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A cellular automata model to simulate development density for urban planning

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Abstract. **Most cellular automata (CA) urban models assume densities to be uniform for all cells. This is not true in real cities because densities vary substantially from city to city and from urban center to periphery areas. Development density, which affects urban form, is an important factor in urban planning. The authors present a CA model that incorporates density gradient in the simulation of urban development for different urban forms. Development density is obtained from density-decay functions and assigned to the cells when they are converted into developed cells according to CA transition rules. The model, which is based on the concept of 'grey cells', can be used as a planning model to explore various combinations of urban forms and development densities. The authors also evaluate and compare the development patterns generated by different density gradients. It is found that development scenarios with high-density development can significantly reduce encroachment on agricultural land and other important environmentally sensitive areas.**

1 Introduction

Cellular automata (CA) were first introduced in 1948 by von Neumann and Ulam to model complex dynamic systems, such as biological reproduction and crystal growth (Goles, 1989). The 'game of life' developed in 1970 by the mathematician Conway can be regarded as an explicit CA game (Gardner, 1971; Portugali, 2000). Although CA models use only very simple rules, they can generate very complex behavior and global structures. They have great potential in simulating urban growth and exploring alternative development forms subject to predefined rules. Many studies on urban CA models with interesting outcomes have been reported (Batty and Xie, 1994; 1997; Couclelis, 1997; Deadman et al, 1993; Li and Yeh, 2000; White and Engelen, 1997; Wu and Webster, 1998).

CA models can provide procedures for the design of optimal forms (Batty, 1997). They may become powerful planning tools when integrated with geographical information systems (GIS), which can supply physical, social, and economic data for the simulation. Recent CA models have generally been linked to GIS by using an inhomogeneous array of cells so that the transition rules are, in a sense, site specific. Remote sensing and GIS are integrated with CA in providing detailed land-use information as well as information on other characteristics of cities to allow realistic urban simulation (Li and Yeh, 2000).

Recently, attempts have been made to develop a kind of CA model that can be used as a model for urban planning (Li and Yeh, 2000; 2001; Ward et al, 2000; Yeh and Li, 2001a). We have used constrained CA and GIS to plan for sustainable urban development aiming at minimizing agricultural land loss and promoting compact development (Li and Yeh, 2000). Various urban forms associated with different development and energy 'costs' can also be explored by using constrained CA models for testing different planning options (Yeh and Li, 2001a). Ward et al (2000) have also developed a constrained CA

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model that has been applied to an area in the Gold Coast, a rapidly urbanizing region of coastal eastern Australia. They demonstrated that CA models can simulate planned development as well as realistic development by incorporating sustainability in the simulation. They showed that economic, physical, and institutional control factors can be incorporated to modify, constrain, and prohibit urban growth.

One of the major drawbacks in existing urban CA models is that most of them do not consider development density, assuming it to be uniform for all cells. However, the density issue is very important for urban planning, especially given the recent concerns over sustainable development and debates on compact development. Furthermore, in real cities, development and population densities are not uniform. An urban population density gradient exists in most cities (Clark, 1951; Papageorgiou, 1971; Thrall, 1988). There is also spatial variation in land values, resulting in spatial variation in development density in monocentric cities (Alonso, 1964) and polycentric cities (Heikkila et al, 1989).

Our main objective in this paper is to present a CA model that integrates a density gradient for the simulation of urban development of different urban forms that can be used as a planning model to explore various combinations of urban forms and development densities to guide future urban development. We will also evaluate and compare the development patterns of different density gradients generated by the model.

2 Development density and land-use planning

Compact development is considered to be the most suitable urban form because it can significantly reduce the consumption of energy and land resources (Ewing, 1997). Compact development usually concerns the contiguity or clustering of land development. The concentration of development is related to the issue of urban morphology, which has been discussed elsewhere (see Brookes, 1997; Webster, 1995; Yeh and Li, 2001b). Urban planners and researchers are concerned with the change in shape, size, and configuration of the built environment. Banister et al (1997) found that there are significant relationships between energy use in transport and the physical characteristics of a city, such as density, size, and amount of open space. Batty and Longley (1994) presented an interesting approach in the measurement of self-similarity by using fractal analysis. Fractal dimensions can be used to measure consistently the distribution of different land uses and its temporal change (Mesev et al, 1995). It provides ways in which the form of development can be linked to its spread and extent. Shape is also a very important element in the optimal location of development. It has been used as a constraint to find the best location for a particular land use in a GIS search model (Brookes, 1997).

Development density should be another important factor for compact development. Unfortunately, development density has not been well integrated in general GIS site-selection processes and urban CA simulation. Development density can be represented by the total number of people that can be accommodated by a developed cell. High-density development can significantly reduce expenditure on infrastructure and public services as well as reducing the costs of consuming energy and resources.

Trips get shorter, use of transit and walking increase, and vehicle trip rates drop as densities rise (Newman and Kenworthy, 1988; Pushkarev and Zupan, 1977). It has been found that per capita infrastructure costs almost certainly fall as densities rise, although extremely high densities may cause an increase in costs (Ewing, 1997). Urban sprawl leads to the encroachment on much more land than does compact development. For example, an assessment of two development plans for the State of New Jersey indicates that a compact plan could reduce land consumption by as much as 60% (CUPR, 1992; Ewing, 1997). An urban sprawl plan will result in five times greater loss of environmentally sensitive land and two-thirds greater loss of farmland than will compact development. In addition to compact development, one solution to contain urban sprawl is to increase development density properly. This can reduce a series of costs in terms of land development and environmental protection.

3 The method

The main focus of the urban density CA model is the configuration of transition rules so that the density factor can be taken into account in the simulation. The transition rules of the model deal with three important factors in urban development—urban forms, development density, and environmental suitability. Conventional urban CA models concern only the conversion of states. Usually, the conversion of state at a cell is determined by a development probability that is a function of the states and other site attributes in the neighborhood. The simulation consists of many iterations or loops for computation so that cities will grow gradually at each iteration. At the end of an iteration, CA models will decide whether the state at a cell will be converted or not for development. Only a binary value is used to indicate the change—1 for converted, and 0 for not converted. This type of urban CA model has limitations because variations of development density across space cannot easily be simulated. CA models can use only one unique value to represent a developed cell. There are difficulties in simulating development densities. A developed cell should be associated with a development density during the simulation so that more realistic and meaningful results can be generated. The urban density CA model is represented by the following two-dimensional model:

$$(S^{t+1}, D^{t+1}) = \mathrm{f}(S^t, D^t, N), \tag{1}$$

where S is the state of development, D is the development density, N is neighborhood, and t is the simulation time.

A 'grey-cell' CA model is devised to address the change of density at each cell during the simulation of urban growth. The model can generate various scenarios of development densities subject to different conditions and assumptions. The urban density CA model consists of two parts—the identification of cells to be developed (converted) and the allocation of development densities to developed cells. The novelty of the model is to incorporate the density factor in the sequential iterations of simulation based on grey cells. Development density is used to provide more detailed information on the cell to be developed. A binary value can indicate only whether a cell is developed or not. In contrast, development density can indicate to what extent the cell is developed. This is very important for actual urban planning because development density is directly related to total land consumption. A higher development density means that more people can be accommodated in a cell and that the total number of cells required for conversion can be reduced.

In a general CA model, the probability for a cell to be developed is decided by the number of cells already developed in the neighborhood. There is a higher chance for a cell to be developed if it is surrounded by more developed cells. If the density factor is considered, development probability should be related to the total density of development (population) in the neighborhood. The probability should be explicitly proportional to the total amount of development density or population in the neighborhood. A CA model should be devised to simulate urban growth and the distribution of development density. The proposed CA model is based on grey cells that have continuous values. First, whether a cell is selected for development or not is decided by the grey value (Li and Yeh, 2000). The calculation is based on the following iteration equation:

$$G_{xy}^{t+1} = G_{xy}^{t} + \Delta G_{xy}^{t}, \tag{2}$$

where G_{xy} is the grey value for cell xy with regard to development, and ΔG_{xy} is the gain of the grey value at each loop. The grey value falls within the range of 0 to 1. A cell will not be regarded as a developed cell until the value reaches 1. The value should be assigned to 1 when it is greater than 1 during the calculation.

There are advantages to using grey values instead of development probability in defining transition rules. The factors of urban form and development density can easily be integrated in a CA model that uses grey cells. When a cell is selected for development, a development density should be assigned to the cell. Development density in terms of population should be dependent on the distance to urban centers. Density-decay functions can be used to determine the development density of a developed cell. For the density-decay function, it is assumed that development density (population density) declines in an inverse exponential way. The notion that population density declines with distance from centers has been well discussed in many studies (Clark, 1951; Papageorgiou, 1971; Thrall, 1988). The function is given by (Clark, 1951):

$$D_{xy} = A\exp(-\beta l_{xy}), \tag{3}$$

where D_{xy} is development density, l_{xy} is the distance to the center, and A and β are parameters of the density-decay function. The function has been tested repeatedly over the past 150 years and found to be statistically significant (Papageorgiou, 1971). In particular, for most large cities, the negative exponential model seems to describe real-world observations fairly well as a first approximation (King and Golledge, 1978).

There are substantial fluctuations of population distribution because of uncertainties in the real world. A stochastic disturbance variable is added to the density-decay function to make the simulation resemble reality more closely. The perturbation term, R, is given by:

$$R = 1 + \frac{\gamma - 0.5}{0.5}\alpha, \tag{4}$$

where γ is a random variable within the range [0, 1], and α is used to control the size of stochastic perturbation. For example, a value of 0.1 means that $\pm 10\%$ of maximum fluctuation can be produced by the density-decay function. The density function is then revised as:

$$\begin{aligned} D_{xy} &= RA\exp(-\beta l_{xy}) \\ &= \left(1 + \frac{\gamma - 0.5}{0.5}\alpha\right) A\exp(-\beta l_{xy}) . \end{aligned} \tag{5}$$

The essential part of the simulation is to determine the increase in grey value for a cell based on neighborhood functions and constraints. The increase in grey value is proportional to the development density in the neighborhood and a series of constraint functions. A circular neighborhood is used to calculate the total development density. The increase in grey value is given by the following expression:

$$\begin{aligned} \Delta G_{xy}^{t} &= \mathrm{f}(D_{xy}, N) \prod_{k=1}^{m} \delta_k \\ &= \frac{\sum_{xy \in \Omega_N} D_{xy}}{D_{\max} \pi \xi^2} \prod_{k=1}^{m} \delta_k , \end{aligned} \tag{6}$$

where Ω_N is the set of developed cells in neighborhood N, δ_k is the constraint function for the kth constraint, ξ is the radius of the circular neighborhood, and $D_{\max}$ is the maximum value of development density.

In conventional CA models, development probability is proportional to the number of developed cells in the neighborhood (Wu, 1998). A greater number of developed cells in the neighborhood can result in a higher development probability. However, it is more appropriate to use population (development density) to indicate attractiveness because developed cells can have various development densities. A larger population in the neighborhood can be associated with a higher rate of increase in the grey value. This can result in the faster diffusion of urban areas (urban growth) away from the more crowded areas.

Urban geometry and environmental factors can be conveniently handled by the constrained CA model through a step-by-step approach. Constraints can be used to regulate urban simulation in generating idealized development patterns. Without constraints, cities will grow based on past trends, which are usually economically oriented and resource consuming. This cannot lead to the formation of sustainable cities because the compensation costs for resources and environment are not properly considered in such growth. Constraints in CA models are important for achieving sustainable development objectives, especially for the protection of resources and the environment. For example, one can restrict land development in environmentally sensitive areas in the urban simulation. Constraint scores can be defined to indicate the degree to which land development should be controlled. Constraint scores can be estimated from land evaluation (McRae and Burnham, 1981). Usually, linear functions are used to transform suitability scores into constraint scores, but nonlinear transformation of suitability scores into constraint scores helps to discriminate between development patterns (Li and Yeh, 2000). The values of constraints should be normalized into the range [0, 1] to facilitate simulation. Constraint functions can be regarded as scaling factors for readjusting the increase in grey value. Low values for a constraint function indicate that the environmental and resource conditions are not suitable for land development so that low growth rates should be applied to urban development. When the value is 0, no urban growth is allowed.

Many types of constraints can be defined to reflect different planning objectives for urban simulation. We have explored elsewhere environmental constraints (Li and Yeh, 2000) and urban forms (Yeh and Li, 2001a). The urban density model incorporates two constraints—urban forms and environmental suitability—into the model. Urban forms are usually related to development centers. Compact development emphasizes the role of major urban centers in promoting urban development. The costs of development and energy consumption can be significantly reduced if development is contiguous around existing urban centers (Ewing, 1997). Compact development can be either monocentric based or polycentric based with regard to a hierarchy of centers. Constraint functions for urban forms are defined to promote the formation of a preferable type of urban geometry. Weights are used to indicate the importance of various centers in promoting urban growth. The constraint function for the hierarchy of a major center and subcenters , $\delta_{xy}^{\mathrm{form}}$, is expressed by:

$$\delta_{xy}^{\mathrm{form}} = \exp\left[\frac{-(w_{\mathrm{R}}^2 l_{\mathrm{R}}^2 + w_{\mathrm{r}}^2 l_{\mathrm{r}}^2)^{1/2}}{(w_{\mathrm{R}}^2 + w_{\mathrm{r}}^2)^{1/2}}\right], \tag{7}$$

where l_{R} is the distance from a cell to the main center, and l_{r} is the distance from the cell to its closest subcenter; w_{R} and w_{r} are the corresponding weights for the two types of distances (Yeh and Li, 2001a).

A higher value of $w_{\mathrm{R}}/w_{\mathrm{r}}$ applies more weight to the main center than to the subcenters. In contrast, a lower value of $w_{\mathrm{R}}/w_{\mathrm{r}}$ gives more weight to the subcenters. The growth rate of the grey value at a location is affected by the constraint accordingly. Different types of urban forms can be made to emerge simply by changing the value of w_R / w_r. The value decides whether a monocentric pattern or a polycentric pattern emerges.

The constraint function for environmental suitability is also incorporated in the model. Land evaluation can be carried out to obtain various types of suitability criteria (Yeh and Li, 1998). The constraint for environmental suitability can be measured by the potential environmental costs associated with development. For example, urban encroachment on fertile agricultural land or ecologically fragile land will bring about large environmental costs. The environmental constraint function, δ_{xy}^{env}, will correspond to a small value so that urban growth is restricted in important environmental areas (Li and Yeh, 2000). The function δ_{xy}^{env} is calculated by the following expression (Yeh and Li, 2001a):

$$\delta_{xy}^{\text{env}} = \sum_{i=1}^{n} w_i (1 - E_{ixy})^k , \tag{8}$$

where E_{ixy} is the environmental suitability score for cell xy for the ith environmental criterion, and w_i is the weight for the ith environmental criterion. Each factor is normalized within the range 0 to 1; k is a parameter of nonlinear transformation, a higher value of k ensuring that the environmentally sensitive land is strictly protected. However, the simulated patterns may be fragmented.

On incorporating factors relating to density, urban form, and environmental suitability in the urban density CA model, equation (6) becomes as follows:

$$\begin{aligned} \Delta G_{xy}^{t} &= \frac{\sum_{xy \in \Omega_N} D_{xy}}{D_{\max} \pi \xi^2} \delta_{xy}^{\text{form}} \delta_{xy}^{\text{env}} \\ &= \frac{\sum_{xy \in \Omega_N} D_{xy}}{D_{\max} \pi \xi^2} \exp\left[- \frac{\left(w_R^2 l_R^2 + w_r^2 l_r^2\right)^{1/2}}{\left(w_R^2 + w_r^2\right)^{1/2}} \right] \sum_{i=1}^{n} w_i (1 - E_{ixy})^k . \end{aligned} \tag{9}$$

At the end of each iteration, the total density (population) across the whole region is summed to see if it has reached a predefined value (for example, the planning population or the maximum population that can be accommodated by a region). The simulation will stop automatically when the total population has reached a predefined value. The same predefined value can be used to examine how different density distributions can affect development patterns and land consumption. The total population that can be accommodated by a development scenario, P^{tot}, is calculated by:

$$P^{\text{tot}} = \sum_{xy \in \Omega} D_{xy} , \tag{10}$$

where Ω is the set of developed cells in the whole region for a development scenario.

It is apparent that use of a higher density development can reduce the amount of land consumption if the planned population is the same. Low-density development can bring about unnecessary encroachment on agricultural land and can also result in urban sprawl, which will significantly increase development and transportation costs. However, more detailed and accurate information is needed for estimating the consequences of various development density scenarios. The urban density CA model can provide detailed spatial information for the measurement of development impacts.

4 Simulation results

The urban density CA model was programmed using Arc Macro Language (AML) within a GIS package, Arc/Info GRID (ESRI Inc., Redlands, CA). The development of the CA model within a GIS package can facilitate the retrieval of spatial information and the use of its powerful spatial processing functions. The model is tested in Dongguan, a very fast-growing region in the Pearl River Delta of southern China. The study area covers 2465 km^2 and exhibited a tremendous speed and scale of urban development in the 1990s (Yeh and Li, 1997; 1999). It has a city proper and 29 towns. Remote sensing and GIS data were used to provide the basic information for the simulation. The 1988 and 1993 TM Landsat images were classified to retrieve land-use and land-use-change information (Li and Yeh, 1998). A GIS database was built to contain the information of land use, transportation, population, and administrative boundaries. The database was finally converted into a raster format for the simulation. The basic unit is a cell of area 50×50 m^2 on the ground.

Urban development inevitably consumes land previously used for farming, forestry, or wetland. However, for most situations the encroachment on agricultural land can be minimized if the development density is raised properly. More options will then be available for the protection of strategic agricultural land, wetland, and forest when there is a large reserve of land resources. The protection of important agricultural land has been a major issue in the Pearl River Delta since the economic reform in 1978 (Yeh and Li, 1999). The rate of agricultural land loss as a result of rapid urbanization was astonishing in the Pearl River Delta in the 1990s. An extreme case of land loss has been witnessed in the Shenzhen metropolitan region, which is the region closest to Hong Kong. The entire agricultural land base was almost destroyed by massive land development in the early 1990s according to analysis of satellite images.

From the analysis of multitemporal remote-sensing images (Li and Yeh, 1998; Yeh and Li, 1997), one can see that Dongguan has three major types of land-use problems. First, there is too much abandoned land that used to be agricultural land (Yeh and Li, 1999). Second, land development is in a dispersed or chaotic pattern because of the lack of proper planning and management (Yeh and Li, 2001b). Third, the average population density is too low compared with the national standard. According to national regulations, the population density for urban land use requires a minimum of 100 and 60 persons per hectare in the city proper and the towns, respectively. The study area was found to have a very low development density in the 1990s according to statistical data and remote-sensing images. The population density of urban land use was 69 persons per hectare in 1988 (table 1). Massive land development took place in the Pearl River Delta as a result of property development in the 1990s. The population

Table 1. Population density for urban land use in the study area (Pearl River Delta) (source: Dongguan Statistics Bureau, 1988; 1993; TM Landsat 1988 images; TM Landsat 1993 images).

Year	Area[a] (ha)	Population	Population density[b]
1988	18 347	1 267 605	69
1993	41 080	1 389 232	34
National standard			
city			100
town			66

[a] Built-up and development sites.
[b] Average population density, in persons per hectare.

density accordingly dropped to only 34 persons per hectare in 1993, which was about half of that in 1988. This is unacceptable according to the national standard.

The urban density CA model attempts to deal with the density issue by simulating alternative development patterns by using different planning scenarios. The year 1988 is used as the baseline for the simulation. The initial map for the simulation was from the land-use classification of the 1988 satellite TM image. The model attempts to generate land-development alternatives for the period 1988 – 93. This can help planners to explore different forms of planned development as compared with the dispersed unplanned development that had taken place. The actual urban areas (built-up areas and development sites) for 1993 were also obtained from the classification of the 1993 satellite TM image for comparison with the results of the simulation.

The urban areas and their population in 1988 were used for the initial stage of the simulation. The development density was estimated from the remote-sensing images and population data. The initial density was disaggregated into each cell by using density-decay functions. The model results were obtained based on two major categories of urban forms—monocentric and polycentric development. Each category was further divided into four subtypes of development scenarios. These scenarios are related to various types of density-decay functions. Figure 1 illustrates the eight types of hypothetical density-decay functions that may be applied to the region in the urban simulation.

In this study, the environmental constraints used are the protection of cropland, forest, and wetland. Agricultural suitability, which is one of the major environmental considerations, was calculated from the slope and soil maps in the GIS. The locations of forest and wetland were also obtained from the GIS and are used as environmental constraints in the model (Li and Yeh, 2000). The urban form and density parameters for producing the development scenarios are listed in table 2. The urban density CA model can generate either monocentric or polycentric development by using different weighting values of w_R and w_r. The parameters of A and β further control the density surface for the simulation. There is a higher density at the center if a higher value of A is chosen. The city center should have a reasonably higher value of population density compared with the town centers. In the case of high-density development, the city center was assigned a value of 80 persons per hectare, and town centers were assigned a value of 60 persons per hectare for parameter A. These values are chosen according

Table 2. Parameters for generating various urban forms and development densities.

Development scenario	Urban form		A		β
	w_R	w_r	city	town	
Monocentric					
high density and fast density decay	1	0	80	60	0.005
high density and slow density decay	1	0	80	60	0.001
low density and fast density decay	1	0	40	30	0.005
low density and slow density decay	1	0	40	30	0.001
Polycentric					
high density and fast density decay	0	1	80	60	0.005
high density and slow density decay	0	1	80	60	0.001
low density and fast density decay	0	1	40	30	0.005
low density and slow density decay	0	1	40	30	0.001

Note: w_R, w_r, weight associated with distance of a cell to the main center and to the closest subcenter, respectively; A, density-decay parameter (in persons per hectare), see equation (3) in text; β, density-decay parameter, controlling rate of density decay, see equation (3) in text.

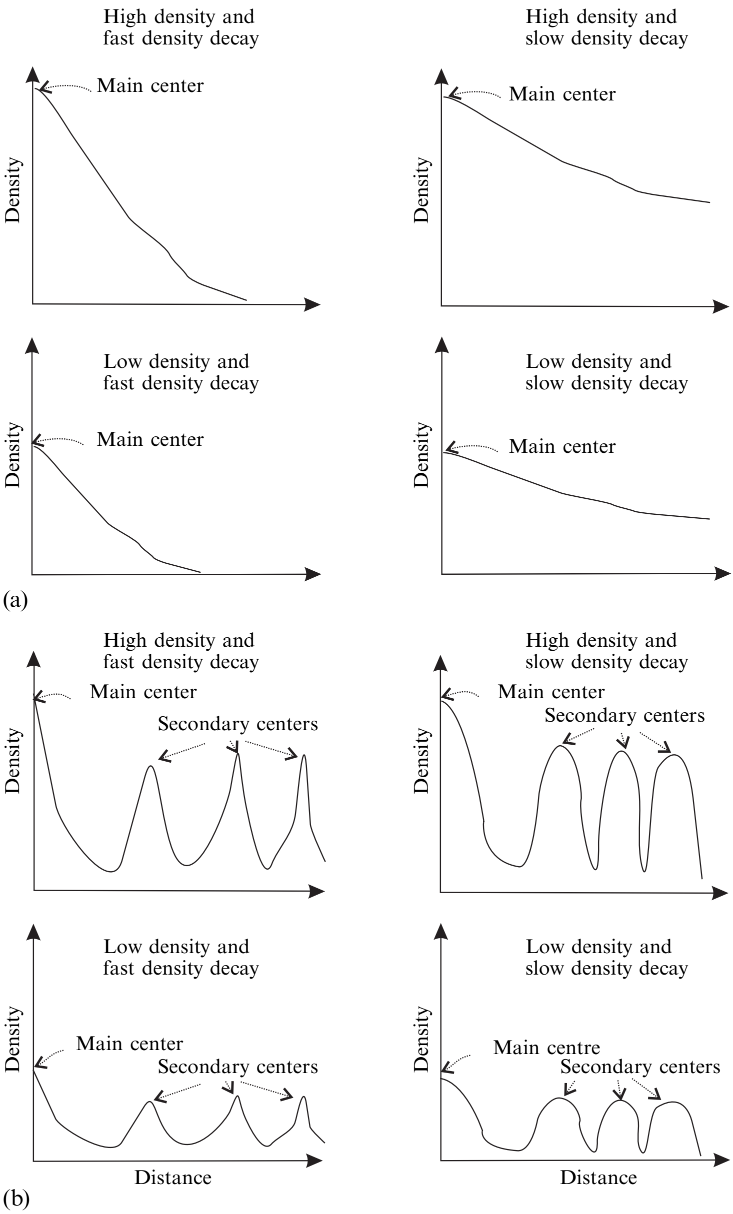


Figure 1. Hypothetical density-decay functions for various (a) monocentric development scenarios, (b) polycentric development scenarios.

to the national standard. Low-density development was obtained when a small value of A was chosen, which generated a pattern very similar to the actual development. In low-density development, the city center was assigned a value of 40 persons per hectare, and town centers were assigned a value of 30 persons per hectare for the parameter A.

In most cities, development density usually decays outwards from a center. The parameter of β controls the rate at which density decays. The density surface will decay rapidly if a high value of β is chosen. From the experiments, a relatively constant surface can be obtained when the value is as small as 0.001. In reality, the density surfaces of cities will never strictly fit the curves of density-decay functions because of uncertainties. A random variable (γ) was used to make the simulated density more like that of a real city. The random variable can model the unforeseen fluctuation of development density. The parameter α was used to control the size of stochastic perturbation by restricting it within the normal range of fluctuation. In this study, the fluctuation is controlled within the range of $\pm 10\%$.

For comparison with actual development in 1993, the total population at the end of the simulation is kept the same as the actual population in 1993. The total population that can be accommodated by the developed cells for each density option will be summed at each iteration of the simulation. The simulation will stop when the developed cells have accommodated the target population. The population data were obtained from statistical yearbooks. The total population of 1389 232 in 1993 was used for this simulation.

At each iteration of the simulation, the development density of a cell is decided by the grey value and density-decay function. Different values of the parameters will result in different urban forms and development densities. The analysis of CA simulation results can help to identify which types of density distribution can give better performance in terms of resource savings. The baseline scenario is the actual land development in the period 1988 – 93, which is considered as very-low-density development. Table 3 shows the details of urban encroachment on agricultural and other environmentally sensitive land by actual development and under the eight planning scenarios.

Table 3. Development densities and urban encroachment on agricultural and environmentally sensitive land.

Development scenarios	Encroachment of land development (ha)					Density[a]
	forest	orchard	cropland	water	total	
Monocentric						
high density and	351.6	2 523.1	11 618.6	478.5	14 971.9	54
fast density decay	(35)	(18)	(83)	(36)	(63)	
high density and	743.9	5 467.1	1 077.6	17 974.4	25 263.1	78
slow density decay	(20)	(9)	(41)	(24)	(43)	
low density and	2 453.8	16 348.4	43 350.5	1 450.1	63 602.9	18
fast density decay	(242)	(115)	(312)	(109)	(188)	
low density and	954.4	7 212.5	22 622.1	702.2	31 491.2	32
slow density decay	(94)	(51)	(163)	(53)	(106)	
Polycentric						
high density and	533.3	3 712.8	12 248.9	487.2	16 982.2	49
fast density decay	(53)	(26)	(88)	(37)	(69)	
high density and	257.0	1 616.6	5 631.2	353.7	7 858.6	75
slow density decay	(25)	(11)	(40)	(27)	(45)	
low density and	1 855.4	15 216.0	40 898.7	982.0	58 952.1	19
fast density decay	(183)	(107)	(294)	(74)	(175)	
low density and	953.6	7 201.8	22 580.4	697.9	31 433.8	32
slow density decay	(94)	(51)	(162)	(52)	(105)	
Actual land development	1 012.6	14 213.6	13 915.8	1 330.4	30 472.3	34
	(100)	(100)	(100)	(100)	(100)	

[a] Average density of the total urban area, in persons per hectare.
Note: figures in brackets are the percentage of land consumption compared with actual land development.

4.1 Monocentric development scenario

4.1.1 *High development density and fast density decay*

The parameters in this scenario take the highest values of A and β of all the scenarios. The weight that addresses the importance of town centers (secondary centers) is assigned a value of 0. This means that there are no attractions from town centers in promoting urban growth. Instead, the city gradually grows around the existing city proper during the simulation. The population density is high at the city center, but it drops rapidly outwards because of the high value of β. Urban growth is confined mainly within a narrow region around the existing urban areas in the north (figure 2). The average population density is 54 persons per hectare. It is still smaller than the national standard, although it uses only 63% of the actual land consumption according to the 1993 satellite image. It can save 82% of orchard and 17% of cropland compared with actual land development.

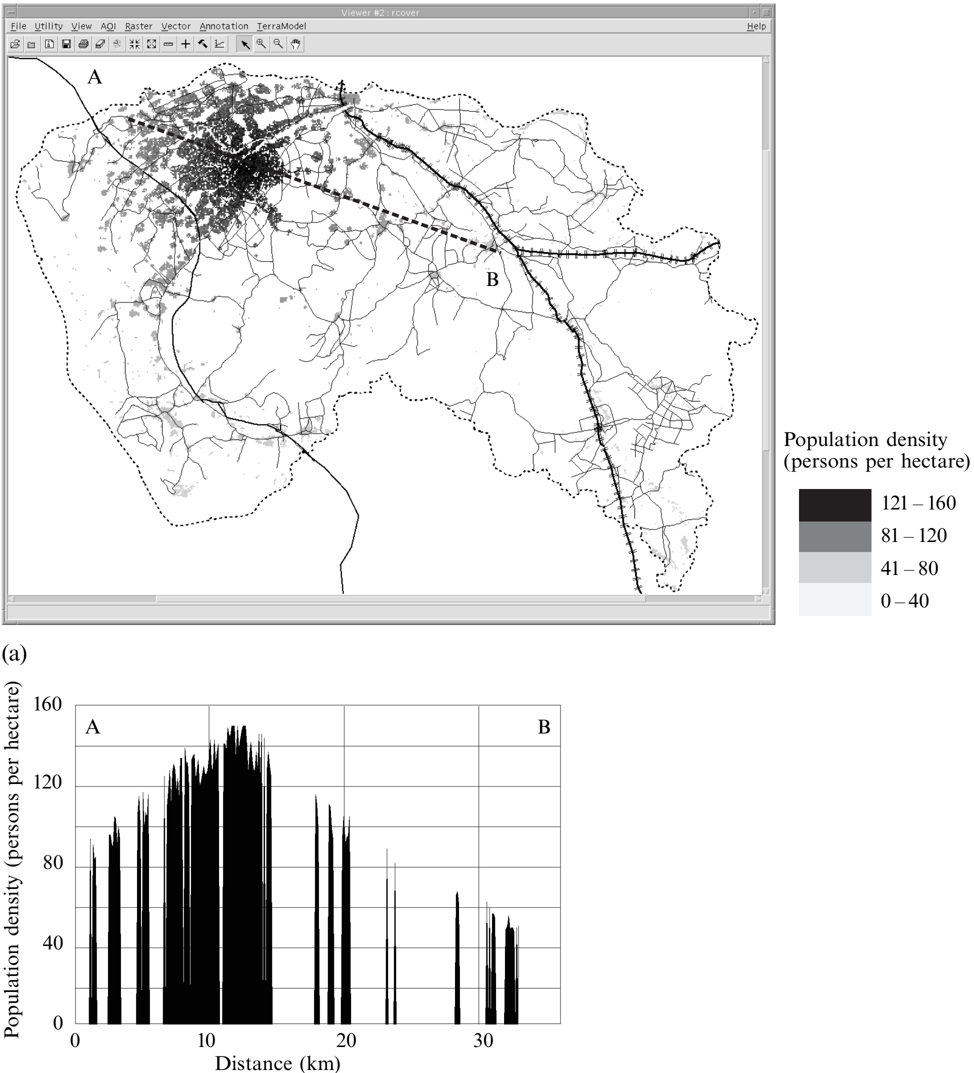


Figure 2. Monocentric development scenario with high density and fast density decay: (a) simulation results (density-decay coefficient, $\alpha = 0.005$) and (b) density profile.

4.1.2 *High development density and slow density decay*

Development density is constantly high compared with other alternatives. It keeps almost constant from the inner areas to the outer areas because of the low value of β. As a result, land development is very compact, with only the cells around the existing city proper being urbanized (figure 3). The average density is as high as 78 persons per hectare, which is close to the national standard. This scenario can save as much as 57% of land consumption compared with actual land development. It significantly reduces the encroachment on orchard by 91% and that on cropland by 59%. It is the most favorable development pattern in terms of resource and energy savings.

4.1.3 *Low development density and fast density decay*

This scenario assumes that the strategy of low-density development is adopted by the local government. The remote rural areas have even lower density development because of the fast density decay. The average density is only 18 persons per hectare, which is

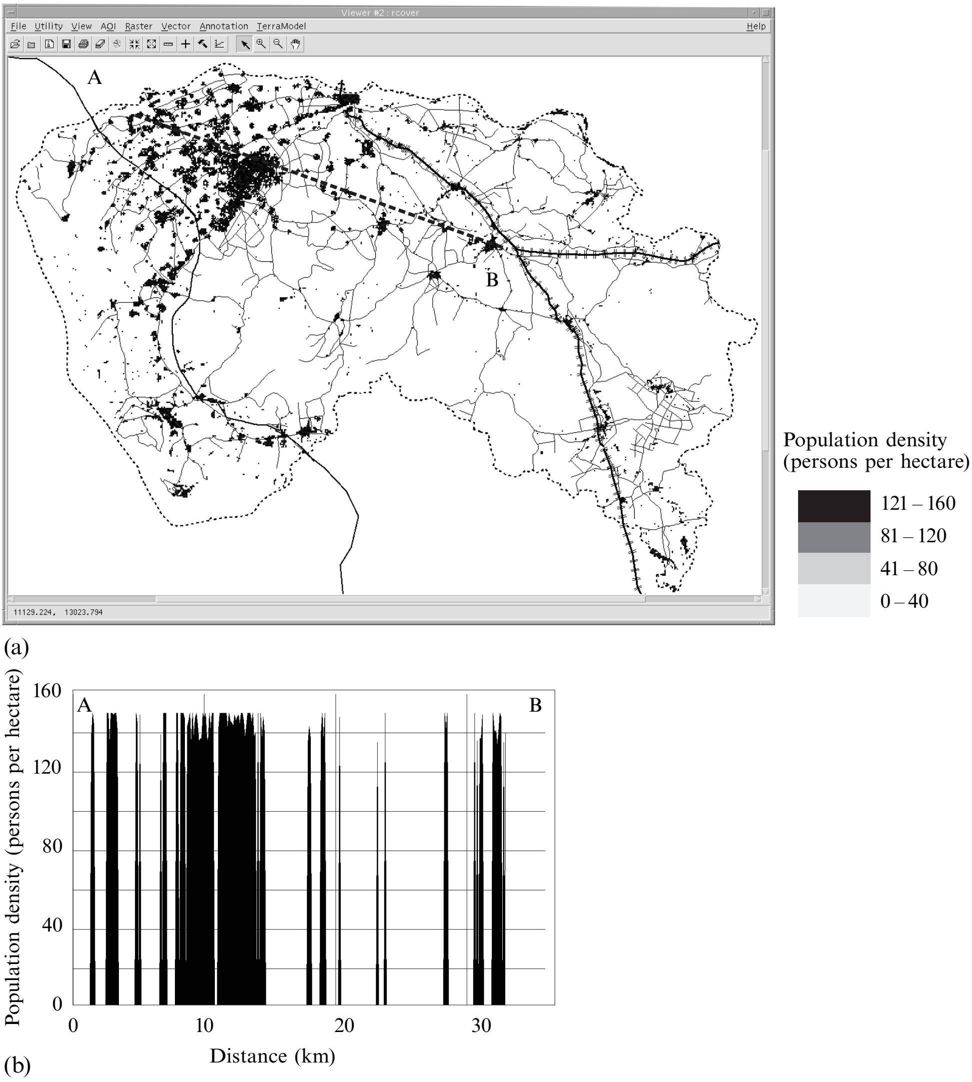
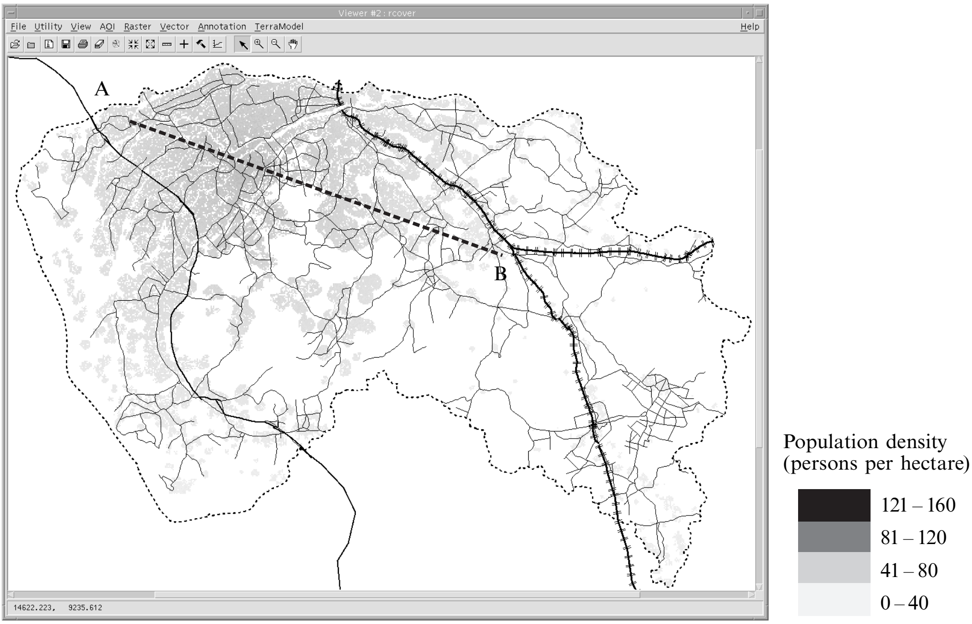


Figure 3. Monocentric development scenario with high density and slow density decay: (a) simulation results (density-decay coefficient, $\alpha = 0.001$) and (b) density profile.

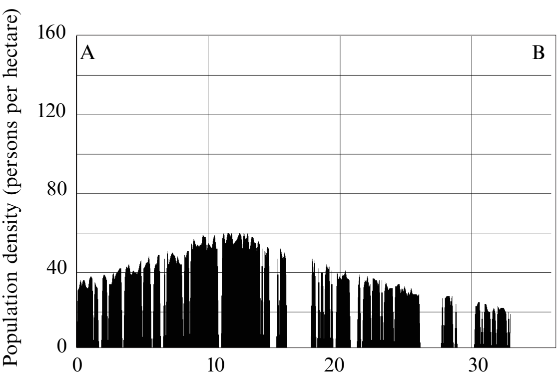
much lower than the national standard. Urban areas are spread out from the city proper to the outer rural areas (figure 4). It uses a greater amount of land for development than the actual development pattern because the density is very low. There are large amounts of land loss in the categories of forest, orchard, and cropland. This type of land development will bring about a disaster in terms of the protection of environmental and ecological systems because it exhausts natural land resources.

4.1.4 *Low density and slow density decay*

This scenario assumes that the surface of low-density development keeps almost constant from the city proper to the outer areas. There is a large amount of land conversion near the existing city proper because of the low-density development (figure 5, see over). The average density is still low but relatively higher than that of the scenario described in section 4.1.3. The total land consumption and average development density are very close to those of actual land development.



(a)



(b)

Figure 4. Monocentric development scenario with low density and fast density decay: (a) simulation results (density-decay coefficient, $\alpha = 0.005$) and (b) density profile.

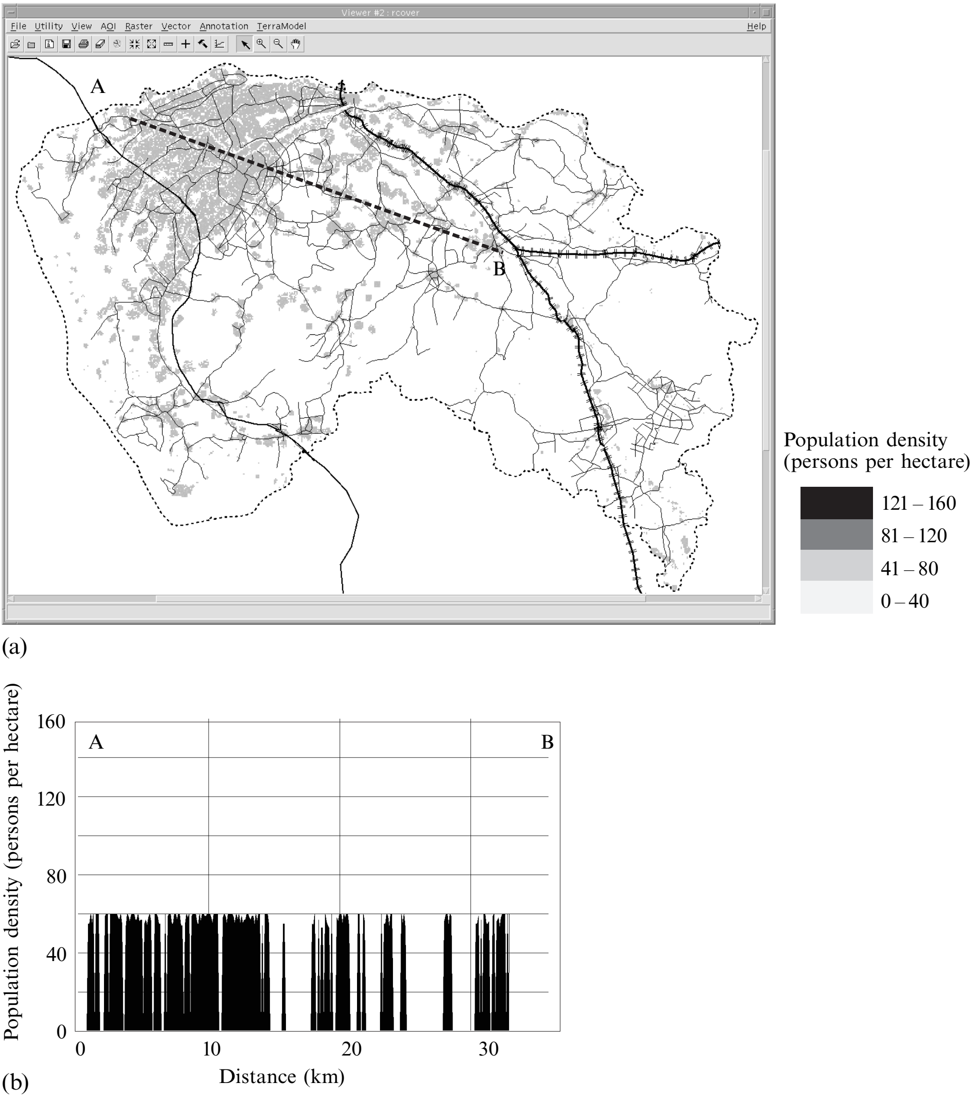


Figure 5. Monocentric development scenario with low density and slow density decay: (a) simulation results (density-decay coefficient, $\alpha = 0.001$) and (b) density profile.

4.2 Polycentric development scenarios

4.2.1 *High development density and fast density decay*

This scenario adopts the strategy of polycentric development (figure 6). The population density is 80 persons per hectare at the center of the city proper, and is 60 persons per hectare at the town centers. The surface of development density decays rapidly because of the high value of β. This scenario can save as much as 74% of orchard, 12% of cropland, and 31% of total land compared with actual land development.

4.2.2 *High development density and slow density decay*

The population density surface is almost constant from the centers to the outer areas. It is also a very compact development pattern (figure 7, see over). The plan can save a

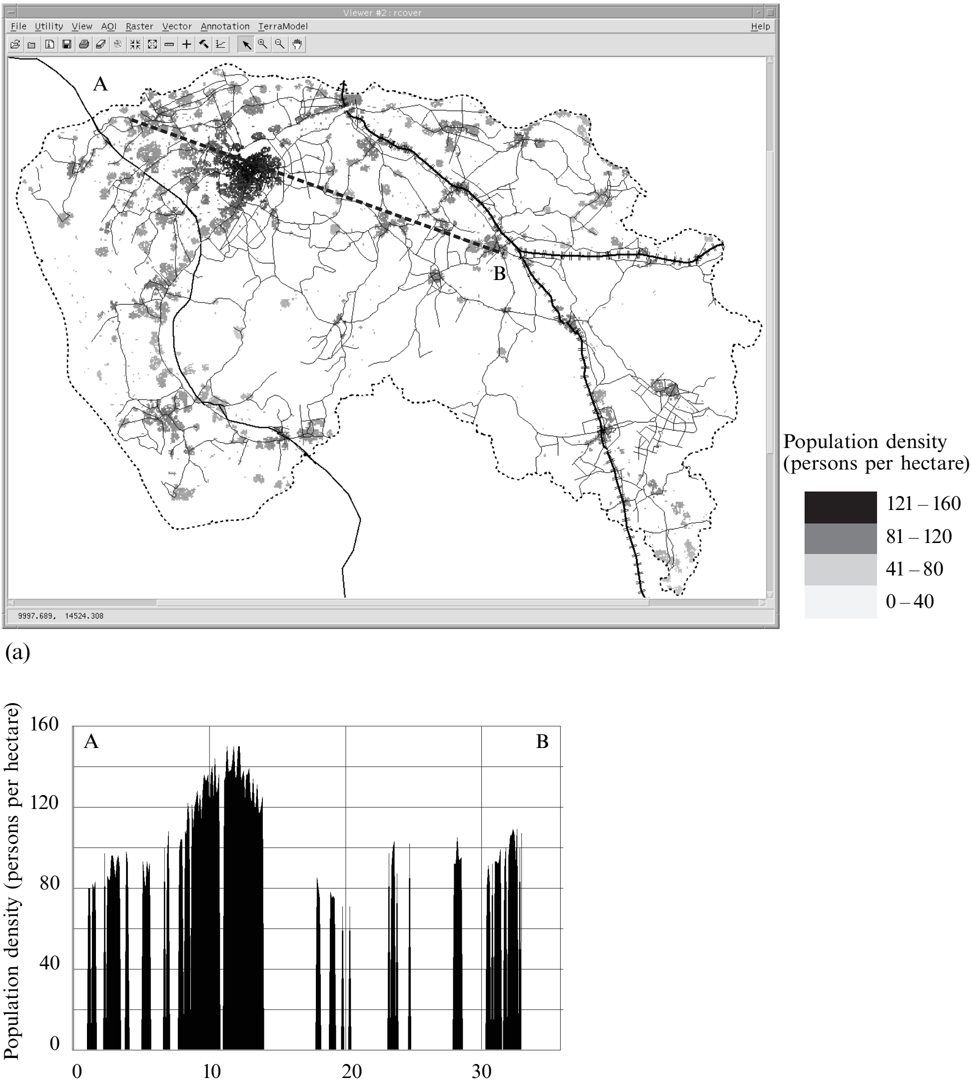
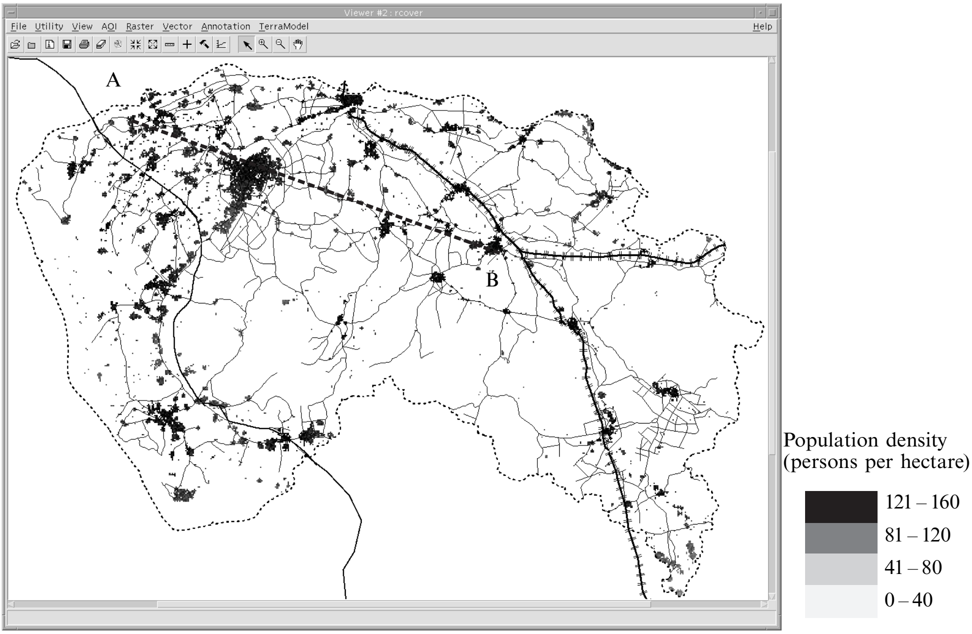


Figure 6. Polycentric development scenario with high density and fast density decay: (a) simulation results (density-decay coefficient, $\alpha = 0.005$) and (b) density profile.

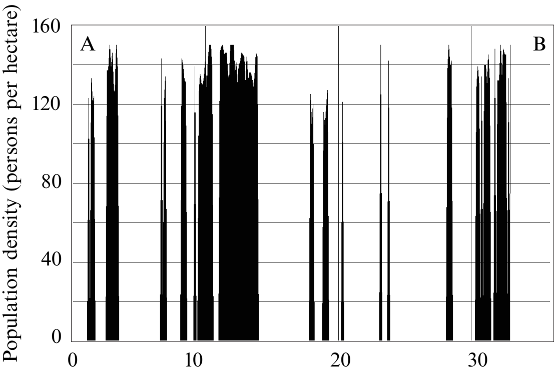
significant amount of agricultural land and other ecologically sensitive land. The total land consumption could be reduced by 55% if the plan were to be implemented.

4.2.3 *Low development density and fast density decay*

A dispersed and low-density development pattern is witnessed in this scenario. The average density is as low as 19 persons per hectare, which is much lower than the 66 – 100 persons per hectare of the national standard. Land consumption is also astonishing because of the low-density development (figure 8, see over). It is even greater than that of actual land development because much low density occurs in the rural areas. This pattern is unacceptable because it uses too much land for development.



(a)



(b)

Figure 7. Polycentric development scenario with high density and slow density decay: (a) simulation results (density-decay coefficient, $\alpha = 0.001$) and (b) density profile.

4.2.4 *Low density and slow density decay*

The low-density surface keeps almost constant from the centers to the outer areas. Although this scenario produces very-low-density development, it uses less land than does the scenario 2 described in section 4.2.3. Low-density development is witnessed around the existing urban areas of towns (figure 9, see over). The total land consumption is very similar to that of actual land development.

4.3 Discussion

It can be seen that the urban density CA model can generate development scenarios according to different density surfaces and urban forms. This can help urban planners to select desirable urban density and urban forms with regard to different planning objectives. Development density is an important factor in urban planning

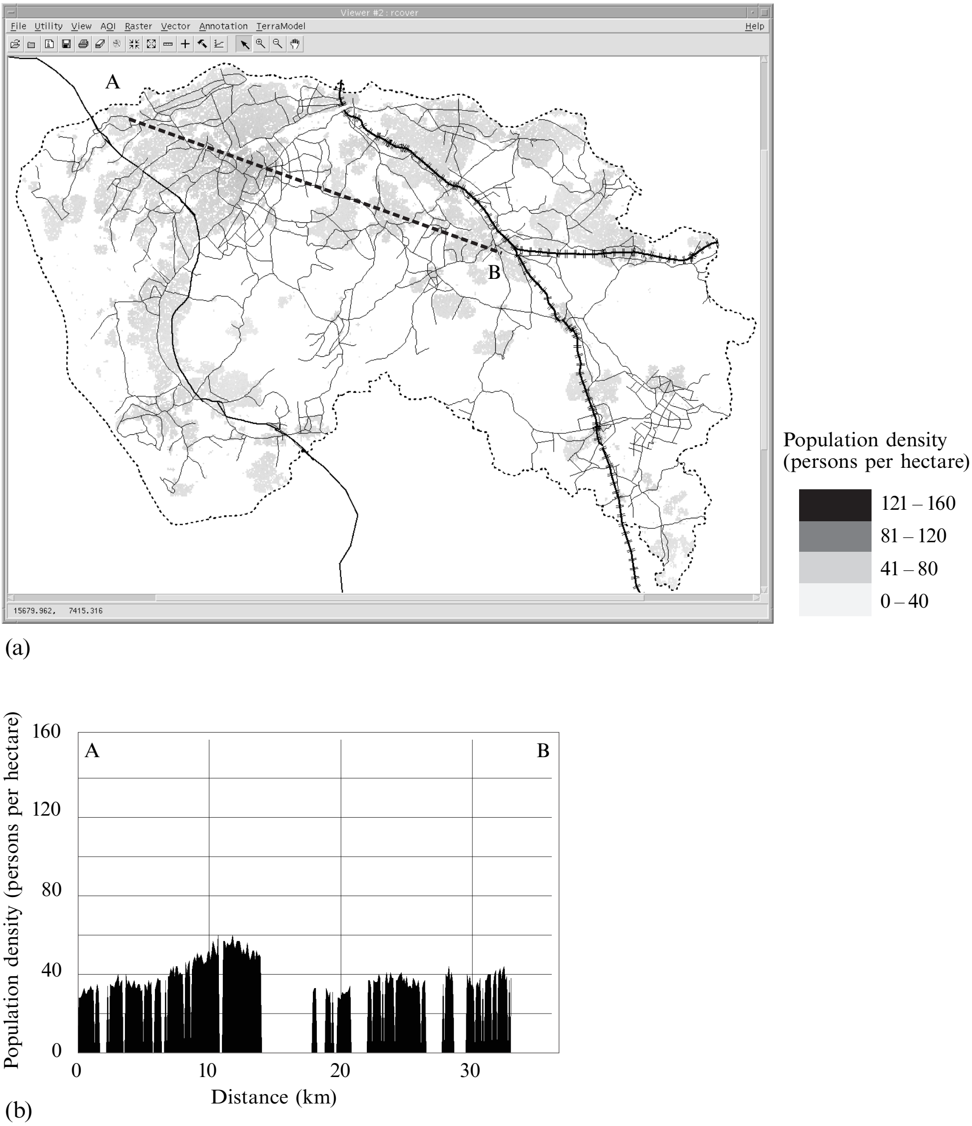
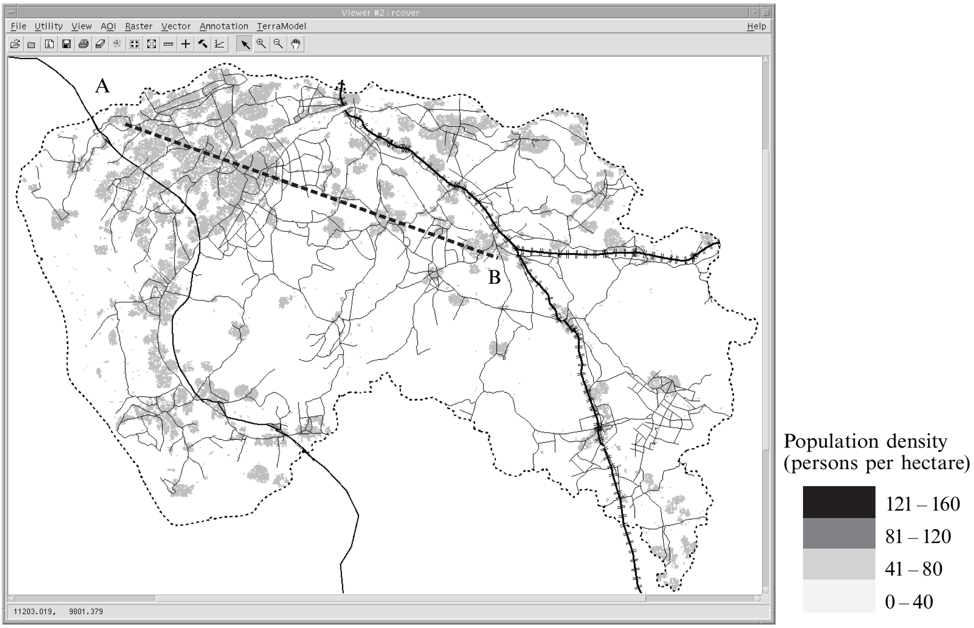
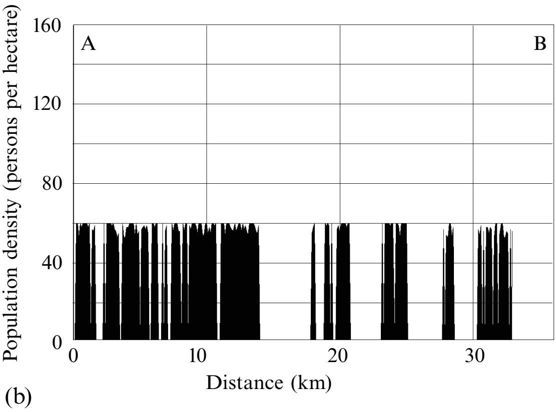


Figure 8. Polycentric development scenario with low density and fast density decay: (a) simulation results (density-decay coefficient, $\alpha = 0.005$) and (b) density profile.

and management. It decides the total land consumption in accommodating a specific size of population and plays an important role in influencing urban form. Urban development density has important impacts on the protection of agricultural land and other environmental resources. High-density development can help to minimize the use of agricultural land and other environmental resources and to leave more options open for future development. The proposed method can incorporate density functions into CA models and explore possible combinations of physical and social factors in planning for different forms of urban development.



(a)



(b)

Figure 9. Polycentric development scenario with low density and slow density decay: (a) simulation results (density-decay coefficient, $\alpha = 0.001$) and (b) density profile.

5 Conclusions

CA models have versatile features for a wide range of applications and purposes. In this paper we demonstrate that the structures of urban CA models can easily be defined to serve a specific requirement, such as the simulation of development density in this study. A single CA model cannot simulate all the features of a complex urban system. The model presents a method to incorporate the density issue as well as other constraints in CA simulation. The forms of development most often characterized as compact have two important features—concentration, and high-density development. There is a need to incorporate development density in urban simulation because most real cities, whether monocentric or polycentric, possess a population density gradient and a development density gradient.

This study has demonstrated that density functions can be conveniently embedded in the CA model based on grey cells. It provides a planning model that can be used to generate various development patterns that are dependent on the factors of development density, urban form, and other environmental considerations. The simulation is based on two major types of urban form—monocentric and polycentric. Various types of density distribution can be defined for generating alternative development patterns. The model can generate and evaluate different planning scenarios for guiding future development by varying the parameters in a combination of density, urban form, and environmental suitability factors according to planning objectives. This can leave more options open for protecting strategic agricultural land and other environmentally sensitive areas.

The development of CA models within GIS is crucial for the simulation and planning of realistic cities because a large number of social, economic, physical, and environmental data should be used. For example, land information can be retrieved from remote sensing and GIS as constraints for simulation. Constraints play an important rule in regulating development patterns and thus in achieving urban sustainability. Urban growth can bring about significant environmental and ecological impacts. The evaluation of the potential impacts of simulated urban growth is convenient within the framework of GIS. For example, overlay analysis can reveal the amount of urban encroachment on agricultural land and environmentally sensitive land.

Like other CA models, the proposed model is not without limitations, as social and nonspatial factors are not easy to quantify and incorporate. The force behind dynamics and evolution cannot be well explained. It is not so easy to explain the meanings of the parameters used in the urban simulation. A unique CA model does not exist, and the definition of transition rules is rather arbitrary. It would also be more convincing if monocentric and polycentric urban forms were to emerge out of the simulation process. At this stage, the two basic urban forms are postulated before the simulation is carried out. Moreover, the density gradients are imposed only as a boundary condition based on general observations. Nevertheless, there are significant benefits of using the CA model to simulate urban growth and to formulate idealized patterns, because the structure and parameters of the CA mode are transparent. Development patterns can be consistently generated, compared, modified, and even calibrated according to empirical information.

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