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Urban Development in the Chicago Area - A Dynamic Model Study

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Abstract

Urban development in the Chicago area has increased dramatically in the past one hundred years. This study utilizes the Clarke Urban Growth and Land Use Change Model that is based on cellular automaton to develop on understanding of urban growth in the Chicago area. The processes and mechanisms that govern the development of urban growth in this region are investigated. Historic maps and satellite data are used to calibrate the model. National High Altitude Photography (NHAP) from the 1970's and Multi-Resolution Land Cover (MRLC) data collected in the 1990's was used to develop the land use transition matrix used in the model. The model provides a spatially realistic representation of future development patterns. Model calibration procedures are used to determine the best parameters setting for a simulation. Based on the calibration results which assuming that current urban growth trends continue, the model was used to make projections of growth to the year 2050. Land use change drivers that include transportation infrastructure and restrictions on land use are used by the model to influence future urban growth and land use change.

Keywords

Urban growth model, Chicago, Calibration, Cellular automaton

Introduction

Urban areas contain very complex land use structures. It is not enough to study urban growth as a spatial description that is normally captured in a Geographic Information System (GIS). To better understand the complexity of urban systems and its spatial and temporal dimensions, urban growth models need to be linked with land use change model.

One type of urban model is built on the principle of cellular automata (CA). Widely used by many researchers, CA consists of very simple dynamic spatial systems in which the state of each cell in an array depends on the previous state of the cells within the neighborhood of the cell, according to a set of state transition rules. The CA system is discrete and iterative and involves interactions only within local regions. A CA model allows one to work at very fine spatial resolutions and to model complex spatial dynamics, such as land use change.

White, et al., (1997), used a constrained cellular automata model to study development in the Cincinnati metropolitan area. The model simulated three active land use types, housing, industry, and commerce, and three fixed land use features, railways, roads, and rivers. Their simulation results suggest that the transportation network was the primary control on the urban growth in Cincinnati. Xie and Batty (1997) and Batty et al., (1999) developed their cellular automata urban dynamic model (Batty and Xie, 1994, Xie, 1996). Their "Dynamic Urban Evolutionary Modeling (DUEM) Model" combined probabilities that determine future activities around selected cells. The growth or declining rate of a spatial system is computed using a self-contained system package. Without calibration procedures, the DUEM can process spatial data with up to nine million cells. Their generic model described five distinct land uses: housing or residential population, resource and manufacturing employment or industry, service or commercial-retail-shopping activity, streets or transportation routes and vacant land. Clarke (1996) developed a cellular automaton model to focus on urban growth. The model was developed to simulate the influence of urban growth at Anderson Level I categories through the USGS supported GIGALOPOLIS project. Clarke and Gaydos (1997, 1998) used this Urban Growth Model (UGM) to study the long-term urban growth in San Francisco and Washington-Baltimore. Their model was calibrated by historical data while considering spatial behavior rules modified to reflect topography, transportation, and land exclusion. After extensive calibration, the model generated urban growth predictions to 2050.

In this paper, we use Clarke's UGM to study urban development and land use change in the Chicago metropolitan area. The transportation and land exclusion influences on urban growth and the land use transitions induced by urban development are also discussed. Historical data used to calibrate the model was produced from USGS maps and landsat satellite data using a GIS. Anderson level 1 land use and land cover data are used in the model to estimate the land use change.

Simulations of urban growth and land use change

The growth rules in the UGM

Four types of urban growth are simulated in the UGM: spontaneous, diffusive, organic and road influenced. The growth rules are applied to randomly chosen pixels during each iteration of the model. Spontaneous growth simulates the impact of an urban area on its surroundings. Diffusive growth urbanizes pixels whose slopes are flat enough to be desirable locations for development. Organic growth captures the expansion of established cities. Road influenced growth encourages urbanization along the transportation network. Topographic influence is included by using slope resistance in the model. The model calibration process uses urban historical data to identify the optimum model parameters. All pixels are tested and calibrated by growth rules. The best-fit parameters are found through a statistical analysis. The trends obtained from the calibration are then applied to make future projections of urban and land cover change.

Calibration of the model

The model is designed to use raster images as input. Five types of baseline images are used: historical urban extent, transportation routes, exclusion areas, topography-slope and land use. In the calibration process, information generated by the model and known information obtained from historical data is compared for each seed year. The growth rule parameters are then adjusted for the next growth. The calibration process is normally very CPU intensive because of the number of growth control parameters and Monte Carlo iterations used in the model. In our study area, the dataset size was 605x535 pixels. If the full size image was calibrated and all parameter choices were included, it would take many hours of computing time to finish the calibration. To make the calibration process more efficient, we first reduce each input image to one quarter of its original size. By using the lower resolution image data to cover all possible parameter selections, the calibration time is significantly reduced. After the one-quarter size dataset is calibrated, the resolution of the input image is increased to one-half of its original size and the parameter selection range is reduced to a reasonable subset defined by the one-quarter calibration results. The full size image data are used for final calibration with a smaller parameter selection range.

There are 152x133 pixels in the one-quarter resolution image. The maximum range of each parameter is tested. To simplify the following graphics, only the five highest statistically weighted scores from the model output are listed.

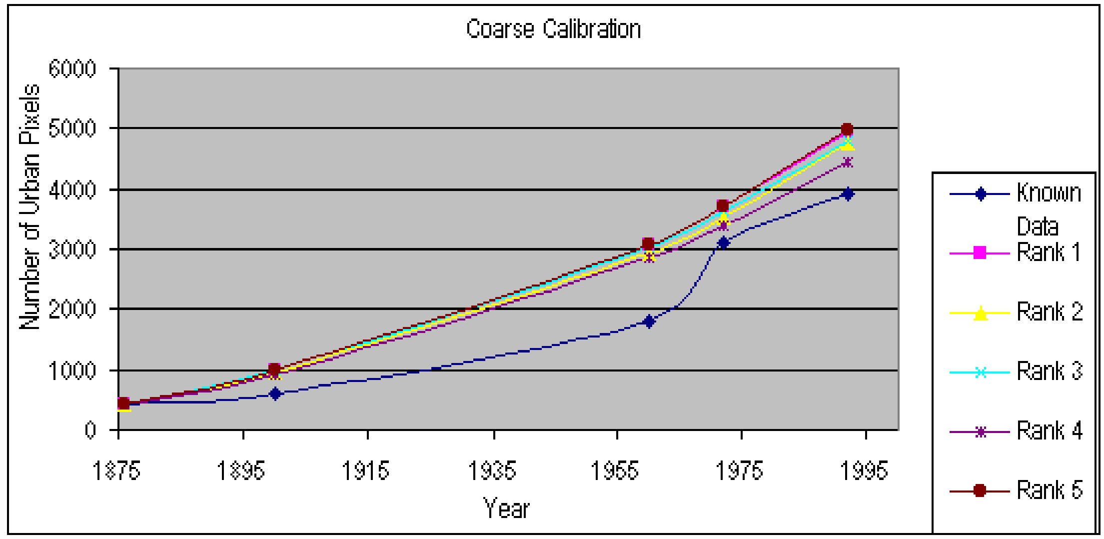

Figure 1. Coarse Calibration for number of urban pixels

Figure 1 is a comparison between numbers of urban pixels from historical data and data generated from the model. The model over estimates the number of urban pixels most of the time during calibration at one-quarter resolution. However, the model does much better at estimating the number of urban pixels (Figure 2) in the calibration of the half-size resolution where there are 304x267 pixels in each image. In the full size calibration, the model very closely simulates numbers of urban pixels from the starting year to 1960 (Figure 3). Figure 4 displays the r^2 values for urban edges and pixels from ten statistically weighted scores. The r^2 values of all ranks are below 0.9. In the half-size calibration, the r^2 magnitudes of urban pixels are 0.9 to 0.93 and edges are 0.86 to 0.90. All r^2 values of urban pixels are above 0.91 in the full size calibration.

A model prediction is made from the first seed year (1876) to 1992 to review the model’s overall performance and obtain the best growth control parameters for future prediction. Figure 5 is the comparison between known urban pixels and edges and model predicted pixels and edges. The model captures exactly urban pixel numbers and trends to the year 1960. After that time, the model still follows the change pattern but does not exactly predict the number of pixels and edges. In general, the calibrated results capture most land use variation associated with Chicago's urban development. From historical experience we know that transportation infrastructure is very important in helping to shape the development of the Chicago area. New residential areas were built along major roads. Model calibration results suggest that the parameter for road gravity has the largest affect in all growth control parameters. The topography-slope parameter is the second highest. After that are diffusive and organic growth parameters. We can conclude that most of new urban pixels are formed in established urban areas and topographically influenced areas.

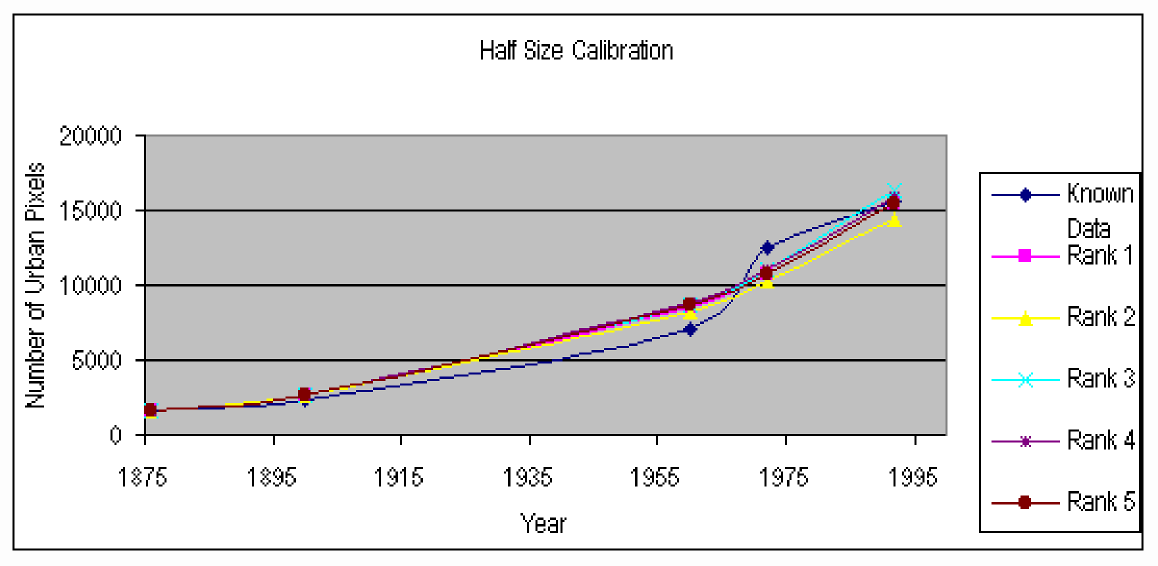

Figure 2 Half-size calibration for the number of urban pixels

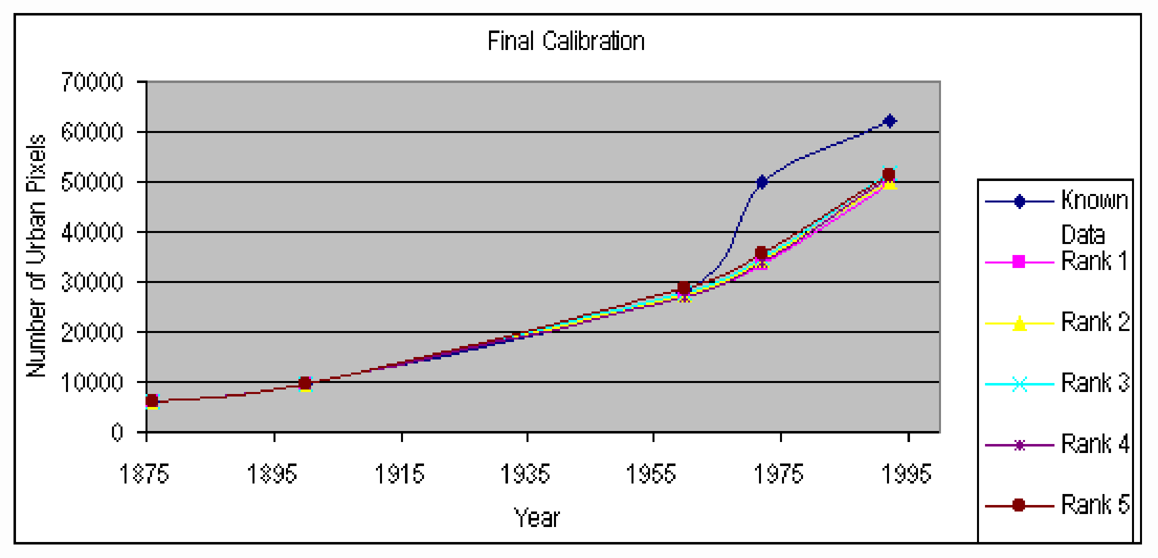

Figure 3 Full size calibration for the number of urban pixels

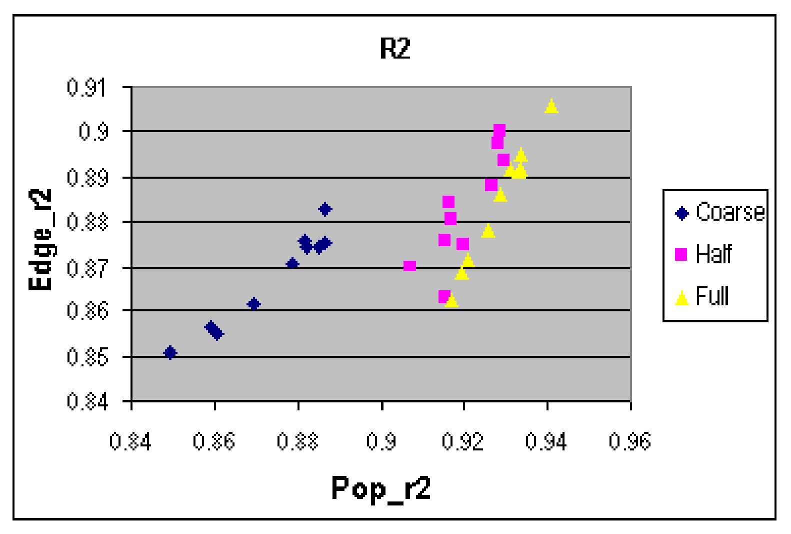

Figure 4 R^2 of urban edges and pixels

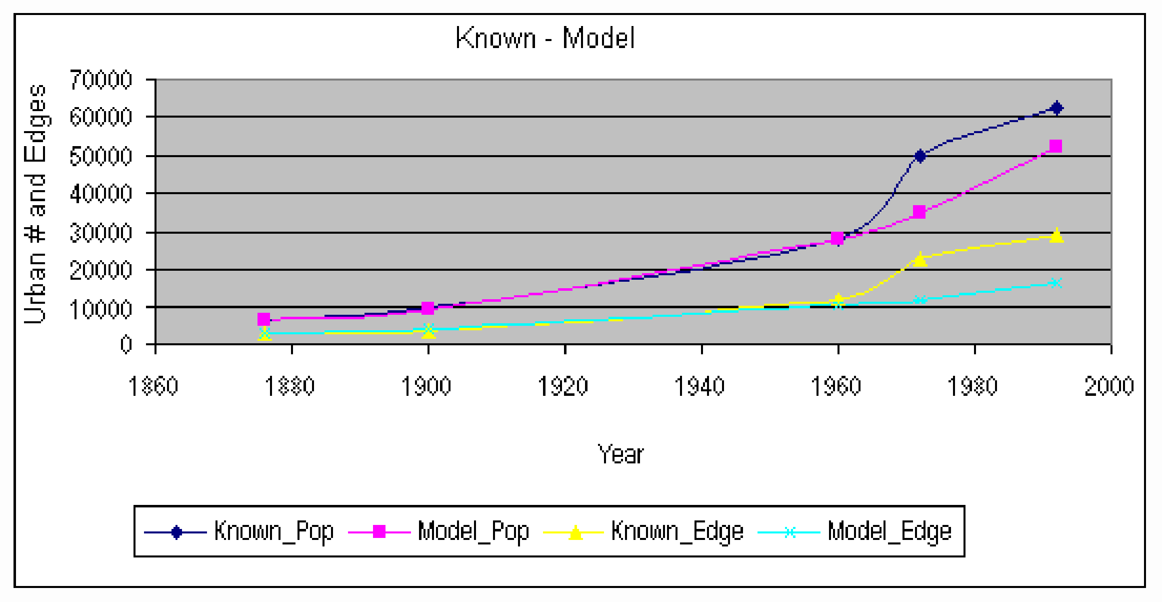

Figure 5 The comparison between model and real data.

Characteristics of land use and land cover in Chicago area

The land use and land cover input data was used to estimate the land cover change from 1972 to 1992 in our study area. Figure 6a and b are the land use characteristics by percentage in 1972 and 1992. Within the study area 15.4% pixels belong to the urban class in 1972 and 19.2 % in 1992. Agricultural areas decrease from 58.0% to 52.9% in the same time period. Table 1 is the annual land use transition matrix.

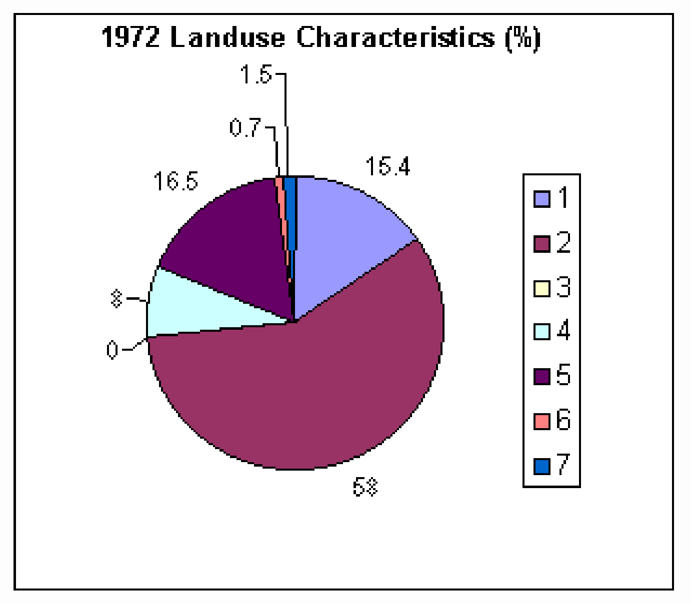

Figure 6a

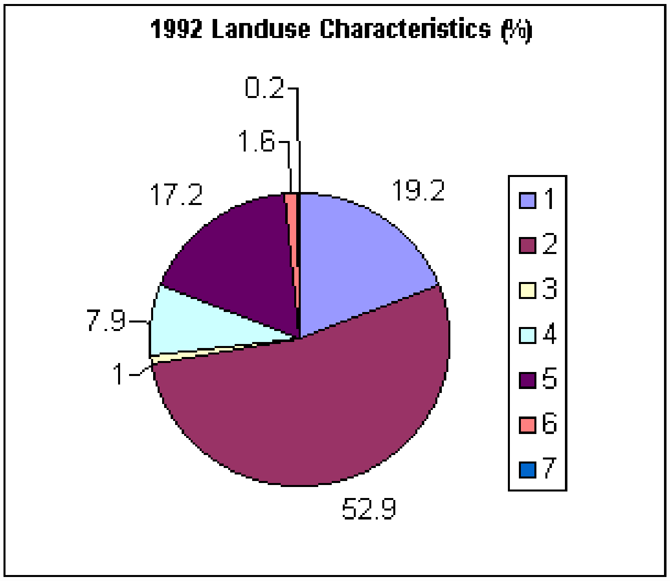

Figure 6b

Figure 6 Landuse characteristics in 1972 and 1992. The numbers in the legend represent Anderson Level 1 categories, 1 is for urban, 2 for agriculture land, 3 for rangeland, 4 for forest land, 5 for water, 6 for wetland and 7 for Barren land.

It shows that about 0.2 % of agricultural land was converted to urban land. The agricultural land has the largest land use transition from non-urban to urban in this area. About 0.2% of forest pixels are converted to urban over all 20 years. Obviously, most newly developed urban land comes from agriculture land.

				Land Use Change Matrix 1972 -1992						
	Unclass	Urban	Agric	Range	Forest	Water	Wetland	Barren	Tundra	Ice&Snow
Unclass	95.0 [0]	0.5 [12]	0.0[1]	0.1[3]	0.2[5]	3.8[96]	0.2[4]	0.2[6]	0.0[0]	0.0[0]
Urban	0.0 [0]	100.0 [49966]	0.0[0]	0.0[0]	0.0[0]	0.0[0]	0.0[0]	0.0[0]	0.0[0]	0.0[0]
Agric	0.0 [0]	0.2 [8883]	99.3[163779]	0.1[1988]	0.3[10736]	0.0[1031]	0.0[1859]	0.0[237]	0.0[0]	0.0[0]
Range	0.0 [0]	3.0 [3]	0.0[0]	95.0[0]	2.0[2]	0.0[0]	0.0[0]	0.0[0]	0.0[0]	0.0[0]
Forest	0.0[0]	0.2 [1272]	1.2[6126]	0.2[1020]	97.6[13494]	0.3[1504]	0.5[2341]	0.0[162]	0.0[0]	0.0[0]
Water	0.0[0]	0.0 [246]	0.0[161]	0.0[30]	0.0[243]	99.9[52820]	0.0[179]	0.0[10]	0.0[0]	0.0[0]
Wetland	0.0[0]	0.3 [132]	1.3[564]	0.2[64]	1.0[406]	0.5[207]	96.7[739]	0.0[7]	0.0[0]	0.0[0]
Barren	0.0[0]	1.9 [1875]	1.6[1590]	0.1[128]	0.7[722]	0.3[292]	0.2[176]	95.2[159]	0.0[0]	0.0[0]
Tundra	0.0[0]	0.0 [0]	0.0[0]	0.0[0]	0.0[0]	0.0[0]	0.0[0]	0.0[0]	0.0[0]	0.0[0]
Ice&Snow	0.0[0]	0.0 [0]	0.0[0]	0.0[0]	0.0[0]	0.0[0]	0.0[0]	0.0[0]	0.0[0]	0.0[0]

Table 1 Land use and land cover change transition matrix. The values outside of square bracket are the percentage change from one type of land use to other type from 1972 to 1992. The values in the square bracket are the number of pixels in 1972.

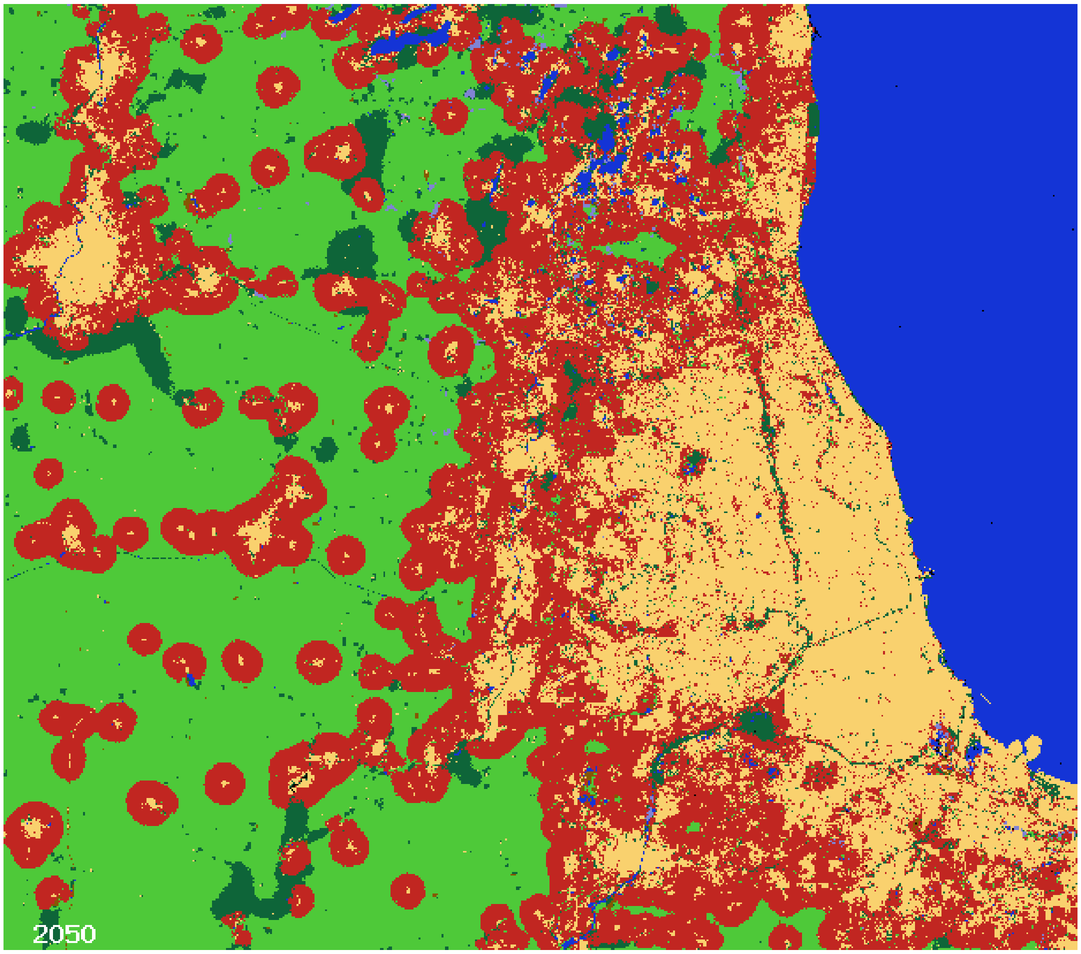

Figure 7 Model prediction of land use and land cover in 2050. The yellow is existing urban. Red is new growth urban. Light green is agriculture. Dark green is forest. Blue is water and light blue is wetland.

Model Prediction of year 2050 urban growth and land use change

Urban growth and land use change in the future will be influenced by many factors. Future development scenarios must make certain assumptions. The prediction for this study assumes that current urban growth trends continue. Assuming that there is no new external forces applied, the water areas, wetland and other exclusion lands will still be restricted from urban development. The existing transportation infrastructure is assumed to be static. Through the calibration process, we identify a set of growth controlling parameters that most closely simulate the historical urban growth patterns. The 1992 urban and land use change data are used as the model's seed point and a prediction is made to 2050. Figure 7 is the land use change prediction for 2050. The yellow colored pixels are urban areas in 1992 and red colored pixels represent new urban growth from the seed year. The figure shows that most new urban areas grow along the major highways. On the north part of Chicago, new urban areas will be built around Fox Lake and Lake Geneva (Wisconsin). On the west side of Chicago, the current urban gap between Kane county and Du Page county will be urbanized. New urban areas will also be developed on the southwest side of Chicago. The results suggest that if urban growth continues at its current rate and no restriction in land use is applied, 48.5% of the study area will become urbanized by 2050. Agricultural land will be reduced from the current 52.9% to 29.9%. Figure 8 is the percentage of land use characteristics in 2050.

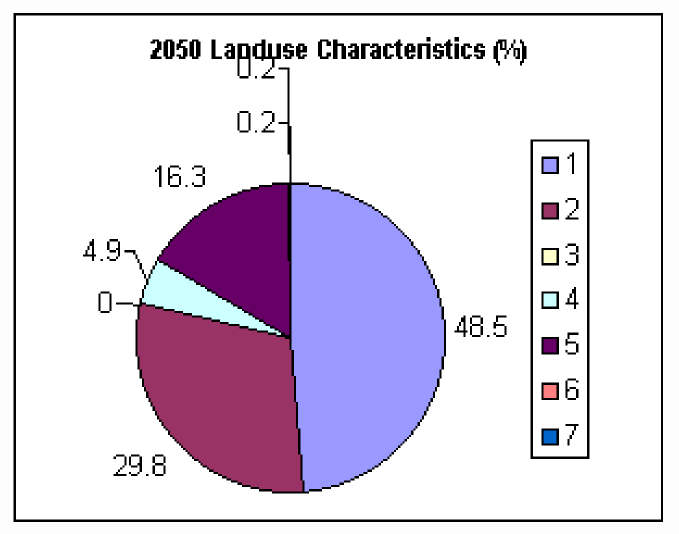

Figure 8 Land use characteristics in 2050. The labels in the legend are the same as explained in figure 6.

Conclusions

Historical urban growth information for Chicago suggests that the area has undergone tremendous expansion over the last one hundred years. The percentage of urban area in our study was only 1.92% in 1876. It increases to 19.18% in 1992. Urbanization causes tremendous change in land cover characteristics. The use of CA models helps us to simulate this variation in urban spatial growth and land use change. The model calibration results also suggest that the transportation infrastructure strongly shapes urban growth. The type of urban development over the past century was primarily diffusive and organic growth. The prediction based on these historical trends suggests that the urban area will continue to expand and consume 48% of the area.

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