the five cell size groups. The forest area results show that as the cell size increases more forest area are preserved, except for the 30 m cell size which preserves almost as much forest area than the 1000 m cell size. This situation can be better understood when the number of patches are observed. The simulations with a 30 m cell size generate, in average, more than 30 times the number of patches present in the original map while all other cell sizes stay relatively close with values ranging from 0.6 to 3.

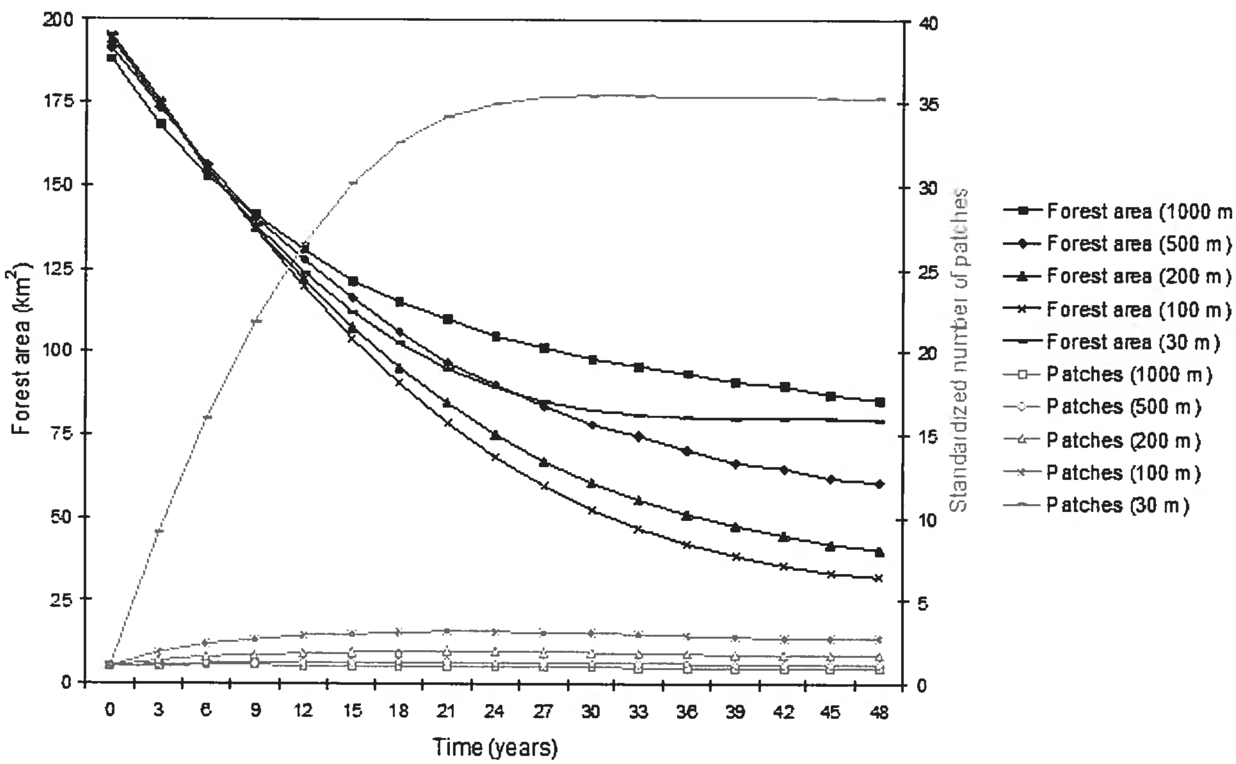


Figure 3.6 Mean forest area and standardized number of patches through time of all simulations grouped by cell sizes

The mean forest area and mean standardized number of patches through time for the six neighbourhood configurations present a different situation (Figure 3.7). The different neighbourhood configurations produce relatively similar amounts of forest area and number of patches in comparison to the results observed with the cell size groups. No clear relationship emerges between neighbourhood configurations and the indicators. However, it is the largest and the smallest neighbourhoods (C5 and Von Neumann) that preserve the most forest areas. This situation relates well with the recent findings of Bolliger et al. (2003) who found that their CA of an historical landscape did not self-organized to realistic critical states when small or large neighbourhoods (radius <3 or >3 cells) were used. It is clear from the results presented in Figures 3.6 and 3.7 that cell size is the most structuring of the two scale components. The cell size groups display more variability in simulation results than the neighbourhood configuration groups. Also, it reinforces the necessity of understanding better the extreme and unrealistic results produced by simulations with a 30 m cell size.

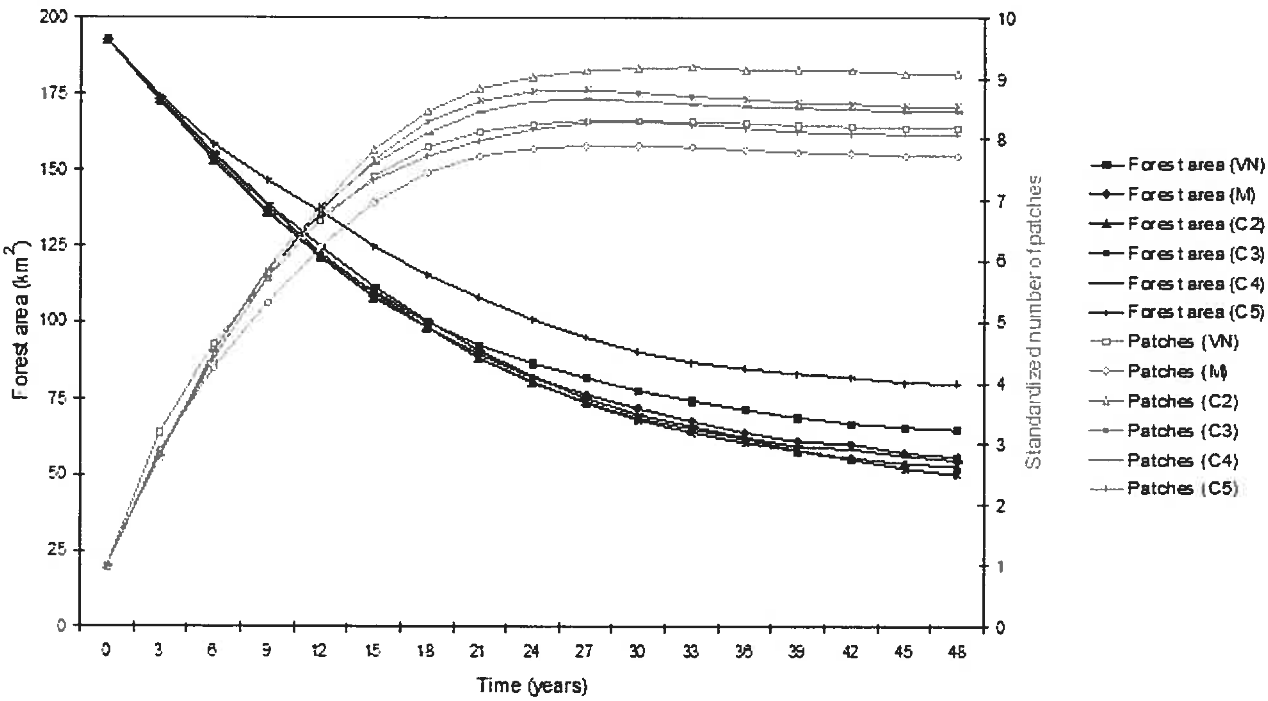


Figure 3.7 Mean forest area and standardized number of patches through time for all simulations grouped by neighbourhood configurations

The key to the understanding of the behaviour of the 30 m cell size lies in the observation of the patches that changed state between the two land-cover maps used (dynamical patches). There are 6436 dynamical patches in the data set used in this study. The mean patch size of these patches is 10 010 m^2. The 30 m cell size is the only cell size smaller than the majority of the dynamical patches. The 30 m (900 m^2), 100 m (10 000 m^2), 200 m (40 000 m^2), 500 m (250 000 m^2) and 1000 m (1 000 000 m^2) cell sizes have percentages of dynamical patches larger than them that are equal to 76%, 19%, 5%, 0.3% and 0.02%, respectively. This situation explains why the simulations with a 30 m cell size generate unrealistically large amounts of forest patches. In fact, the majority of the forest cells are portions of forest patches when a cell size of 30 m is used. Transition rule probabilities derived upon those cells are essentially representing the evolution of portions of dynamical patches. A cell representing a portion of a dynamical patch will be surrounded by other cells of the same state. Consequently, the neighbourhood situation of this cell will be characterized by a low pressure to change. However, this neighbourhood situation will be tabulated as one that generates state change because the cell is part of a patch that changed state. The 30 m cell size therefore erroneously biases the transition rule probabilities because it increases the probabilities of change associated with low-pressure neighbourhoods. In our simulations with a 30 m cell size, important numbers of small forest patches in agriculture environments were created and forest environments were disaggregated too much and too rapidly.

3.4.3 Individual dynamics of the spatial scale scenarios

Now that the presence of spatial scale sensitivity in GCA has been confirmed and that the influence of each spatial scale component has been uncovered, it is now relevant to inquire about the individual dynamics generated by each scenario. Since every scenario reflects the combination of a cell size and a neighbourhood configuration, its response both in terms of mean forest area and mean standardized number of patches at each time step can ultimately be positioned in a bi-dimensional space constructed using both spatial scale components. In such a conceptual space, the patterns that scenarios with similar results create can reveal the interplay of both components and the existence of spatial scale domains. A spatial scale domain is a part of the spatial scale continuum where the values of a particular indicator are relatively homogeneous (Marceau, 1999; Meentemeyer, 1989)

The first step in this investigation of individual scenarios is to plot their responses by using the forest area and number of patches results at the end of the simulations (Figure 3.8, left). Then, groups of scenarios were visually delineated (Group #1: 1000-VN, 1000-M, 1000-C3, 1000-C4, 1000-C5 and 500-C5; Group #2: 500-VN, 500-M, 500-C2, 500-C3, 500-C4 and 1000-C2; Group #3: 100-C5 and 200-C5; Group #4: 200-VN, 200-M, 200-C2, 200-C3 and 200-C4; Group #5: 100-VN, 100-M, 100-C2, 100-C3 and 100-C4; Group #6: 30-VN, 30-M, 30-C2, 30-C3, 30-C4 and 30-C5). A variety of clustering techniques (e.g.: k-means partitioning, tree clustering, two-way joining) were also used for verification purposes and gave the same results. Spatial scale domains are formed and illustrated when the clusters of scenarios are located in a bi-dimensional space constructed using the two GCA spatial scale components (Figure 3.8, right). Each cell of the matrix of spatial scale domains represents a scenario. The shades of grey indicate the membership to a particular domain. A particular weft was given to the scenarios with a 30 m cell size to emphasize that their results are very different from the others scenarios for the reasons mentioned before. The domains show that the choice of a cell size is the main determinant of simulations results. The only occasions where neighbourhood configurations significantly influence simulation results are when the large C5 neighbourhood are utilized and when the medium-sized C2 neighbourhood is used in combination with a 1000 m cell size. The C5 neighbourhood configuration seems to produce results similar to using a larger cell size.

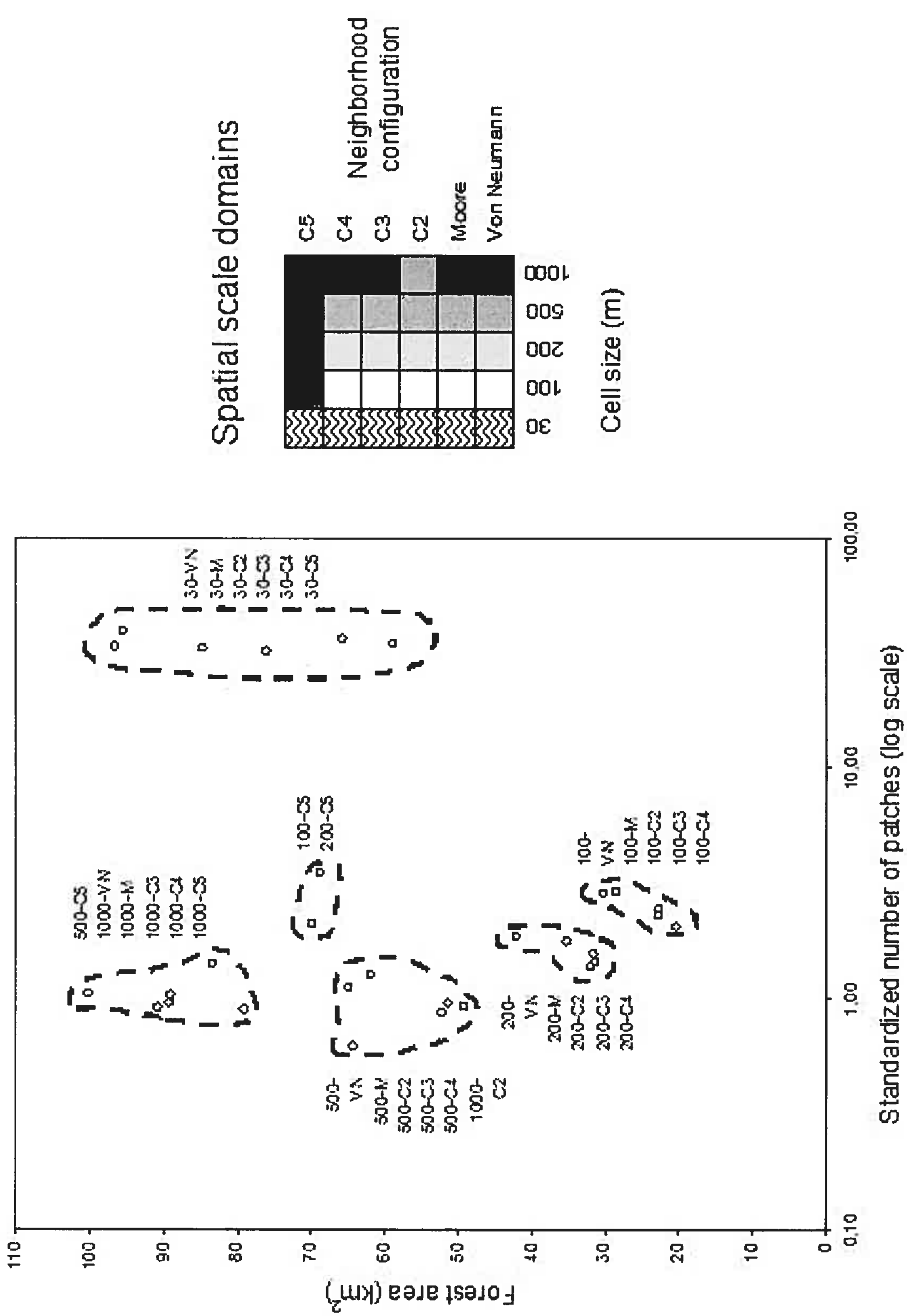


Figure 3.8 Visual delineation of spatial scale domains from a 2D scatter-plot of scenario results after 48 years (shades of grey identify domains)

The contribution that this detailed look at the simulation results demonstrates is twofold. First, it shows that relatively small changes in neighbourhood configurations can lead to different outcomes in terms of forest area. For example, switching from the Moore to the C2 neighbourhood (from 8 to 12 neighbours) in simulations with a cell size of 1000 m generates significantly different outputs of mean forest areas and number of patches after 48 years of simulation. Second, certain major modifications of cell size and neighbourhood configuration do not produce significant changes in results. In fact, using a neighbourhood composed of four neighbours compared to 40 neighbours does not significantly alter the simulation results when using the 100 m, 200 m and 500 m cell sizes. Potential reasons for these situations of important or nonexistent spatial scale sensitivity include the following: 1. The extent of the spatial influence of the land covers lies somewhere between the C4 and C5 neighbourhood configurations, 2. The use of the C5 neighbourhood accelerates the diffusion process of change and stabilizes the forest dynamics sooner and, 3. The C2 neighbourhood configuration is the neighbourhood of choice but its impact is only perceived through the use of the large 1000 m cell size.

3.4.4 Simulation results from the fixed transition rule experiment.

As mentioned earlier, simulations with fixed transition rules were performed to compare with the dynamics obtained from the original, empirically derived and changing transition rules. As expected, the responses of the spatial scale scenarios were not identical even if they were all generated from the same set of transition rules. Figure 3.9 shows the mean forest areas for all scenarios with fixed transition rules and Figure 3.10 illustrates the mean standardized number of patches. The only notable differences between these two graphs and the ones from the simulations with empirically-derived transition rules are the fact that the scenarios diverge faster from one another in mean forest area and that the scenarios have more spread out results in mean standardized number of patches. The influence of each spatial scale component was also investigated and showed no particular structure because each scenario does not adequately represent a particular scale. Their transition rule probabilities are not adapted to a spatial scale; they are only used and implemented at a particular spatial scale. These results ensure that the differences observed between scenarios in the original simulations were not caused by the differences between transition rule sets because, just as shown, even scenarios with the same transition rules generate different outcomes. The differences observed are therefore caused by the spatial scale parameters chosen when elaborating the transition rules.

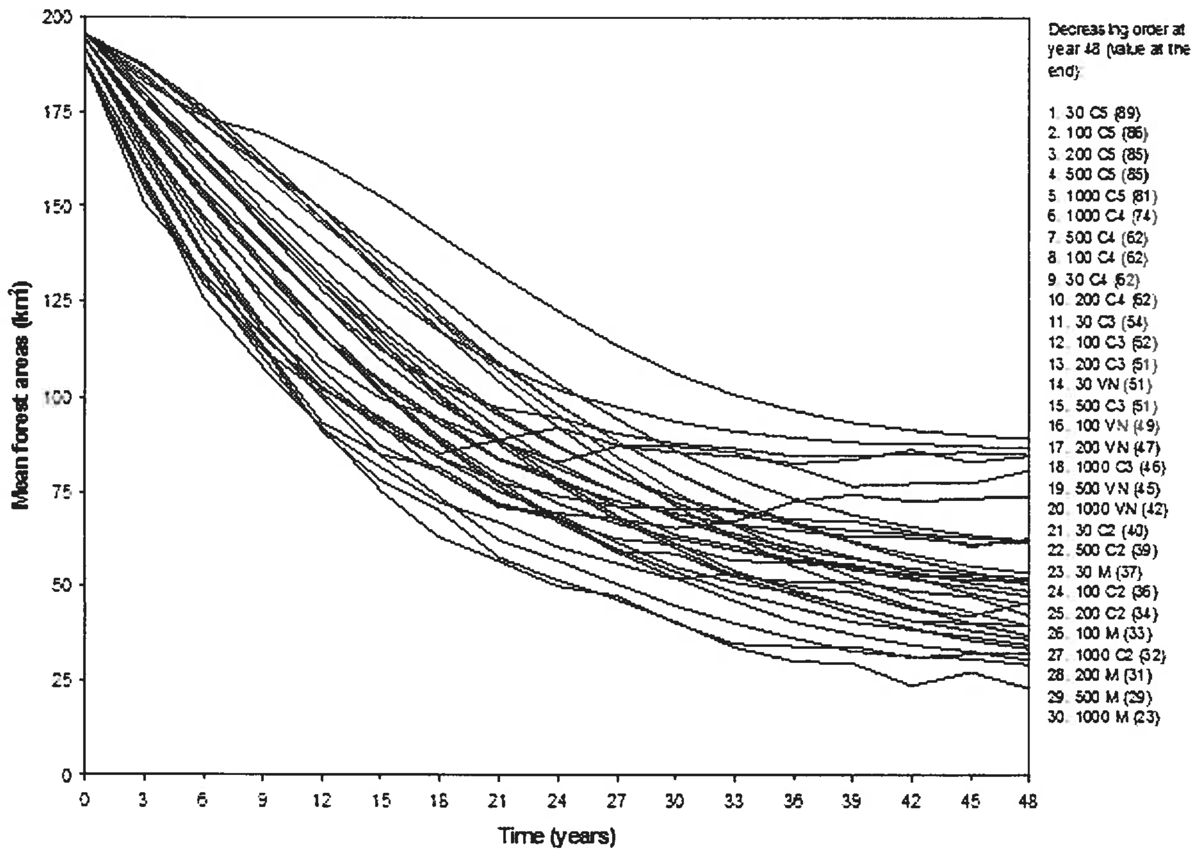


Figure 3.9 Mean forest area through time for all scenarios of the fixed transition rule experiment

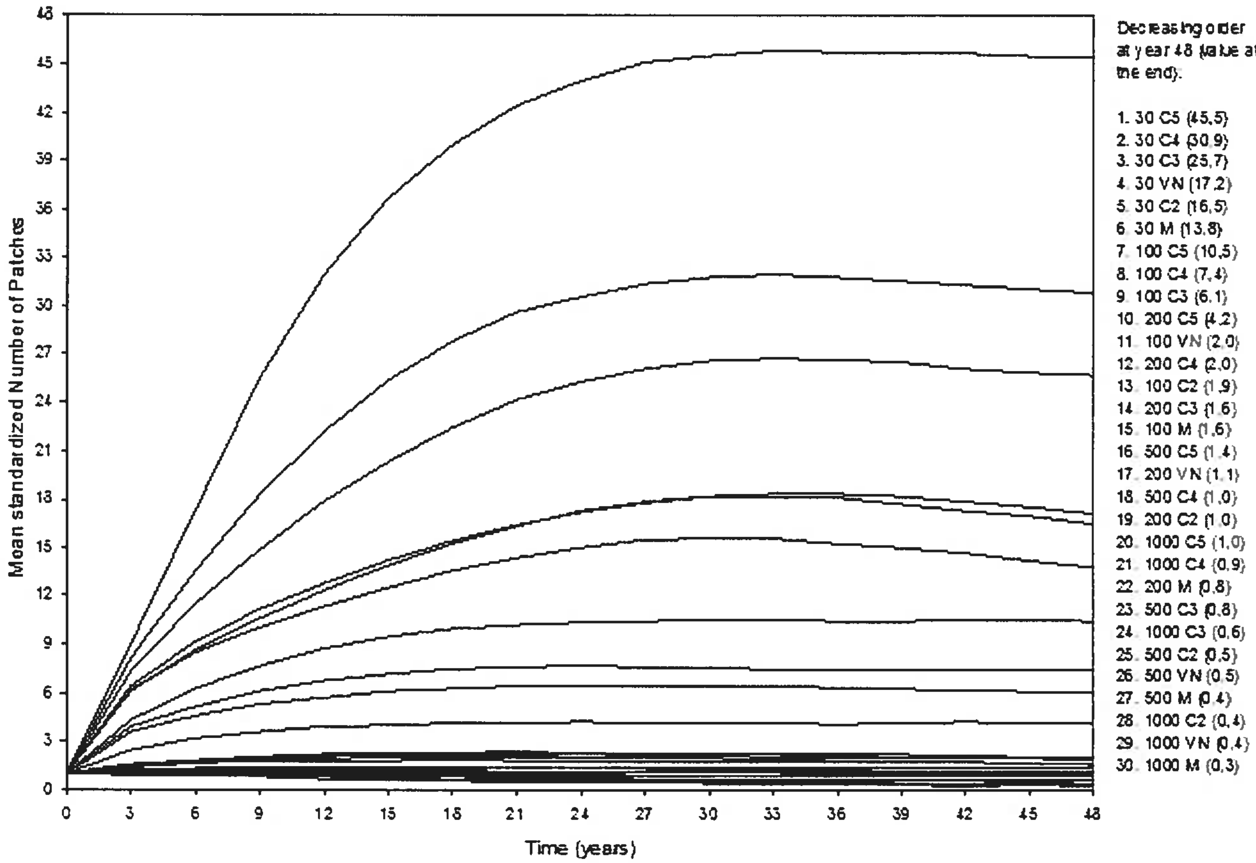


Figure 3.10 Mean standardized number of patches through time for all scenarios of the fixed transition rule experiment

3.4.5 Finer analysis of cell size sensitivity

So far, the results highlighted the structuring effect of cell size on the simulation outcomes. They have also clearly shown that simulations with a 30 m cell size generate dynamics which are very different than those performed with the other cell sizes. It was discussed earlier that the 30 m cell size is probably too small in comparison with the majority of the dynamical patches of the territory used to create the transition rule probabilities. On the other hand, the 100 m cell size is the closest to the average area of the dynamical patches and generates forest dynamics which are of the same order of magnitude than the other cell sizes. It is therefore legitimate to wonder what happens between the 30 m and the 100 m cell size. Is there a gradual or sharp transition from realistic to unrealistic behaviours between the two cell sizes? This situation calls for a finer exploration of spatial scale sensitivity.

The analysis of the results obtained from the additional simulations performed with 40 m, 50 m, 60 m, 70 m, 80 m and 90 m cell sizes suggests that the transition between the two opposing cell sizes (30 m and 100 m) is relatively sharp and that a threshold is present. A scale threshold is a relatively small portion of the scale continuum where simulation results significantly vary. The mean forest area time series for the six intermediate cell sizes show that the curves of cell sizes larger than 50 m exhibit the same trend as the 100 m cell size (Figure 3.11). The forest areas of the 40 m and 50 m cell sizes do not settle at the same value as the 30 m cell size but they clearly depart from the other cell sizes, which are very clustered around 25 km^2 of forest area after 48 years of simulation. The analysis of the number of patches also suggests that the transition between the 30 m and the 100 m cell size is non-linear (Figure 3.12). As cell size decreases, the number of patches generated increases. However, from cell sizes of 100 m to 60 m, the increase in number of patches is small and comparable to the results obtained with the other scenarios (200 m, 500 m, 1000 m). With smaller cell sizes (50 m, 40 m, 30 m), the increases are more substantial and increasingly larger. This finer exploration of spatial scale sensitivity in GCA is both reassuring and troubling. On one hand, it suggests that small variations in cell size do not dramatically alter simulation results. On the other hand, it confirms the presence of thresholds on each side of which simulation results are different. It the present study, no knowledge about the modeled territory could have suggested that such a threshold would be present between the 50 m and the 60 m cell sizes.

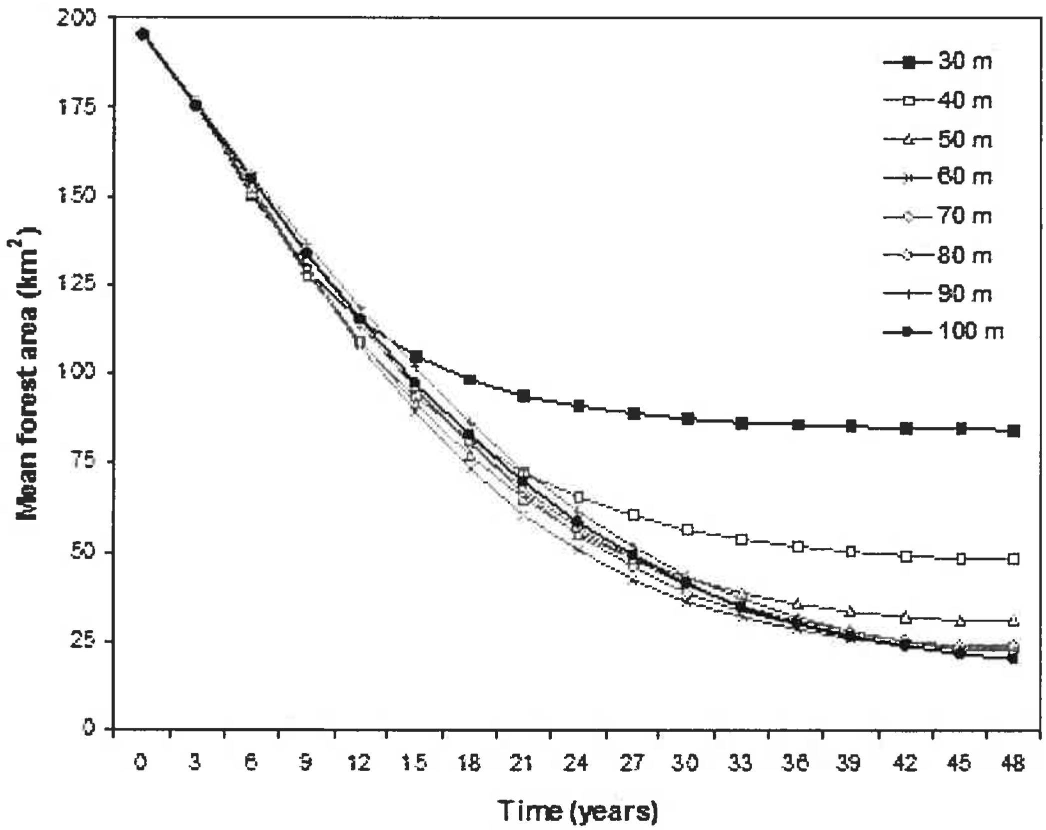


Figure 3.11 Mean forest area through time of the simulations performed with cell sizes between 30 m and 100 m (results for the 30 m and 100 m cell sizes are only given as references)

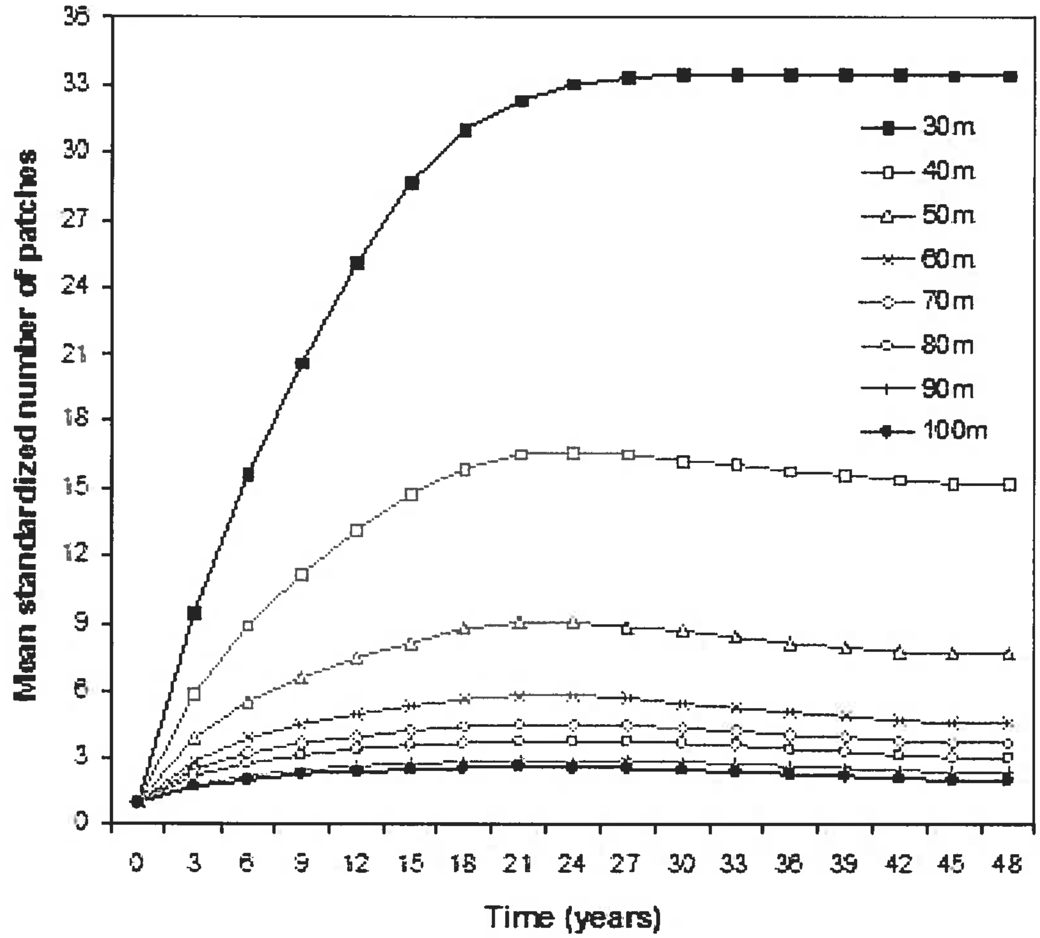


Figure 3.12 Mean standardized number of patches through time for the simulations performed with cell sizes between 30 m and 100 m (results for the 30 m and 100 m cell sizes are only given as references)

3.5 Conclusion

This research represents one of the first studies entirely centred on the characterization of spatial scale sensitivity in GCA. This sensitivity is very apparent in our results. Global and spatial indicators of GCA simulations are both influenced by the choices made regarding cell size and neighbourhood configuration. In our results, choosing a larger cell size conserved more forest areas but created proportionally less patches. An exception to that rule is the case of the 30 m cell size. The transition rule probabilities of this cell size, for all neighbourhood configurations, are biased because of the size distribution of the dynamical patches present in the original dataset. This situation reveals that using the finest resolution available is not always a wise decision and reiterates the importance of adapting the cell size to the objects composing the landscape. Further, the finer exploration of cell size sensitivity suggests that even small variations in cell size can produce significant divergence in results when scale thresholds are crossed. The choice of a neighbourhood configuration is less influential on simulation results but the relationship between this spatial scale component and the indicators is not always linear and caution is needed. Spatial scale sensitivity affects all cellular automata where the cells actually represent a real portion of the geographic space. Geographers and other scientists elaborating GCA should be concerned by this situation and should grant it more attention.

The goal of a sensitivity analysis is to establish the overall behaviour of a system or model to the variation of a parameter. In order to realize the sensitivity analysis of GCA to the spatial scale components, extreme values of cell size and neighbourhood configurations were initially selected and tested. Our GCA was therefore tested for many and very diverse spatial scales. We acknowledge that in the process of elaborating a GCA it is not realistic to drastically change spatial scale. Once the theoretical approach of a study is elaborated and the phenomenon to be investigated is fixed, the spatial scale is usually determined and does not vary so much from then on. However, in too many GCA applications the authors only mention data availability or do not mention anything when explaining their choice of cell size and neighbourhood configuration. Too many are elaborated without considering the coarse or even the fine scale variation sensitivities that might be in effect. The present study reveals that spatial scale sensitivities should not be overlooked.

Since GCA simulations are often used in the context of land and resource management, scale sensitivity of results might introduce considerable consequences in terms of decision-making. We therefore suggest that in such cases, a spatial scale sensitivity analysis should be conducted to assess the envelop of possible outcomes. While it is realistically impossible to test all possible combinations of scale component values, the identification of scale thresholds should be the research priority. Their identification establishes the various scale domains that are present through scale. Without information about scale domains, GCA results are difficult to generalize. Even though it is reasonable to assume that the impact of small variations in scale component values is relatively small, a scale threshold might generate relatively important changes in simulations results. A sensitivity analysis does not remove the scale problem, but is the simplest way of limiting its effects. It is also the easiest way of dealing with this problem while conserving as much as possible the original CA formalism.

Another way of dealing with spatial scale sensitivity that is rapidly gaining popularity in GCA applications is vector or object-based GCA. In such models, each cells has a particular size and shape that corresponds to an actual areal unit present at that scale. Examples of such GCA are provided by the use of polygonal or irregularly-tesselated GCA (Shi and Pang, 2000; O'Sullivan, 2001). Spatial scale problems are less influential in those GCA because units defined based on coherent areal units are not interchangeable. Problems with that apparently simple and effective option include the actual definition of the areal units and the complexity of the neighbourhood topology. These problems, in turn, make the computation of GCA simulation much more time consuming and processing intensive.

3.6 Acknowledgments

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PARAGRAPHE DE LIAISON B

Le chapitre 3 a permis de découvrir que les automates cellulaires (AC) sont sensibles à l'échelle spatiale. Des changements dans la taille de cellule et dans les configurations de voisinage utilisées génèrent des changements dans les résultats globaux et spatiaux des simulations. L'intéraction des deux composantes de l'échelle spatiale permet aussi la localisation de domaines d'échelle spatiale à l'intérieur desquelles des variations de paramètres ne résultent pas en des variations significatives des résultats de simulation. Sur les bases de ces résultats et conclusions de l'analyse de sensibilité à l'échelle spatiale, un AC permettant de tester des scénarios d'utilisation du sol pour la MRC des Maskoutains est développé (chapitre 4). Ces simulations permettent d'entrevoir les impacts spatio-temporels potentiels de scénarios de réduction de la déforestation, de promotion de la ligniculture, de protection de la connectivité des parcelles de forêt et du statu quo.

CHAPITRE 4. A MODELING INVESTIGATION OF FOREST MANAGEMENT SCENARIOS IN AN AGRICULTURAL LANDSCAPE OF SOUTHERN QUEBEC, CANADA[3]

4.1 Abstract

Forest remnants are vital for the overall heterogeneity and health of rural landscapes. However, deforestation is a significant process afflicting large numbers of agroforested regions of the world. The Maskoutains RCM (Regional County Municipality) in southern Quebec, Canada, experiences intense deforestation that has reached critical levels. The goal of this study is to develop a GCA (Geographic Cellular Automata) to model land-use change in this region and test the influence of different management scenarios on the fate of the forested remnants. The GCA was built using a 100 m cell size, a Moore neighborhood configuration, a three years time step resolution and probabilistic transition rules derived from the comparison of two land-use maps for the years 1999 and 2002. Four groups of management scenarios were tested: 1) status quo (SQ), 2) reduced deforestation (RD), 3) promotion of ligniculture (L), and 4) protection of forest connectivity (CONN). Results indicate that none of the scenarios succeed in maintaining the actual levels of forest area. However, certain scenarios (amongst the RD and CONN), significantly alter the loss of forest areas in the short to mid-term and delay the fragmentation, reduction, and isolation of forest patches.

Keywords: geographic cellular automata, land-use change, Maskoutains region, simulation, spatial modeling.

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[3] Ménard, A. and D. J. Marceau (2005) A modeling investigation of forest management scenarios in an agricultural landscape of southern Quebec, Canada. Landscape and Urban Planning (accepté pour publication)

4.2 Introduction

The multiple significant roles of forest remnants in rural environments dominated by agricultural matrices are well documented. They contribute to the overall spatial, structural and aesthetic heterogeneity of rural landscapes (Domon, 1994), they help maintain the biodiversity by protecting a wider range of habitats (Wilcove, 1985), and they constitute corridors that preserve important levels of landscape connectivity for specific wildlife populations (Lynch and Whitcomb, 1978; Robinson et al., 1995; Burke and Nol, 1998). It has also been shown that they participate in the regulation of surface and underground hydrological regimes, they offer protection against wind erosion, and they help reducing the pollution originating from cultivated areas (Gangbazo and Bazin, 2000; Patoine and Simoneau, 2002). However, the status of these forested areas is uncertain in many regions of the world since agroforested landscapes are undergoing important changes (Meeus et al., 1990; Meeus, 1995; Ilbery, 1998; Sylvestre, 2002). Driven by the interactions between biophysical, sociological, economical and political characteristics of the concerned regions (Pan et al., 1999), these changes have resulted in high levels of forest fragmentation and decline (Westmacott and Worthington, 1984; Malecki and Sullivan, 1987).

The agroforested landscapes of southern Quebec have also experienced these important transformations (Domon, 1994; Bélanger and Grenier, 1998). Since the second half of the nineteenth century, Quebec agriculture has been primarily devoted to milk production. However, in the 1970s, a series of interacting events (major improvements in crop productivity, milk market stagnation, and increased international demand for grain (Domon et al., 1993; Bélanger, 1999)) prompted the provincial government to encourage the grain corn production. The demands of this more specialized and industrialized agricultural production resulted in the homogenization of the biophysical conditions, in an intensification of agriculture land-use, and in the removal of most typically rural landscape elements (Domon, 1994). Consequently, about 70% of all forested areas in the St. Lawrence valley have been transformed, principally in zones of high agricultural vocation (Bélanger and Grenier, 1998), and it is estimated that the southernmost regions of the province of Quebec have lost 15% to 17% of their forested areas between 1971 and 1986 (Desponts, 1995). From these transformations, some regions have fallen to levels of forest cover that already threaten many species and compromise the ecological and aesthetic integrity of their territory.

The Maskoutains regional county municipality (RCM) in Quebec is a good example of the intensity of the deforestation and landscape homogenization that characterizes certain agroforested areas. This RCM, which is part of the Monteregie administrative region, covers an area of 1312 km^2 situated east of Montreal and centered on the city of St. Hyacinthe (Figure 4.1). This city is considered the capital and techno-center of Quebec agriculture. Close to 97% of its territory is protected from development and is dedicated to agricultural purposes because of its highly productive soils and favorable climatic conditions, and its proximity to the Montreal urban area (Gouvernement du Québec, 2001). The proportion of forested areas in this region decreased from 20% in 1984 (262 km^2) to 15% in 2002 (200 km^2) (Li and Beauchesne, 2003; Savoie et al., 2002; Soucy-Gonthier et al., 2002). In comparison, the percentages of forested cover in the whole Monteregie region have dropped from 33% in 1984 to 26% in 2002. The principal explanation for the continued forest decline since the middle of the 1980s in the Maskoutains RCM is the development and growth of the porcine industry. This industry exhibits an important growth in Quebec, and the east of the Monteregie region, which includes the Maskoutains RCM, is the most important producing region with 29% of the province porcine production (Gouvernement du Québec, 2003). This situation increases deforestation since many producers deforest their wooded lots to scatter manure as fertilizer (Delage, 2004). Moreover, some corn-grain producers also find advantageous to deforest available forested areas in response to the high demand for agricultural territories (Bonin, 2002; Savoie et al., 2002).

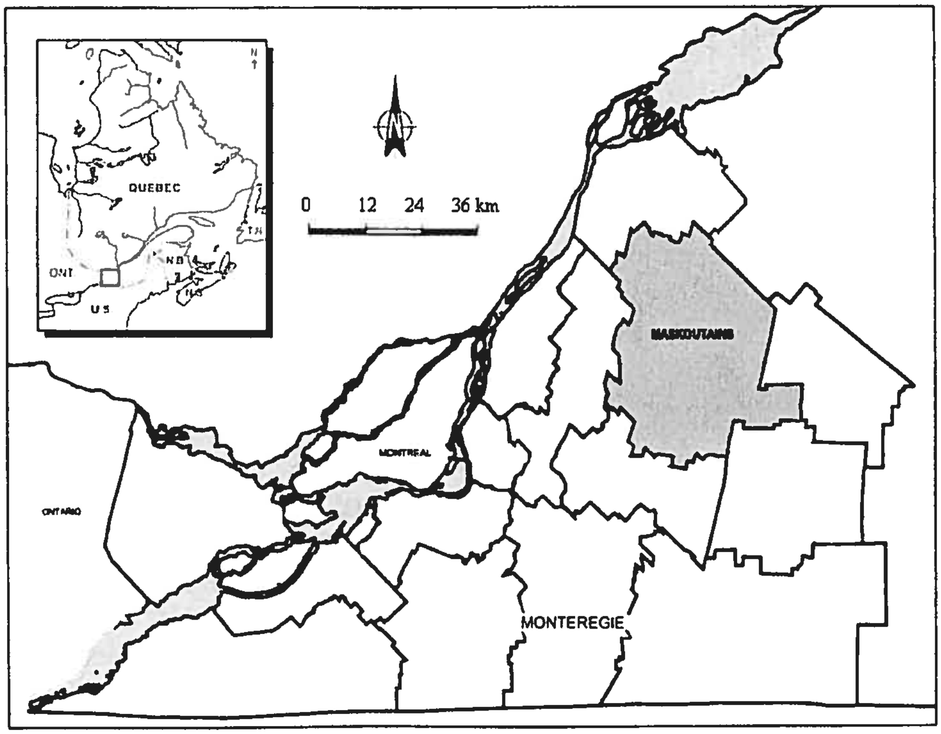

Figure 4.1 Map locating the study area: the Maskoutains regional county municipality (RCM) in the Monteregie administrative region of southern Quebec, Canada.

The past evolution of forested areas and the present dynamics in the Maskoutains RCM both jeopardize the future of this territory in terms of biodiversity and environmental integrity. What will happen to the remaining forest patches? Will there be no more forested environments in the Maskoutains region in a near future? Can management decisions protect what is left of forest? These are some of the questions that are starting to surface from scientists and concerned citizens alike (Soucy-Gonthier et al., 2002; Delage, 2004). While some predict that no forest will remain in about 20 to 25 years based on the direct extrapolation of net amounts of forest area loss each year, others try to ponder what would happen if deforestation were reduced or if the government encouraged ligniculture in the area. These concerns about the future of this region's forest remnants are related to one of the main driving forces in global environmental change: land-use/land-cover change (Lambin et al., 2000).

Recently, research on land-use/land-cover change has been increasingly performed with models. Modeling, especially if done in a spatially-explicit and integrated way, is an important technique for the exploration of alternative pathways into the future, and for conducting experiments that test our understanding of key landscape processes (Lambin et al., 2000). Cellular automata (CA) are dynamic models of the geographic space in which the global properties arise from the many local and spatial interactions of its entities (Wu and Webster, 2000; Lightenberg et al., 2001). Generally speaking, CA are characterized by a matrix space, where each cell possesses a state (a type of land-use/land-cover). Time is discrete and at each iteration the states of the cells are updated through the application of a set of defined transition rules. These rules dictate how the different cell states will react to state configurations present in a specific neighborhood of each cell. Characteristics of CA used in today's models are a mixture of the original CA formalism (Wolfram, 1984) and multiple transformations required for the modeling of the geographic space (Couclelis, 1997; Torrens and O'Sullivan, 2001).

Geographic Cellular Automata (GCA) have been used abundantly in the last decade to model land-use/land-cover change, mostly in urban environments (Batty and Xie, 1994; Clarke et al., 1997; White et al., 1997; Clarke and Gaydos, 1998; Wu and Webster, 1998; Wu, 2002; de Almeida et al., 2003; Barredo et al., 2003). Some regional applications of GCA to the study of land-use change have also been developed (Engelen et al., 1995; White and Engelen, 2000; Li and Yeh, 2000; 2002; Jenerette and Wu, 2001). Few studies focused on the land-use dynamics of rural or more natural landscapes; examples are provided by the modeling of rural residential settlement patterns in the periphery of Toronto (Deadman et al., 1993) and in the Rocky Mountains (Theobald and Hobbs, 1998), and deforestation in the Brazilian Amazonian forest (Soares-Filho et al., 2002). These studies have consistently shown that the GCA modeling framework is well suited to capture the highly decentralized, multi-criteria, and spatial dynamics of the geographic space.

The goal of this study is to develop a GCA to model land-use change in the Maskoutains RCM and test the influence of different hypothetical management scenarios on the fate of the forested remnants. The originality of this study lies in the investigation of the spatial expression of the deforestation process that occurs in the region and its use in the modeling of alternative pathways into the future. These alternative pathways will provide glimpses as to the ability of forest remnants to provide elements of heterogeneity in an increasingly homogenizing landscape.

4.3 Methodology

4.3.1 Dataset used

The dataset used in this study includes two land-use maps of the Maskoutains region, for the years 1999 and 2002, derived from the classification of two Landsat-TM remote sensing images (Soucy-Gonthier et al., 2002). The original spatial resolution of these images is 30 m and the land-use classes are forest, agriculture (also including all non-forested vegetation like herbaceous and arbustive fallow lands) and others (urban areas, roads, water, ...). Based on exhaustive field verification, the final land-use maps created had an overall reliability of 88,5%. These classified maps were combined with a simplified map of soil capability for agriculture (Gouvernement du Canada, 1972). This was done because evidence suggests that land uses are correlated with superficial deposits in this region (Pan et al., 1999). The combination of the land-use map with a binary version (high potential vs. moderate-to-low potential) of the soil capability for agriculture map results into a new land-use map composed of four classes, which are forest and agriculture on both high potential and moderate-to-low potential soils.

4.3.2 GCA elaboration

As explained before, a GCA is composed of five main components: a matrix space, a neighborhood configuration, a time step resolution, an ensemble of cell states, and a set of transition rules. This section details how each component was defined.

The three first GCA components determine the operational spatial and temporal scales at which the model is built. Scale sensitivity analyses were performed on this dataset to determine the appropriate scale parameters (Ménard and Marceau, 2005; Ménard and Marceau, unpublished results). On the basis of these results, the original maps were re-sampled, using a nearest-neighbor method, to a cell size of 100 m, which better corresponds to the spatial entities of the territory. The matrix space of the present model is therefore composed of cells of 1 ha and covers the entire Maskoutains RCM (429 columns by 528 lines). The neighborhood configuration chosen is the Moore neighborhood that takes into consideration the eight first-order neighbors of each cell. Finally, the time step resolution was set to three years, which also corresponds to the temporal interval between the land-use maps. The simulations cover a temporal extent of 45 years or 15 time steps (from 2002 to 2047).

The ensemble of cell states includes five states: 1) forest on soils with high potential for agriculture, 2) forest on soils with moderate-to-low potential, 3) agriculture on soils with high potential, 4) agriculture on soils with moderate-to-low potential, and 5) other land uses (including urban areas, water, roads). Cells of the fifth state do not change status in the simulations and do not influence the fate of the cells of the other states. The urban cells were excluded from the simulations since 97% of the territory is protected from urban development. As expected in the St. Lawrence lowlands, the landscape is very flat and topography that can deter the establishment of any of the two main land uses is essentially absent, with the exception of the Rougemont Hill. However, this hill, which is mostly forested, is protected from agricultural intensification by its slope values but also by a landowner association devoted to ecological preservation and sustainable development (APDDMR, 2004). No land-use changes are therefore allowed on the Rougemont Hill.

The main component of any GCA is the set of transition rules (Torrens, 2000). The method used here empirically derives the transition rules from a comparison between the two land-use maps acquired in 1999 and 2002, respectively, to determine the cells that have changed between maps. From that comparison, four land-use changes were identified: 1) forest changing to agriculture on soils with high potential for agriculture, 2) forest changing to agriculture on soils with moderate-to-low potential, 3) agriculture changing to forest on soils with high potential, and 4) agriculture changing to forest on soils with moderate-to-low potential. The first two land-use changes correspond to a deforestation process and the last two to an agricultural abandonment process. For each land-use change, the probability that a cell with n neighbors of the other state changes state is computed by dividing the number of cells with n neighbors of the other state at time t_1 that changed state at time t_2 by the total number of cells with n neighbors of the other state at time t_1. In mathematical terms, the following equation is applied to compute the transition rule probabilities for all four possible land-use change transitions:

$$\underset{n=0}{\overset{N}{P}} = \frac{\sum_{i=1}^{a}\sum_{j=1}^{b}(C_{ijn_{t_1}} \neq C_{ij_{t_2}})}{\sum_{i=1}^{a}\sum_{j=1}^{b} C_{ijn_{t_1}}}$$

where P is the probability of change, N is the number of neighbors of the opposite state in the neighborhood (maximum is 8), a is the number of rows, b is the number of columns, C represents the cells of the state for which the probabilities are computed, t_1 is the first land-use map of year 1999 and t_2 is the second land-use map of year 2002. The rationale behind this linear interpolation method (Jenerette and Wu, 2001) is that the presence of cells of the opposing state in the neighborhood of a cell increases this cell's chances of changing state. A total of 36 transition probabilities were derived this way since there are four possible land-use transitions and the number of neighbors of the opposite state in the Moore neighborhood configuration ranges from zero to eight (Table 4.1). Since the simulations performed with these transition rules are probabilistic, ten replicates were executed for each scenario tested.

Table 4.1 Transition rule probabilities of the status quo scenario (SQ)

	Pressure to change (number of neighbors of the opposing state)								
Transitions	0	1	2	3	4	5	6	7	8
AtoFonMod[1]	0,00	0,04	0,08	0,12	0,20	0,28	0,40	0,38	0,51
AtoFonGood[2]	0,00	0,04	0,06	0,12	0,27	0,28	0,36	0,80	0,80
FtoAonMod[3]	0,07	0,15	0,21	0,26	0,37	0,45	0,53	0,64	0,79
FtoAonGood[4]	0,10	0,12	0,23	0,27	0,38	0,44	0,59	0,71	0,89

[1] Agriculture to Forest on soils with Moderate-to-low potential for agriculture
[2] Agriculture to Forest on soils with Good potential for agriculture
[3] Forest to Agriculture on soils with Moderate-to-low potential for agriculture
[4] Forest to agriculture on soils with Good potential for agriculture

Table 4.1 Transition rule probabilities of the status quo scenarios (SQ)

A strong relationship was observed between the cells that changed state between the two years and the pressure found in their neighborhood. In fact, a significant 0.91 correlation (Pearson coefficient at alpha =

0.05) was found between the probabilities of change of cells and the number of cells of the opposing state in their neighborhood. This situation indicates that local dynamics are drivers of the land-use change in this region and reinforces the adequacy of using GCA as a modeling tool (Jenerette and Wu, 2001).

4.3.3 Description of the scenarios tested

Through the use of this model, four main groups of scenarios were elaborated and tested: 1) *status quo* (SQ), 2) *reduction in deforestation* (RD), 3) *development of ligniculture* (L), and 4) *protection of forest connectivity* (CONN). The elaboration of these scenarios is based on the following comprehension of the territory. The analysis of the two land-use maps revealed two main processes occurring in the landscape: deforestation, resulting from the cutting of forest remnants, and aforestation caused by agricultural abandonment. Some agriculture cells of the 1999 map, which were actually old fallow lands, became forest cells on the 2002 map in aproportion of 2,3%. In comparison, 21,8% of the 1999 forest cells changed to agriculture. This analysis confirms that the opposition between forest and agriculture land uses is the major land-use transition present in the Maskoutains RCM.

The status quo (SQ) scenario represents the baseline scenario of land-use change in the region. It illustrates the application of the transition rule probabilities computed from the two maps. The application of the probabilities determines the evolution of the state of the cells (Figure 4.2). In order to restrict the occurrence of improbable land-use transitions, four alterations were added to this framework (numerical indices in Figure 4.2). First, forest cells on both high and moderate-to-low potential soils that changed to agriculture during the simulations were restricted from changing back to forest (#3 in figure 4.2). It was assumed that in the temporal extent used in the simulations (45 years), it was highly improbable that deforested areas would be abandoned long enough to go back to their forest state. Second, the agriculture-to-forest-to-agriculture transition was partially restricted. In fact, on high potential soils, it is possible for abandoned agricultural territories (rare cases) to be deforested. However, this situation is less probable on moderate-to-low potential soils where agricultural pressures are relatively less intense. This explains why agriculture cells on moderate-to-low potential soils that changed to the forest state were restricted from changing back to agriculture while their neighborhood remained composed of four to eight forest cells (#1 an #2 in Figure 4.2). If the number of forest cells in their neighborhood falls below four, then these forest cells are no longer protected from deforestation (#4 in Figure 4.2).

While the SQ scenario extrapolates the rate of land-use changes that occurred between 1999 and 2002 over the simulation period of 45 years, the reduced deforestation (RD) scenarios were elaborated to simulate less intense deforestation process. Many circumstances could contribute to reducing deforestation: decline in demands for pork and corn-grain, new technologies for manure elimination, governmental incentives for cleaner manure elimination, etc. But would these hypothetical circumstances be sufficient to change the overall tendency of decline of forest areas? To answer this question, three scenarios were defined. They correspond to reduction in deforestation of 10%, 30% and 50%, respectively. The transition probabilities of the forest-to-agriculture transition on both types of soils were uniformly reduced by these percentages in order to model these reductions (RD in Figure 4.2).

The development of ligniculture (L) scenarios were implemented to model the hypothetical repercussions on the Maskoutains RCM of the forest management principle called TRIADE (QUAD) (Hunter, 1990), which is gaining popularity in Quebec. In the present context, where Quebec forests have difficulty keeping up with the wood demands (Coulombe et al., 2004) and where the pressure for integral conservation is growing (Messier, 2001), it clearly appears that the fertile and climatically favorable territories of the south of the province, traditionally neglected because they are too spatially and administratively fragmented, need to be more effectively used. In that optic, the TRIADE principle relies on a territorial allocation scenario in four zones: 1) eco-systemic management and planning of 74% of the forested territories, 2) integral protection of 12%, 3) traditional intensive management on 10%, and 4) ligniculture on 4% (Messier, 1999). Ligniculture is defined as the intensive culture of trees in plantations with the goal of obtaining the optimum rates of timber production (Réseau Ligniculture Québec, 2004). In order to use the many advantages of the agroforested territories of the south of the province, it was suggested that fallow and abandoned lands be used for the development of ligniculture (Messier, 2001).

To model this situation and elaborate appropriate scenarios, the following modifications were made to the status quo scenario (L in Figure 4.2). First, once all transition probabilities have been applied at a time step, the transition probabilities of the agriculture-to-forest transition on moderate-to-low potential soils were reapplied in order to identify agriculture cells with potential for ligniculture. Cells that would change to forest are essentially abandoned agriculture that became fallow lands. Out of all these agriculture cells with potential for ligniculture, only a certain proportion is actually converted to ligniculture. These proportions correspond to adherence level from the part of the landowners. Three percentages were tested: 10%, 20% and 30% of landowner adherence to a hypothetical ligniculture program. Then, each ligniculture cell is perceived as a forest cell by its neighboring cells.

Finally, the protection of forest connectivity (CONN) scenario was designed to test the impact of a forest landscape management strategy aimed at protecting the interconnectedness of the forested environment. Connectivity is defined as the degree to which a landscape facilitates or impedes movement of organisms among resource patches (Tischendorf and Fahrig, 2000). One of the most important threats to ecological diversity is patch isolation and some scientists mention that one of the rare solutions to this problem in the agro-industrialized landscapes of southern Quebec is to protect forested corridors (Messier, 2001). Therefore, a simple rule was added to the status quo scenario in order to model this situation: if the removal of a forest cell (changing to agriculture) increased the total number of forest patches then this removal was restricted (C in Figure 4.2). The increase in number of patches indicates that a forest cell is important for the connectivity of two or more forest cells. The Moore neighborhood was used to assess cell connectivity in this exercise.

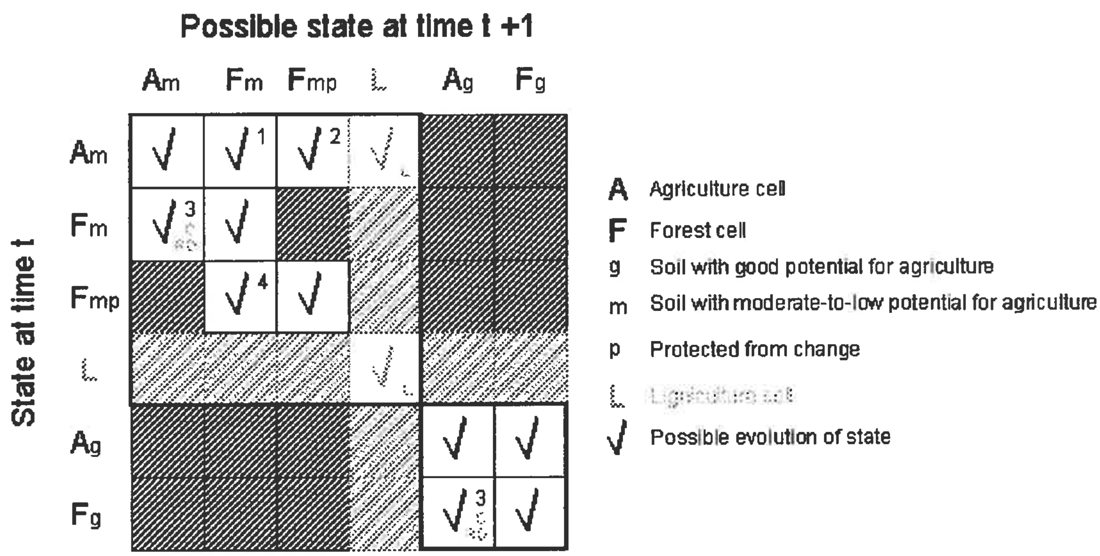

Figure 4.2 Illustration of the possible transitions of the status quo (SQ) scenario and all modifications performed to model the other scenarios (Notes: All black indications in the figure represent details of the SQ scenario and all grey ones represent modifications for the other scenarios: 1) transition to forest state if change occurred with 0 to 3 forest neighbors; 2) transition to protected forest state if change occurred with 4 to 8 forest neighbors; 3) transition to agriculture is irreversible; 4) change automatically performed if the number of agriculture cells increases to more than 3; RD) probabilities of this transition are reduced of 10%, 30% and 50%; L) transition explained in the text with adherence levels set at 10%, 20% and 30%; C) transition restricted if the number of forest patches increases in consequence of the potential transition)

4.4 Results and interpretation

The impact of each of the eight scenarios is assessed by the analysis of the composition (total area), fragmentation (number of patches), complexity (total edges) and proximity (euclidian nearest neighbor distance) of the forest patches through time. Since ten replicates per scenario were performed, mean values for all these indicators are analyzed. The choice of these spatial metrics was based on commonly applied metrics seen in the literature (Jenerette and Wu, 2002; McGarigal, 2004; Herold et al., 2005)

4.4.1 Forest composition

The analysis of the mean forest areas through time reveals that none of the scenarios can maintain the actual levels of forest area (Figure 4.3). Starting with more than 190 km² in 2002, the forest areas range from 9 to 34 km² after 45 years for all scenarios. No matter what scenario is used, less than 3% of the territory of the Maskoutains RCM is covered by forest at the end of the simulations. The SQ, L10%, L20% and L30% scenarios exhibit the same overall dynamics of forest areas, characterized by an abrupt decline in the first half of the simulations (0 to 21 years), and a stabilization in the second half (21 to 45 years). This stabilization around 10 km² of forest areas can mainly be attributed to the constant abandonment of agriculture lands by a few landowners. The three scenarios where deforestation is reduced (RD10%, RD30% and RD50%) produce a smaller initial decline of forest areas. While the effect is almost imperceptible in the RD10% scenario, it is obvious in the results of the RD30% and RD50% scenarios. After 21 years of simulations, these two scenarios respectively still present 62 and 115 km² of forest area, which is significantly more than the other scenarios, with the exception of the CONN scenarios. The latter also displays a smaller initial decline in forest area with 59 km² of forest areas after 21 years but also stabilizes faster and ultimately conserves the largest amounts of forest areas of all scenarios at the end of the simulation (34 km²).

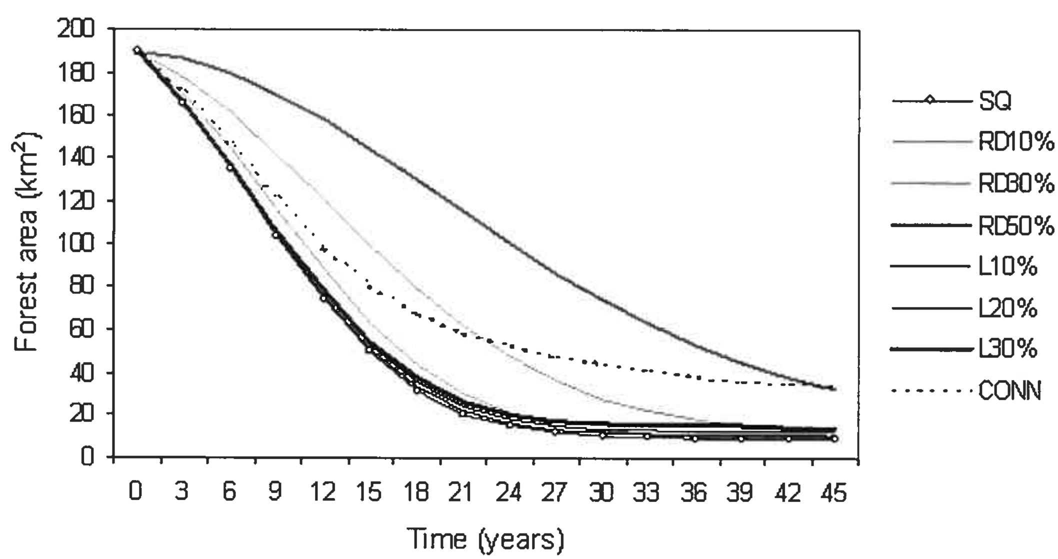

Figure 4.3 Mean forest areas through time for all scenarios

4.4.2 Forest fragmentation and patch complexity

The high levels of deforestation observed in the temporal dynamics of all scenarios originate from three main spatial processes: fragmentation, shrinkage, or complete elimination of forest patches. These three processes respectively increase, do not alter, and reduce the number of forest patches present in the landscape. If fragmentation and elimination are equally influential in the spatial dynamics generated by the GCA, then the total number of forest patches, or forest overall fragmentation, would remain stable. The analysis of the mean number of forest patches for all scenarios clearly shows that the situation is far from stable (Figure 4.4). The number of forest patches initially abruptly increases for the majority of the scenarios until between years 15 and 18. Then, a similarly intense decline affects the number of forest patches and they ultimately end the simulations at values relatively close to what they were at the start of the simulations. What causes this dual dynamics is the successive importance of the fragmentation and elimination processes. The initial effect of deforestation simultaneously reduces and fragments the forest patches. Once the majority of the forest patches are small and isolated, deforestation primarily results in the elimination of forest patches. While all scenarios relatively display this dual dynamics in terms of forest fragmentation, certain scenarios present unique characteristics. First, the presence of ligniculture cells tends to reduce the destruction of forest patches in the second half of the simulations. In addition, the phenomenon intensifies as the ligniculture adherence probability increases. Second, the RD30% and RD50% scenarios significantly slow down the initial fragmentation process. The maximum numbers of forest patches are reached after 24 years of simulation for the RD30% scenario and after 36 years for the RD50% scenario, which is, respectively, 9 and 21 years after the SQ scenario.

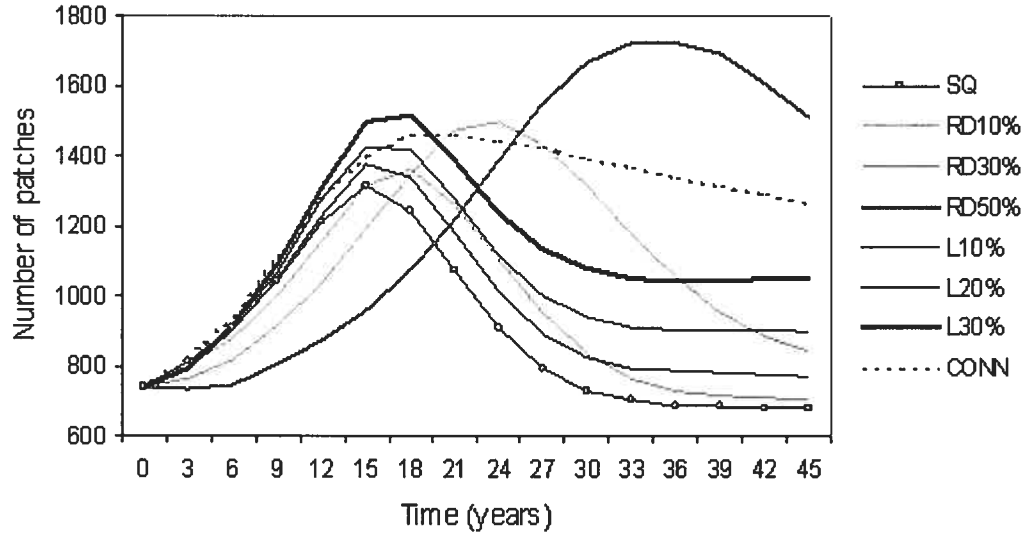

Figure 4.4 Mean number of forest patches through time for all scenarios

The CONN scenario, which was designed to reduce forest fragmentation, also presents a particular patch dynamics since it generates as many patches as the other scenarios. The explanation for this unexpected behaviour lies essentially in the shape of the forest patches created by this scenario. In fact, in all scenarios a certain amounts of new forest patches are created at each time step to model agricultural abandonment and the ultimate evolution of fallow lands. However, in seven of the eight scenarios this dynamics is not predominant. In the CONN scenario, this phenomenon takes more importance in the tabulation of the number of forest patches since the initial deforestation can only reduce in size the forest patches and cannot fraction them. This situation tends to generate more elongated and complex forest patches. Consequently, these resulting forest patches have initially more edges than the patches of the other scenarios (Figure 4.5) and therefore, more interactions with agriculture cells. These interactions in turn promote the apparition of more forest patches since they locally reduce the pressures of the agriculture cells. It is also evident from the mean number of forest edges that the massive deforestation occurring in all scenarios is significantly reducing the complexity of the forest patches. Again, the RD30% and RD50% scenarios delay this decline by maintaining for a longer period a wider variety of forest patches, both in terms of morphology and size. Finally, in relation with this last point, the Maskoutains RCM counted 34 forest patches larger than 1 km^2 (100 ha) in 2002 and in all but one of the scenarios none of them remained after 24 years in average. The RD50% still presented in average more than 25 very large patches after 18 years and it takes 33 years for the last one to shrink under the 1 km^2 threshold. These large forest patches are often perceived as an indicator of ecological viability since they insure the presence of core habitats.

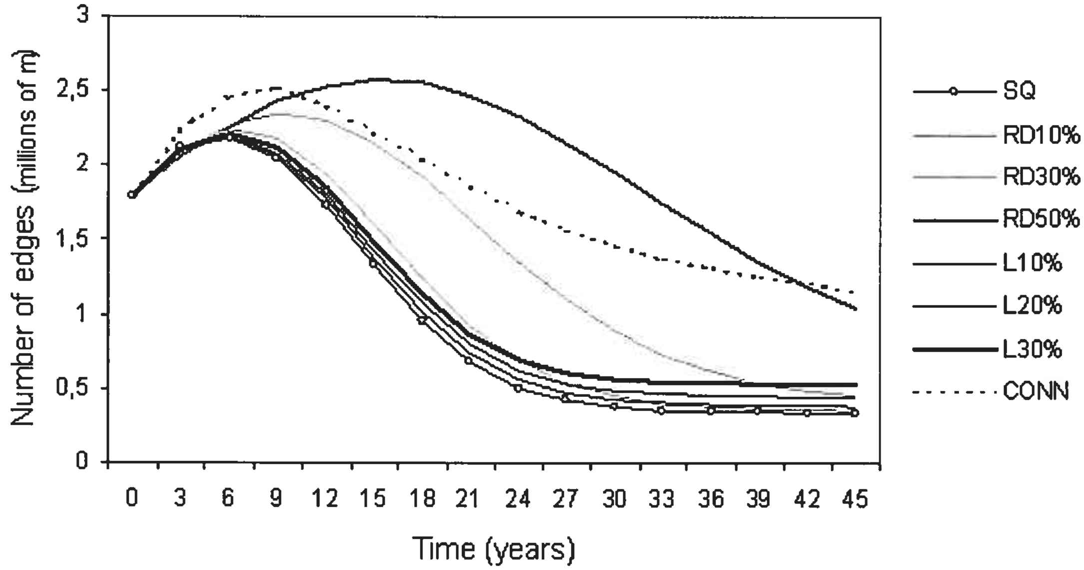

Figure 4.5 Mean number of forest edges through time for all scenarios

4.4.3 Forest patch proximity

Another important ecological component of landscape forest is patch proximity. The mean distances of the euclidean nearest neighbor were used to characterize the level of proximity of the forest patches (Figure 4.6). As expected, patch proximity initially decreases from close to 350 m to less than 300 m for all scenarios (0 to 12-15 years). This is essentially caused by the fragmentation of large forest patches into many smaller patches. Then, the forest patches become increasingly isolated as time advances. For example, the mean nearest neighbor distance for the SQ scenario changes from 276 m to 417 m in only 18 years (year 12 to 30). Many other scenarios experience a similar increase (RD10%, L10%, L20%, L30% and CONN), but their values ultimately stabilize at a smaller distance (with the exception of RD10%). Again, the scenarios that depart the most from this overall dynamics are RD30% and RD50%. They notably attain their smallest proximity distances a few years after the other scenarios (years 18 and 27 respectively), but the results for RD30% suggest that both scenarios, given more simulation increments, would not produce significantly different isolation values than the other scenarios.

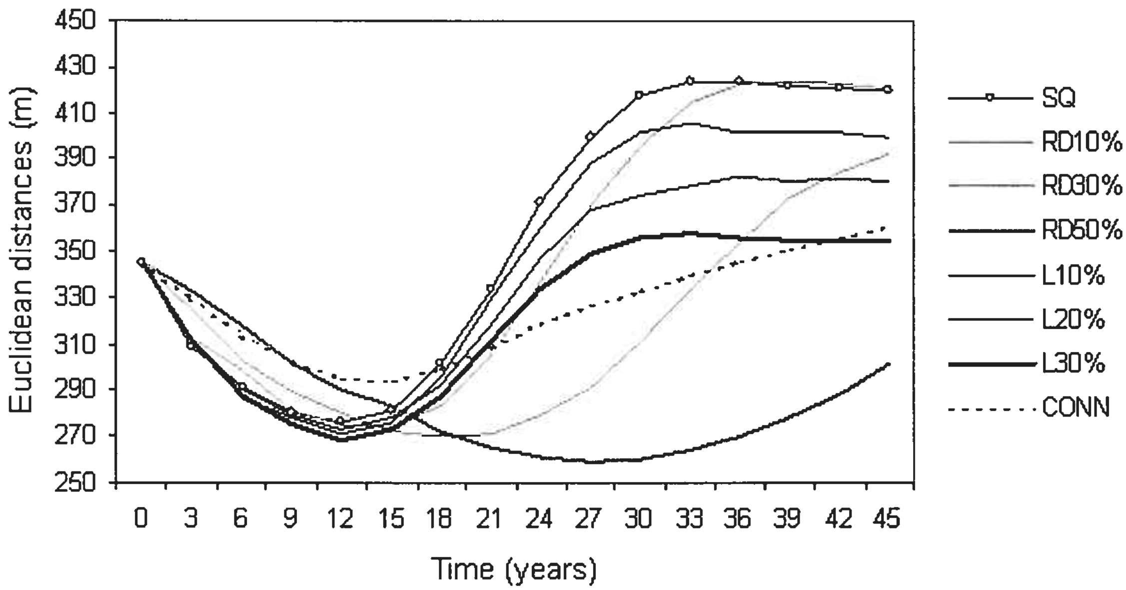

Figure 4.6 Mean euclidean nearest neighbor distances of the forest patches through time for all scenarios

4.4.4 Additional results for the ligniculture scenarios

The results presented so far for the three ligniculture scenarios only translate their influence on the forested environments. Even thought they are ultimately composed of trees, the ligniculture cells generated in all the simulations of these scenarios cannot be considered as forested environments and this is why they were not aggregated with the forest class. However, they can potentially contribute to the ecological integrity of this region in addition to their contribution to timber production. Ligniculture results after 45 years for the four indicators used before are summarized in Table 4.2. Only the results after 45 years are presented since the temporal dynamics of the different indicators used are relatively linear due to the cumulative and permanent aspects of the modeled ligniculture process. Depending on the adherence probability used, the mean areas devoted to ligniculture vary nonlinearly between scenarios from 5.3 km^2 to 22.5 km^2. For L20% and L30%, it actually represents more areas than what is left of forest after 45 years. From the mean number of ligniculture patches computed, it is clear that the average patch size is small and that patch complexity is rather simple. In terms of patch proximity, only the L20% and L30% scenarios reach nearest neighbor distances of the order of those obtained for forest patches. The L10% scenario does not seem to be sufficiently intense to generate the kind of spatial feedback necessary to cluster ligniculture cells and create more elaborated patches.

Table 4.2 Ligniculture results after 45 years

	L10%	L20%	L30%
AREA[1]	5.3	12.7	22.5
NP[2]	423	796	1099
TE[3]	0.20	0.45	0.74
ENND[4]	600	405	330

[1] Mean area (km^2)
[2] Mean number of patches
[3] Mean total edges (millions of m)
[4] Mean euclidean nearest neighbor distance (m)

Table 4.2 Ligniculture results after 45 years

Even though ligniculture cells cover respectively 0.4%, 1.0% and 1.7% of the Maskoutains territory after 45 years of simulation for the three scenarios, their impact on timber production in the region could be significant. Based on the hypothesis that hybrid poplar, the most used ligniculture tree species in Quebec, is planted on these cells and that its rate of growth is conservatively fixed at 12 m^3/ha/year because of the moderately good soils and appropriate climatic conditions of the region (Réseau Ligniculture Québec, 2004), the volumes of wood potentially produced are considerable. After 45 years, the L10%, L20% and L30% scenarios could potentially produce 220 860 m^3, 494 608 m^3 and 824 310 m^3 of timber respectively.

4.4.5 Visual analysis of the dynamics generated

A final way of analyzing the effect of the scenarios tested is to look at the spatial-temporal arrangement of forest cells through the use of maps. Because of the size of the study area (1314 km^2) and because multiple replicates were performed for each scenario, a representative spatial subset covering 20 km^2 was selected for analysis out of one representative replicate of each scenario. These spatial subsets were extracted for time steps #7 (Figure 4.7) and #15 (Figure 4.8), which are years 21 and 45 respectively. These maps visually display part of the forest configuration, fragmentation, and patch complexity and isolation that were analyzed earlier. This visual analysis also reinforces three important conclusions. First, it re-identifies the CONN and RD50% as the only two really different scenarios in terms of the amount of forest territories that is preserved (Figures 4.7 and 4.8). While the RD50% scenario is identifiable by its conservation of more forest areas in both years, the CONN scenarios differentiates itself mainly by the shape of its forest patches. The RD30% scenario is also visually different from the other scenarios, but only at 21 years (Figure 4.7). Second, the differences between the CONN and RD50% scenarios and the others are more apparent after 21 years than at the end of the simulations. This clearly shows that time will homogenize the Maskoutains landscape no matter which interventions are used and applied. Finally, the ligniculture scenarios do not significantly influence the state of forest areas in the region. The only thing that really changes when the adherence probability to ligniculture increases is the total area of ligniculture, and therefore, the amount of timber that could potentially be produced.

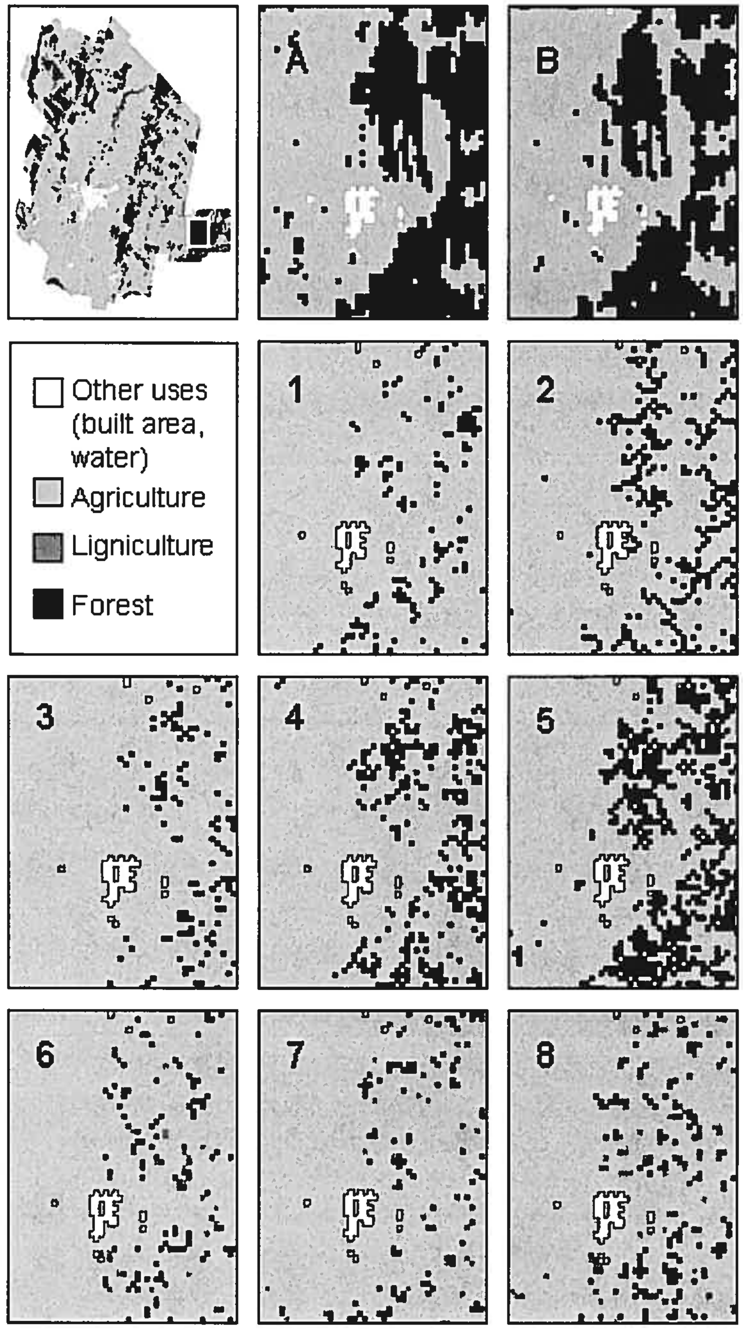

Figure 4.7 Spatial subsets of the region at year 21 (time step #7) for one representative replicate of each scenario (A) 1999 situation; B) 2002 situation; 1) Status quo; 2) Connectivity; 3) Reduced deforestation 10%; 4) Reduced deforestation 30%; 5) Reduced deforestation 50%; 6) Ligniculture 10%; 7) Ligniculture 20%; 8) Ligniculture 30%)

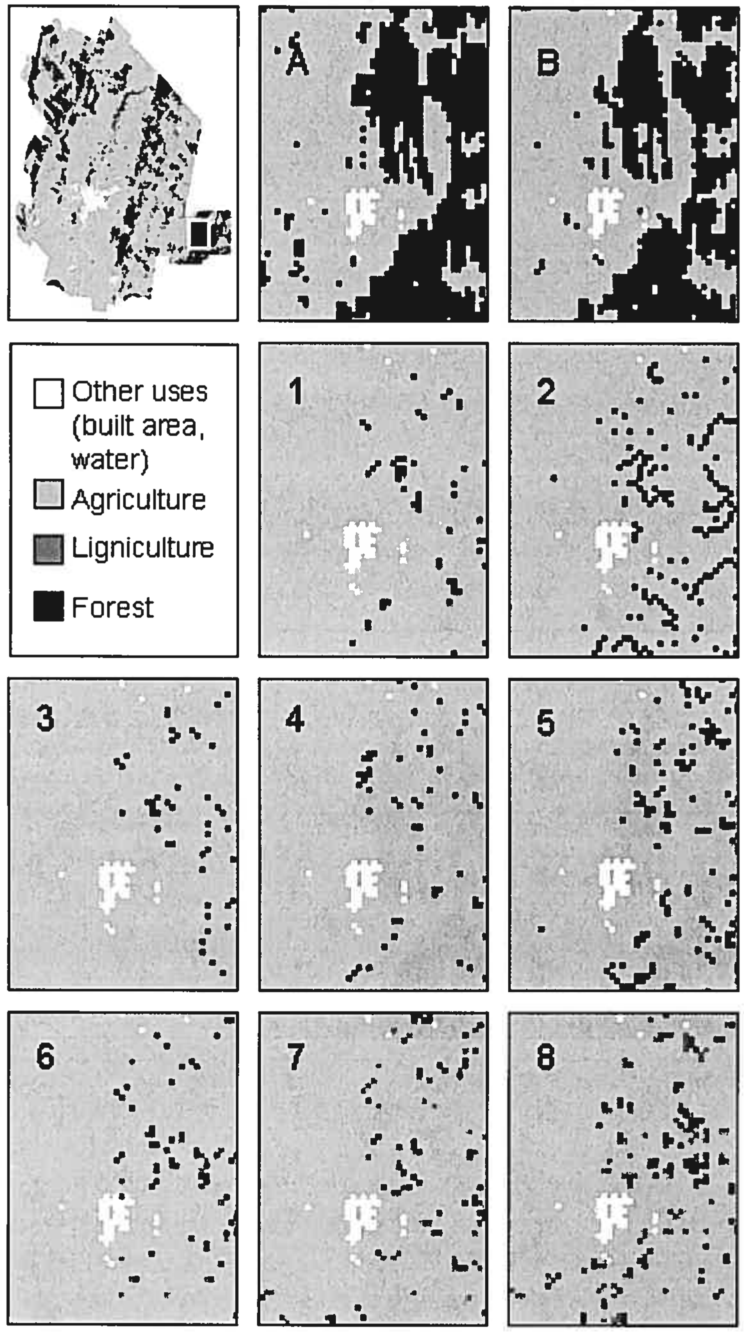

Figure 4.8 Spatial subsets of the region at the end of the simulation for one representative replicate of each scenario (A) 1999 situation; B) 2002 situation; 1) Status quo; 2) Connectivity; 3) Reduced deforestation 10%; 4) Reduced deforestation 30%; 5) Reduced deforestation 50%; 6) Ligniculture 10%; 7) Ligniculture 20%; 8) Ligniculture 30%)

4.5 Conclusion

So far, the studies using GCA to model land-use change have primarily focused on urban areas and have rarely been developed to explicitly tests management scenarios. This study constitutes one of the first researches using the GCA modeling formalism to study land-use change in a rural landscape, within an environmental resource management context. This study constitutes an important contribution to the environmental debate over the future and socio-ecological health of the Maskoutains RCM. The results indicate that no matter which management scenario is applied, from the ones tested in this study, the long-term outlook for forest presence in the region is relatively the same. It would take a total moratorium on deforestation (100% reduction in deforestation or absence of agricultural growth) for the conservation through the next half-century of what is presently left of forest areas. However, results suggest that three scenarios, namely the maintenance of connectivity between forest patches (CONN) and the reduction of deforestation at certain levels (RD30% and RD50%), can significantly alter the loss of forest areas in the short to mid-term. In addition, these two latter scenarios have displayed forest spatial dynamics that significantly delay the fragmentation, the simplification of patch morphology, and the isolation of forest patches. Among other advantages, this delay maintains large forest patches separated by a shorter distance longer. This situation might translate into an increased persistence of habitats and movement facilitation for animal populations. Finally, even though the ligniculture scenarios do not seem to significantly alter the deforestation trends of this region, they nonetheless possess a utility on a larger scale. If, for a variety of reasons, nothing is done to protect the forested environment of this highly cultivated area, at least the promotion and development of ligniculture indirectly protects forested environments located elsewhere in the province. As mentioned earlier, the ligniculture initiative is only one of the four components of the TRIAD forest management principle. The idea behind this principle is to intensively use certain abandoned agricultural territories located on the productive lands of the south of the province to increase the timber production, in order to manage public forest in a more ecological fashion and to integrally protect more forest areas. Therefore, ligniculture in the Maskoutains RCM could at least contribute to the protection of forest elsewhere.

The elaboration of the GCA for this study was based on a high-quality dataset of the region used to establish the initial conditions of the simulation and to derive appropriate transition rules, and on a scale sensitivity analysis to adequately identify the scale components. Nonetheless, this modeling experiment presents some methodological and application limitations. First, the transition rule probability sets were empirically derived from the comparison of only two land-use maps. Even though the deforestation and abandonment dynamics observed between the years 1999 and 2002 were consistent with forest evolution data collected from multiple sources, using land-use maps covering a greater temporal extent would have refined the probabilities. Second, more insights into this region potential future could have been gained by the use of more scenarios, including the elaboration of mixed scenarios (e.g.: RD50% - CONN combined scenario). However, the scenarios used in this study were intentionally kept relatively simple in order to better grasp the influence of each one.

Land-use change investigations using dynamical and spatially-explicit models are increasingly performed. They are becoming important tools in the comprehension and management of urban and rural landscapes and GCA have become the main modeling formalism in achieving this goal. GCA have been developed to model numerous cities and their vicinities, and this study shows that GCA can be used to model rural regions and tackle environmental issues as well. The increasingly multidisciplinary nature of scientific research, the complexity of contemporary issues, and the importance of transparency and public involvement in the decision-making process all combine to reinforce the potential contributions of GCA. They are visual, explicitly multi-criteria in nature, relatively simple and highly flexible. And, as this study as clearly shown, they allow for the testing of management scenarios, which can guide decision making of scientists and managers.

4.6 Acknowledgments

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PARAGRAPHE DE LIAISON C

Le chapitre 4 a présenté le développement d'un automate cellulaire (AC) pour l'étude du territoire de la MRC des Maskoutains et l'examen des conséquences de certains scénarios d'aménagement forestier sur les trajectoires évolutives de ce territoire. Cette étude s'ajoute donc à l'ensemble des études utilisant les AC pour modéliser des espaces géographiques réalisées durant la dernière décennie. Quelles soient de nature comphéhensive ou prédictive, simple ou compliquée, urbaine ou rurale, elles ont toutes contribué à façonner un domaine de recherche effervescent et prometteur. Dans cette optique, le chapitre 5 a pour but de positionner cette recherche dans l'ensemble des études de modélisation de l'espace géographique par AC, de présenter un bilan des contributions à la géographie de ce type d'utilisation des AC et de faire ressortir les grandes tendances de recherche dans ce domaine.

CHAPITRE 5. CELLULAR AUTOMATA MODELS OF CITIES AND REGIONS[4]

5.1 Abstract

Geographical territories are increasingly modeled using cellular automata (CA). This very effervescent field of research has produced numerous models of cities and regions, which are reviewed in this article. Collective contributions to geography of the CA simulations performed are offered (CA effectiveness in modeling and managing cities and regions, crucial role of local interactions in pattern formation, hierarchical nature of territorial dynamics, environmental awareness). Finally, trends in CA model development are presented (alternative transition rule methods, scale sensitivity analysis, object-based CA, integration of CA with multi-agent systems).

KEYWORDS: cellular automata, CA, modeling, geographical territories, cities, contributions, trends, applications

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[4] Ménard, A. and D. J. Marceau (2005) Cellular automata models of cities and regions. Soumis à la revue Progress in Human Geography.

5.2 Introduction

Geographers interested in the dynamical study of the geographical space have become increasingly familiar with one of today's most widely employed modeling tool: cellular automata (CA). Reasons behind this flourishing popularity include the fact that CA are simple, spatially explicit, decentralized, highly visual, and structurally similar to raster geographic information systems (GIS) and remote sensing images (Torrens, 2000). CA have also been tightly associated to the unraveling of complexity theory since it is partly through CA simulations that the emergence of complex behaviors and patterns from simple local interactions was first contemplated. Furthermore, CA bring an important advance in the treatment of time over traditional models of geographical space since they are inherently and interactively dynamic. Tobler introduced CA to geographers in 1979, but their applications to geographical territories were only elaborated many years later. The original formalism of CA may partly explain this situation. A CA is an array of cells that evolves in time by updating the state of its cells through the application of deterministic transition rules, which specify the consequences of neighborhood compositions (Wolfram 1984). This strict traditional formalism was later relaxed, and increasingly more geographers acknowledged the potential of CA for spatio-temporal modeling of geographical territories (Couclelis, 1985; 1988; Itami, 1988; Phipps, 1989; White and Engelen, 1993). The modifications considered to better reflect the geographic space include non-neighborhood related potentials for cells, constraints from higher-scale external models, alternative transition rule formulations, stochastic rules, non-uniform arrays and extended neighborhoods. The research of these early CA pioneers, in combination with significant improvements in computing technologies and data accessibility in the 1990s, facilitated the development of CA models and their popularity.

CA models of geographical territories, in which cells represent a portion of the geographic space, and cell states are territorial attributes, have been developed for both urban and rural landscapes, for regions on all continents and by a very diversified group of scientists. From an exhaustive literature review, close to forty articles reporting the development of such CA models were retrieved and from these, twenty-five different modeled territories were identified. More than two thirds of these papers have been published in the last five years, showing the growing popularity and effervescence of CA modeling in geography. The goal of these articles is to obtain new knowledge about territories through the execution of simulations. Some models are developed to simulate past territorial dynamics in order to better understand the processes and factors that have created contemporary patterns, to reconstruct temporal datasets, or to validate CA models by comparing present-day situations to simulation outputs. Other CA models attempt to simulate the future by extrapolating existing dynamics or by testing possible scenarios of development. Each model generates new insights into the dynamics of a particular territory. But what has the geographic community learned from this collection of CA models? What are the main geographical contributions of all these simulations? Additionally, what are the challenges facing scientists elaborating CA models of geographical territories today? The objective of this paper is to provide answers to these questions. Specifically, this article reviews published CA models of geographical territories, highlights key contributions to geography of the CA simulations performed, and identifies recent trends in the development of CA models. The review will present the models according to the type of simulations performed: simulations of past dynamics, and simulations of future dynamics and scenarios. This paper can serve as a starting point for geographers interested in using this modeling tool. It offers an overview of which territories and issues have been studied with CA and a geographic perspective on the implications of the numerous simulations performed.

5.3 Review of CA models of geographical territories

5.3.1 Simulation of past dynamics

A pioneer research has been conducted by Deadman et al. (1993) who studied the residential development in the rural township of Puslinch in Ontario, Canada from 1955 to 1983 using transition rules derived from the region's planning policies and socio-environmental conditions. They showed that their CA model was able to adequately replicate the settlement patterns observed in that area. In a similar rural setting, Theobald and Hobbs (1998) developed a CA of Summit County in Colorado, United States, and tested its ability to recreate the development patterns between 1970 and 1995. Comparisons with a regression-based model of development was also performed and showed that the CA model was more efficient in reproducing the observed land-use patterns.

Batty and Xie (1994) elaborated one of the first urban models of CA. Their model was designed to simulate the urbanization processes around the city of Amherst located in the Buffalo metropolitan area in United States. Based on the ideas of diffusion of development, on higher-level neighborhoods (interaction field) and on land-suitability constraints, they accurately reconstructed the evolution of this region over the last century. At about the same time, White and Engelen (1993) presented a theoretical CA study of land-use dynamics that used a significantly different CA framework. Their "constrained CA" presented major modifications from the original formalism, the most important being the external determination of overall amounts of cell changes, but also the use of extended neighborhoods and the computation of cell potentials for change. This investigation of urban spatial structure showed that CA models could generate realistic fractal land-use structures similar to that of cities like Atlanta, Cincinnati, Houston and Milwaukee (United States). This paper was instrumental in demonstrating the potential of CA for land-use modeling. A few years later, they developed a CA model that simulated land-use changes for the city of Cincinnati between 1840 and 1960 (Engelen et al., 1997; White et al., 1997). They showed that factors such as the transportation network, site features and the existing pattern of land use combine to restrict the possible pattern of urban development, and that, in spite of the inherent stochasticity of the model. Finally, they elaborated an integrated multi-scale modeling framework consisting of macro-scale socio-economic models, a CA and a GIS that was calibrated by simulating the Netherlands from 1988 and 1993 (White and Engelen, 2000). This experiment revealed that the integration of CA with macro-scale models significantly improves the socio-economic estimates of the macro-scale models.

Ward et al. (2000) studied urban growth based on transport networks for the city of Gold Coast in the Melbourne metropolitan area, a rapidly urbanizing region of coastal eastern Australia. Using a constrained CA model, their simulations (1988-1995) demonstrated the significance of local planning constraints, and the influence of physical and economic constraints on the spatial configuration of urban form. Li and Yeh (2000; 2001; 2002a; 2002b) and Yeh and Lie (1998; 2001, 2002) have extensively modeled the rapidly growing region of Dongguan, China in the last few years. They have developed a constrained CA of urban growth and have focused on the urban/agriculture opposition. Methodologically, one of their main research objectives has been the integration of CA and GIS (Li and Yeh, 2000; 2001; Yeh and Li, 1998; 2001) and the development of alternatives methods to elaborate their CA (Li and Yeh, 2002a; 2002b). In a regional context of extreme urban growth and resource utilization, they developed a CA-based modeling framework to produce sustainable urban development alternatives (for 1988 to 1993) to the existing development patterns. The value of compact urban development for sustainability was observed as assessed by its reduction of environmental and development costs in comparison to the very dispersed actual urban development of Dongguan.

In a study of urbanization in the vicinity of the city of Phoenix in United States, Jenerette and Wu (2001) elaborated a CA by deriving the transition rules both empirically and with a modified genetic algorithm and two cell sizes. They found through simulations of the region between 1912 and 1995 that very simple probabilistic rules could replicate urban encroachment. They also illustrated that cell sizes affected simulations results, in this case the coarser spatial resolution being more suited to capture the spatio-temporal dynamics of the study area. A CA model, based on the constrained CA put forward by White and Engelen (1993), was developed for the city of Dublin, Ireland by Barredo et al. in 2003. The initial simulations performed were from the past (1968) to the present (1998) in order to verify the ability of the model in reproducing urban patterns. They observed that the model generated a dual urban structure comparable to reality. In fact, fractal measures clearly identified an inner fully urbanized zone in which the urbanization process is in equilibrium, and an outer zone where the urbanization process continues to progress and where urban structure is dynamic.

Finally, two models of Brazilian territories have been recently developed. First, Soares-Filho et al. (2002) used DINAMICA, a CA model of landscape dynamics, to study the spatial patterns of land-use and land-cover changes produced by the Amazonian colonists in clearing the forest, cultivating the land, and eventually abandoning it for vegetation succession. Applied to simulate the dynamics of the Mato Grosso state (Brazil) from 1986 to 1994, their model displayed interesting replicating capacities and potential to forecast landscape fragmentation produced by different colonization architectures and predict the spatial pattern evolution of regions. Second, in a modeling investigation of the Brazilian city of Bauru in West Sao Paulo State (Brazil), de Almeida et al. (2003) developed a land-use change CA in which the transition rules originate from elementary probabilistic methods. Running simulations from 1979 to 1988, they were able to characterize the main land-use transition determinants. Among others, the non-urban to urban (residential, service or industrial uses) transition largely depends on proximity to commercial/industrial activity clusters and on general accessibility conditions.

5.3.2 Simulation of future dynamics and scenarios

CA models in which future dynamics are simulated have all for primary objective to generate a realistic overview of possible territorial trajectories. While some models concentrate on the temporal extrapolation of past processes in order to ponder what and how social, demographic, economic or environmental issues will affect a geographical territory in the future, others incorporate hypothetical scenarios or management initiatives in order to assess their spatio-temporal consequences.

A series of CA models of geographical territories have been developed using the general framework of the SLEUTH model (Slope, Land cover, Exclusion, Urban, Transportation, and Hillshade). This CA framework developed by Clarke et al. (1997) has become a reference in the study of urban growth as the binary representation of the expansion of urbanized territories into undeveloped territories. SLEUTH models urban development through spreading and diffusion of four types: spontaneous urbanization, generation of new diffusing centers, diffusion from urban edges, and road-influenced diffusion. This CA was used to simulate the urban expansion in the San Francisco Bay area (Clarke et al., 1997) and the San Francisco and the Washington / Baltimore corridor (Clarke and Gaydos, 1998). In the later model, which simulates the development of the two areas through the next century, they observed that urbanization was likely to occur around the edges of already established urban centers, that roads were the second-most influential geographic feature on the location of newly developed areas, and that elevated terrains are almost always exempt from development.

The SLEUTH framework has also been used to simulate other regions as well. Silva and Clarke (2002) successfully calibrated SLEUTH for the Portuguese cities of Lisbon and Porto in an effort to see if the CA framework could be applied to the study of European urban dynamics. Herold et al. (2003) and Goldstein et al. (2004) used SLEUTH to successfully reconstruct the discontinuous historical time series of urban spatial extent for the city of Santa Barbara, California, in United States. In the former model, simulations for the next thirty years were also performed and they permitted to spatially attribute probabilities of urban expansion. This allowed the identification of development zones and new spreading centers. Yang and Lo (2003) tested future urban growth scenarios using a CA model of Atlanta in Georgia, United States. Their results indicated that unrestrained urban growth in this metropolitan area would result in the displacement of almost the entire natural vegetation and open spaces, while reduced growth significantly conserves more greenness and open spaces, including buffer zones of large streams and lakes. Finally, a recent inception of the SLEUTH model was developed for the New York Metropolitan region (Solecki and Oliveri, 2004) to assess the impacts of climate change scenarios on urban land-use change. Their results revealed that approximately 50% of the open space land that was present in 1990 will be converted to urban land by 2020 and it will reach 75% by 2050.

The city of Longhua in southeast China has also been investigated with a CA model (Sui and Zeng, 2001). The goal of this modeling experiment was to study the desakotas, which are regions characterized by an intense mix of agricultural and non-agricultural activities stretching along corridors between large cities. It was found that if urbanization remains as high between 1996 and 2010 as it has recently been, urban built-up areas would continue to expand, would absorb the isolated small non-urban patches nearby, and would consolidate to form a contiguous urban core. Therefore, the desakota landscape would expand and absorb more isolated developed areas if more restrictive growth control policies are not imposed.

The regional model developed for southeast England by Wu and Martin in 2002 uses population surface modeling and CA to study urban growth and project its expansion through 2020. Their results indicate that urban areas will display low growth rates, because they are already fully developed, and that rural districts will display moderate to high development growth rates depending on their adjacency to established urban centers. Ligtenberg et al. (2001) elaborated a model joining a multi-agent simulation with a CA in order to explicitly relate individual planning decisions to the resulting urban spatial organization. Their theoretical investigation focused on the impact of different allocations of actor decision power in thirty years simulations of this area. Barredo and Demichelli (2003) developed a CA model to simulate future urban development for the city of Lagos in Nigeria. Largely inspired by the CA developed by White et al. (1997), the simulations into the future (2000-2020) showed that more residential nuclei will emerge in peripheral areas, while others will be absorbed by the expanding main core of the city. Also, these simulations showed that areas with plain topography would be less driven by land suitability.

In another experiment of their multi-scale, integrated, and constrained CA, White and Engelen tested multiple scenarios of climate change on the land-use dynamics of the Caribbean island of St. Lucia (White and Engelen, 1994; Engelen et al., 1995; 1997; White et al., 2000). Among many findings, they observed lost, tourism activities would be partially relocated and subsistence agricultural activities would increase but also pushed onto steeper terrain in the next 40 years. The fast growing city of Guangzhou in southern China has also been the subject of CA models (Wu, 1996; 1998a; 1998b; 2002; Wu and Webster, 1998). Wu's work focuses primarily on the development of innovative CA rule formulation methods (namely, fuzzy logic and multi-criteria analysis) and calibration methods. This region has been used as a testing study area for all these methodological experiments. Simulations were performed to assess the impact of different management scenarios, including relaxations of cultivated land and woodland protection and network-based development. In 1997, Langlois and Phipps elaborated a CA of urban development for the Ottawa-Hull metropolitan region in Canada. Using 100-years simulations, they tested the influence of different hypothetical development scenarios: high demographic growth, consolidation of the economical space without demographic growth, and possible urbanization outside the green belt surrounding the agglomeration. The relatively high variability between simulation outcomes emphasizes the considerable spatio-temporal impacts of management decisions on the territorial development of urban areas with even less intense growth rates.

More recently, Li et al. (2003) studied urban expansion in the city of Xian, the capital of the Shanxi province in central China. By zoning different sections of Xian on a functional basis, which regulates their urban diffusion response to different components of the overall economy, Li and his colleagues have shown that high economic growth, which is simulated for 1997 to 2040, could be achieved with less land encroachment under a certain distribution of population. Zoning could be one effective way to balance economic growth and destruction of land resource. Sharma et al. (in press) used CA in a modeling exploration of future scenarios of agricultural sustainability in southern British Columbia. They showed the effectiveness and interactivity of the CA-Multi-criteria approach in generating overviews of the rural land use dynamics over 40 years and for a variety of scenarios (Continuing trend, Agribusiness, Protectionist, Vege-business). Finally, Ménard and Marceau (2005; Submitted manuscript) elaborated a model to study the deforestation dynamics in the Maskoutains region, a highly cultivated area of southern Quebec, Canada. Simulations performed using different forest management scenarios showed that the protection of actual forest composition is impossible without a total moratorium on deforestation, and that certain scenarios can significantly alter the loss of forest areas in the short to mid-term, consequently delaying the fragmentation, the simplification of patch morphology, and the isolation of forest patches.

A special mention has to be made of the CLUE (Conversion of Land Use and its Effects) modeling framework (Veldkamp and Fresco, 1996). The main objective of CLUE is to forecast land-use change under different agricultural development scenarios. Originally applied to Costa Rica (Veldkamp and Fresco, 1996; 1997), this model was subsequently applied to Ecuador (de Koning et al., 1999; Verburg et al., 1999a), Java in Indonesia (Verburg et al., 1999b), China (Verburg et al., 2000), Central America (Kok and Winograd, 2001), and to sectors of the Philippines and Malaysia (Verburg et al., 2002). Although these models use a grid structure, cell potentials and global-scale constraints, which are characteristics also used in CA models, they neglect to consider the influence of neighbors in the fine-scale spatio-temporal dynamics of the territories. Therefore, they cannot be considered as CA models.

5.4 Major contributions of CA models

These CA simulations have provided scientists and landscape planners concrete and valuable insights into region's dynamics. However, their collective contributions to geography may prove to be more valuable in several ways. They have established CA as a valuable modeling tool for the study of urban, rural and regional land-use/land-cover change, confirmed the decisive role of local interactions in the development of global geographical patterns, demonstrated the hierarchical nature of urban and regional dynamics, established CA as useful management tools, and contributed to global environmental awareness.

Amongst the CA models in which the simulations were performed from the past to the present, different objectives were pursued: validation of the model, creation of historical datasets, identification of drivers of territorial change in particular regions, etc. Nonetheless, the possibility to compare simulation results with contemporary data has allowed for the establishment of CA as a valuable modeling tool for the study of urban, rural and regional land-use/land-cover change. Over the years, this comparison process has been performed using several different techniques, namely visual analysis (Batty and Xie, 1994; White et al., 1997; Ward et al., 2000; Barredo et al., 2003), landscape/spatial metrics (Deadman et al., 1993; Theobald and Hobbs, 1998; Soares-Filho et al., 2002; Barredo et al., 2003), fractal measures (White and Engelen, 1993; Batty and Xie, 1994; Yeh and Li, 2001), and pixel-by-pixel or map comparison (Ward et al., 2000; Barredo et al., 2003). CA ability in replicating territorial patterns of land uses/covers is therefore confirmed and, in turn, gives the CA user confidence in the un-validated simulations of future dynamics. This adequacy between simulation results and present-day situations also reinforces the decisive role that neighborhood-based interactions and dynamics play in the development of global geographical patterns. In short, the future of each parcel of land in a region is always at least partially related to the fate of the parcels of land in its surroundings. CA studies have shown in numerous disciplines that many properties of complex and emergent spatio-temporal global patterns could be recreated using simple rules that relate, at least in part, to the state of the cells in local neighborhoods (Wolfram, 2002). Still, the step from these theoretical modeling exercises to actual models of geographical territories is not trivial. Geographers have added many components to CA models and have altered most, if not all, original CA characteristics in order to incorporate realism and geographical constraints into CA. However, neighborhood influences still remain a predominant characteristic of CA models of geographic territories and is therefore a recognized driving force of land-use / land-cover dynamics.

Another contribution of CA simulations of the past is the fact that they demonstrate the hierarchical nature of urban and regional dynamics. The emergence of the constrained CA has revealed that the fast and local dynamics of the CA must be somewhat controlled, in most models, by simpler and higher-level economical or demographical models. This is in accordance with hierarchy theory (Allen and Starr, 1982), which states that a hierarchically organized system is a nested system whose overall behavior is limited by its basic components at the lowest level and by the constraints imposed at higher levels. Finally, CA simulations of past dynamics have also contributed to the identification of drivers of land-use/land-cover change. In most CA developed to model urban or residential expansion, distance to the transportation network, connectivity with developed areas, and terrain slope act together to restrict potential development and create spatial realism. The importance of these geographical features relates to one of the most crucial departure from the original CA formalism: homogeneous space. In reality, geographical space is highly heterogeneous and CA states, when they are land uses or covers, are attracted and repulsed by certain locations in space in relation to their attributes.

As for the CA models in which future dynamics or scenarios are simulated, they have principally contributed to the emergence of CA as valuable management tools. By elaborating increasingly more realistic and applied CA, scientists have made them useful to anticipate the future and the potential impacts of decisions we make today. Moreover, because CA are simpler to understand for the general public than traditional analytical models, it is therefore easier to implicate local actors in their elaboration and use. Additionally, CA structure is highly flexible and allows for the elaboration and test of management and evolution scenarios. All these factors favor the multidisciplinary and collaborative elaboration of CA. In a context where the nature of scientific research is increasingly multidisciplinary, where issues are highly complex and where transparency and public involvement in the decision-making process are important, CA emerge as modeling tools with tremendous potential. This situation corresponds well with the principles of post-normal science. Post-normal science rejects the traditional problem-solving way and proposes to explicitly consider system uncertainties, and the multiplicity and impact of decisions on the process of finding solutions to our complex contemporary problems (Ravetz, 1999). In this context, scientific research must not impose solutions but propose potential answers in the form of result ranges and scenario assessments. These substantial contributions will then be considered in the value context of the concerned local actors. CA simulations of the future can be considered as an integral part of this new approach to problem solving. This approach has the potential to demonstrate the outcome of policies, by-laws, societal habits, and processes before they are implemented or pursued and, this way, potentially help avoid making serious and irreversible errors (Deadman et al., 1993).

Through all the simulations of future dynamics performed, CA models have helped raise awareness to the harsh ecological consequences of many contemporary territorial processes affecting regions. In some cases, these regions are confronted to urban encroachment with its destruction of natural areas and its high infrastructure demands, urban intensification with its impact on socio-economical groups and the urban structure, or agricultural intensification with its simplification of rural landscapes and its pressures on forest remnants. This overall contribution of simulations of future scenarios has a dual nature. They reveal the seriousness of the short to long-term consequences of present-day processes and demonstrate the power that knowledge-based and responsible management and societal decisions can have on the destiny of regions. This situation motivates the further development of additional and improved CA models of geographical territories.

5.5. Trends in CA model development

From the very beginning of CA models of geographical territories, scientists were striving to improve their models. In the 1990s, the ways by which CA were improved included the coupling of CA to GIS, the development of multi-scale models and the use of more temporal data to calibrate models. Since the beginning of the new millennium, other avenues are pursued in order to improve CA. From the models presented earlier and other more theoretical essays on CA in geography, the following trends in CA model development can be observed: 1) alternative methods to define and derive transition rules, 2) scale sensitivity analysis, 3) object-based CA, and 4) integration of CA with multi-agent systems.

One of the most difficult aspects of CA elaboration lies in the definition and derivation of adequate transition rules for the territory being studied. Ultimately, there exist almost as many transition rules as there are CA models since scientists have to select the nature of their rules (deterministic or probabilistic), the variables that will drive rule application (land-uses, slope, soil types, distance to roads, etc), and the method to use in order to find the best parameter values (theoretical, empirical). In addition to the transition rule methods of the main CA models developed in the 1990s (White and Engelen, 1993; Clarke and Gaydos, 1998, etc), many others methods have been recently proposed. The use of fuzzy logic in rule definition is one of the most popular new approaches (Wu, 1998b; Liu and Phinn, 2001; 2003). With this approach, membership of a state (usually urban) is assigned to multiple other states (usually levels of urban development) using a fuzzy membership function. Then, by applying linguistic transition rules, the non-deterministic nature of urban development is represented. Other approaches include multi-criteria analysis (Wu, 1998a; Wu and Webster, 1998), genetic algorithm (Jenerette and Wu, 2001), principal component analysis (Li and Yeh, 2002a), regression and discriminant analysis (Arai and Akiyama, 2003), probabilistic methods (De Almeida et al., 2003), and neighborhood characteristics (Verburg et al., 2004). But even with all these developments, two issues remain unresolved. The first is the large amount of parameters to be determined in order to perform simulations with a constrained CA (Benenson and Torrens, 2004), and the second is the lack of objectivity and reproducibility in the calibration process of most transition rules (Torrens and O'Sullivan, 2001; Straatman et al., 2003). While the first problem is far from having found answers, the second one has sparked investigation into automatic calibration methods. Methods proposed so far include the use of a neural-network (Li and Yeh, 2002a) and optimization / search techniques (Straatman et al., 2003). The goal of these methods is to allow the repeated unbiased identification of a set of transition rule parameters on the basis of a specific geographical dataset.

Yeh and Li have recently gathered attention on the important issue of errors and uncertainties in CA (Yeh and Li, 2003; 2005). They pointed out that CA make use of large sets of spatial data which all contain a certain level of error (positional, attribute, and transformation errors). Additionally, the dynamical aspect of CA propagates these errors and mixes them with model errors and uncertainties to considerably affect simulation results. Some scientists have also focused on scale sensitivity in CA. What they are testing is essentially if changes in spatial and temporal scale characteristics affect CA simulation outcomes. Dietzel and Clarke (2004) have studied the effect of different spatial resolutions in the calibration process of the SLEUTH model. Evans and Kelley (2004) tested the influence of varying cell sizes in a CA-MAS model, Ménard and Marceau (2005) tested the impact of both cell sizes and neighborhood configurations in an empirically derived CA model, and Kocabas and Dragicevic (2004) showed that housing development in an urban growth CA of San Diego was influenced by neighborhood sizes and types. In all studies, spatial scale was found to significantly affect model parameters and simulation outcomes. Temporal scale sensitivity was also studied through the examination of the impact of the degree of temporal dynamics on the behavior of an urban growth model (Liu and Andersson, 2004) and the influence of time step resolution on the model outputs of a rural deforestation model (Ménard and Marceau, 2005). In both cases sensitivity to temporal scale was observed but was less influential then variations in spatial scale.

An approach to considerably reduce the sensitivity of CA to spatial scale is the development of object-based CA. In such a CA, variable areal units depicting spatial objects replace traditional cells in representing the modeled landscape. Sensitivity to spatial scale is therefore removed since no other partitioning of the space is possible once the spatial objects have been identified for a particular study. To use spatial objects in a CA it is necessary to use a vector spatial structure. Several structures have been proposed in recent years: Voronoi-based CA (Shi and Pang, 2000), Graph-CA (O'Sullivan, 2001), and vector CA (Shiyuan and Deren, 2004). However, only the latter was actually developed to model spatial objects. Also, these models have been mainly developed for urban contexts, where spatial objects change status but not shape. However, spatial objects (e.g.: ecological patches) often experience numerous morphological transformations and the development of a CA framework that allows these spatial modifications will represent an interesting challenge for CA geographers in the next few years. Moreover, other problems with this approach include the actual definition of the areal units and the complexity of the neighbourhood topology thereby created. These problems, in turn, make the computation of GCA simulation much more time consuming and processing intensive. It seems that the focus on the coupling between CA and GIS, which was more present in 1990s (Itami, 1994; Wagner, 1997; Batty et al., 1999), will resurfaced in light of the numerous advantages that vector GIS offer to those wanting to pursue the development of object-based CA.

Finally, there has been a growing interest in recent years about CA-based hybrid models (Torrens and O'Sullivan, 2001, Benenson and Torrens, 2004). Such models combine CA with equation-based models, system models, statistical techniques, expert models, evolutionary models or multi-agent systems (MAS) (Parker et al., 2003). MAS is rapidly gaining popularity and offers tremendous integration potential with CA. MAS are collection of agents that are autonomous, mobile, goal-driven and that possess irregular and variable neighborhood interactions. All these agents share an environment through agent interaction and they make decisions that link their behavior to the environment. In geography, they are usually used to model human actions, agents representing persons, households, automobilists, companies, etc. The model of Ligtenberg et al. (2001) is a good example of CA-MAS integration since spatial planning decision-making is performed by agents representing planning actors and the CA is then used to infer the knowledge needed by the agents to make decisions about the future of a spatial organization in a certain area. Some authors have just pushed this integration a step further by proposing a new modeling framework that joins together the advantages of both type of models: Geographic Automata Systems (Benenson and Torrens, 2004; Benenson et al., 2005; Torrens and Benenson, 2005). This model consists of geographic automata of various type that are characterized by states and transition rules but also geo-referencing rules for functionality of location in space, neighborhood rules for the flexibility and adaptability in space and time of local interactions, and movement rules to allow for the independent navigation of automata.

5.6 Conclusion

This review of CA models of geographical territories has achieved three objectives. First, it has offered a comprehensive overview of the research domain in terms of the scientists involved, the cities and regions studied and the simulation objectives pursued. Second, it has synthesized the main collective contributions to geography of the numerous CA simulations performed. Third, it has presented where the domain is headed through the analysis of recent CA research. Overviews of this type are important for the development of a fast evolving and maturing research domain. CA possess intrinsic qualities making them valuable for the modeling of cities and regions, and the last few years have supplied a vast literature and a solid background of applications of CA to geographical territories. No evidence suggests CA research in geography will slow down any time soon. In fact, the potential contributions of CA are reinforced by the increasingly multidisciplinary nature of scientific research, the complexity of contemporary issues, and the importance of transparency and public involvement in the decision-making process. In the near future, CA characteristics will be altered and CA use will evolve. All these changes will be anchored on today's innovative and rich models and on their collective contributions to geography.

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CHAPITRE 6. CONCLUSION

Cette recherche traite du problème d'échelle spatiale en modélisation par automates cellulaires (AC) et de la dynamique de déforestation dans la MRC des Maskoutains. À l'instar de la nature des chapitres qui la composent, les contributions de cette thèse sont de trois types : théorique, méthodologique et appliquée.

Au niveau théorique, cette thèse clarifie la problématique entourant les transformations au formalisme de base des AC et la modélisation de systèmes complexes en présentant la double nature et fonction des AC en géographie. En effet, il existe des AC qui tentent d'expliquer les patrons et les dynamiques spatiales des phénomènes géographiques à partir d'hypothèses théoriques; d'autres sont directement appliqués à la simulation de territoires géographiques spécifiques. Les modèles du premier groupe doivent être simples pour permettre d'établir adéquatement le lien qui existe entre patrons et processus. Les transformations apportées aux AC pour les rendre plus aptes à modéliser l'espace géographique sont donc moins présentes dans ce genre de modèles. Les modèles du second groupe doivent quant à eux représenter le plus fidèlement possible le territoire modélisé puisque des impératifs d'aménagement et de gestion en dépendent fréquemment. Ces modèles font généralement appel à plusieurs transformations au formalisme de base des AC. La motivation des chercheurs impliqués dans ce genre d'exercice de modélisation est de produire des AC opérationnels dont les comportements sont plausibles. La complexité ne se situe donc pas au centre de leurs préoccupations. D'autant plus que l'émergence de comportements complexes est rare en simulation par AC et qu'elle risque d'être perçue comme une anomalie de simulation.

Une autre contribution de nature théorique réside dans le bilan des AC de territoires géographiques qui est réalisé et dans l'identification des principales contributions à la géographie des nombreuses simulations effectuées avec ces modèles. Bien qu'individuellement chaque modèle apporte des réponses et une aide précieuse dans la compréhension et la gestion du territoire simulé, c'est collectivement que ces modèles contribuent de façon significative à l'avancement de la géographie. Il est montré dans cette thèse qu'ils ont permis d'établir les AC comme des outils utiles de modélisation et de gestion du territoire et des changements d'utilisation du sol, qu'ils ont confirmé le rôle central des interactions locales dans le développement des patrons spatiaux, qu'ils ont démontré explicitement la nature hiérarchique des dynamiques territoriales et qu'ils ont contribué à la conscientisation environnementale.

La contribution méthodologique de cette thèse consiste en la caractérisation de la sensibilité à l'échelle spatiale des simulations d'AC. Cette sensibilité est très apparente dans nos résultats. Les indicateurs globaux et spatiaux tirés des simulations sont influencés par les variations de taille de cellules et de configuration de voisinage. Les résultats montrent que le choix d'une taille de cellule plus grande génère des simulations conservant plus de superficies forestières mais crée proportionnellement moins de parcelles de forêt, à l'exception de la taille de cellule de 30 m. Les règles de transition dérivées de cette taille de cellule, peu importe la configuration de voisinage, sont biaisées par la distribution de superficies des parcelles dynamiques présentes dans les deux images d'origine. Cette situation révèle qu'utiliser la résolution spatiale la plus fine n'est pas toujours appropriée puisqu'il est préférable d'adapter le plus possible la taille des cellules aux objets du paysage. De plus, l'exploration plus fine de la sensibilité à l'échelle spatiale révèle que même de petites variations de taille de cellule peuvent produire des divergences importantes dans les simulations si ces variations traversent un seuil d'échelle. Le choix d'une configuration de voisinage a moins d'impact sur les résultats de simulations, mais la relation entre cette composante de l'échelle spatiale et les résultats n'est pas toujours linéaire. Les géographes utilisant les AC pour modéliser l'espace géographique devraient donc être prudents dans leur traitement des composantes de l'échelle spatiale. Une analyse de sensibilité comme celle présentée dans cette thèse ne règle pas le problème d'échelle des AC, mais représente une des façons les plus simples de réduire ses effets sur les simulations effectuées. Cette affirmation s'avère d'autant plus juste lorsque la priorité d'analyse est mise sur l'identification de seuils d'échelle spatiale.

Finalement, la contribution de nature appliquée de cette thèse se situe dans la caractérisation de l'effet de différents scénarios d'aménagement forestier sur l'état des superficies forestières de la MRC des Maskoutains. Cette étude représente une des premières recherches utilisant les AC pour étudier les changements d'utilisation du sol en milieu rural dans une perspective d'aménagement forestier. Les résultats indiquent que, peu importe le scénario d'aménagement simulé, la tendance à long terme des superficies forestières sera relativement la même et à la baisse. Les superficies forestières actuelles ne peuvent être conservées par les scénarios simulées et, après 45 ans de simulation, moins de 1% de la MRC est boisée dans tous les scénarios. Cependant, les résultats indiquent aussi que trois scénarios peuvent significativement réduire la déforestation à court et moyen termes. Ces scénarios sont ceux représentant des baisses de déforestation de 30% et 50% et celui protégeant la connectivité des parcelles de forêts. De plus, les deux premiers scénarios présentent des délais importants pouvant retarder ou réduire la fragmentation, la simplification morphologique et l'isolement des parcelles boisées. Cette situation a pour avantage de maintenir plus longtemps des parcelles plus grandes et moins isolées, ce qui pourrait se traduire par le maintien d'une plus grande variété d'habitats et par la facilitation de la mobilité des populations animales. Enfin, bien que les scénarios de promotion de la ligniculture ne modifient pas significativement les superficies forestières, elles génèrent des superficies appréciables de terres en ligniculture qui pourraient contribuer à la santé socio-économique globale de l'industrie forestière québécoise. Au moment de déposer cette thèse, le gouvernement du Québec annonçait des modifications au Règlement sur les Exploitations Agricoles (REA) qui limitent l'expansion des superficies cultivées dans les municipalités de la province se trouvant dans un bassin-versant dégradé, c'est-à-dire dont la concentration en phosphore est supérieure au critère d'eutrophisation. L'ensemble des municipalités formant la MRC des Maskoutains se retrouve ainsi protégé contre la déforestation originant de l'intensification des pratiques agricoles. Cette situation correspondrait à un scénario de simulation équivalent à une réduction de la déforestation de 100%. Bien que ces récents développements modifient la portée des résultats de simulations de scénarios d'aménagement, ils confirment la gravité de la situation qui prévalait au moment d'amorcer cette thèse et sont encourageants pour l'avenir de ce territoire.

La recherche liée à la modélisation de territoires géographiques par l'intermédiaire d'AC est en pleine effervescence à la lumière des nombreux territoires modélisés et du grand nombre de chercheurs qui s'y intéressent. Cet intérêt croissant, combiné à l'augmentation constante des capacités informatique et logicielle, favorise le développement de modèles toujours plus réalistes, conviviaux et utiles. Il ressort de la littérature et des thématiques récentes de recherche que pour continuer à améliorer ces modèles il s'avère essentiel de privilégier les problématiques suivantes : le développement de standards et de méthodes à calibrage automatique dans la définition des règles de transition, l'intégration des AC dans des modèles multi-échelles ou avec des systèmes multi-agents, l'analyse de la propagation des erreurs et de la sensibilité aux variations d'échelle, le développement d'AC basé sur les objets et l'étude de problématiques rurales ou naturelles. Cette thèse s'insère donc très bien dans cet agenda de recherche en abordant les trois dernières problématiques.

L'analyse de l'effet des variations d'échelle spatiale sur les résultats de simulation démontre qu'il est important d'ajuster la taille des cellules à la taille des objets du paysage. Elle renforce ainsi le besoin pour une approche basée sur les objets en modélisation par AC. En effet, avec un telle approche, les objets significatifs du territoire sont représentés par des polygones de formes et de taille variables. L'effet d'échelle spatiale est pratiquement nul avec cette approche puisqu'aucune autre division spatiale du territoire est possible. Pour réaliser un tel AC, il est nécessaire d'utiliser une structure spatiale vectorielle.

Bien que des AC à structure vectorielle aient été élaborés dans les dernières années, ceux-ci ont été exclusivement appliqués à des territoires urbains dans lesquels les objets changent d'état mais pas de forme dans le temps. En milieu urbain, il est possible de définir des objets spatiaux uniformes selon leur état (résidentiel, commercial, industriel, etc) et morphologiquement invariable dans le temps à partir des divisions légales et administratives du territoire (cadastre). En milieu rural ou naturel par contre, les objets spatiaux uniformes (forêt, friche, agriculture, etc) ne correspondent pas nécessairement au découpage légal. La présence de superficies boisées, en friche et agricoles sur un même lot est un bon exemple de cette situation. Les objets géographiques dans ces derniers milieux doivent donc être définis spatialement (notion de parcelle) et non administrativement. Ces unités spatiales peuvent donc varier d'état et de forme dans le temps. Pour inclure cette situation propre aux milieux ruraux et naturels dans les AC, d'importants travaux devront être réalisés sur la définition spatiale des objets, la gestion dynamique complexe de la topologie et des voisinages, et la transformation morphologique des parcelles.

L'avenir des AC pour l'étude de territoires géographiques semble donc être prometteur et parsemé de défis intéressants. Cette thèse fait état de cette situation en montrant à la fois le potentiel des AC pour la gestion et l'aménagement des territoires et le risque inhérent à toute simplification arbitraire de l'espace et de ses caractéristiques. Cette thèse contribue de façon significative à la discipline qu'est la Science de l'Information Géographique, mais plus particulièrement aux domaines de la modélisation spatiale, des automates cellulaires, des problèmes d'échelle, de l'analyse régionale et de l'écologie du paysage.

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