Study on Forecast Scenarios for Simulation of Future Urban Growth in Shenyang City Based on SLEUTH Model

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Abstract The SLEUTH urban growth model was used to simulate future urban growth patterns and to explore potential environmental impacts of urban development under different conditions of development in Shenyang City, China. The SLEUTH model was calibrated with historical data (1988-2004) extracted from a time series of TM satellite images, and the future growth was projected out to 2030 assuming three different policy scenarios: (1) current trends scenario (Scenario CT), (2) regional policy and urban planning scenario (Scenario PP), and (3) environmental protection scenario (Scenario EP). Scenario analysis showed that urban growth would accelerate under all policy scenarios with significant differences in development pattern and sustainability after 2016. Urban development under Scenario CT would lead to substantial loss of resource lands than that under the other two scenarios, and the urban landscape pattern would be increasingly complex and dispersed. In contrast, urban growth under scenario PP and EP would consume less natural resource land and show a relatively compact urban development pattern during the prediction period. This study suggested that it is crucial to take stringent urban planning and management measures to control future urban growth and to protect primary farmland and the support system of urban ecology in Shenyang City. The SLEUTH model is a useful planning tool to guide sustainable utilization of urban land resources to a certain extent.

Keywords SLEUTH; urban growth; scenarios; landscape pattern; Shenyang City

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Introduction

The escalating urban growth and land use change resulting from rapid socio-economic development have a far-reaching impact on global change and have aroused heated discussions over the dynamics of urban systems in the academic field[1]. With the increasing computational power and the greater availability of spatial data, micro-simulation such as the agent-based and cellular automata simulation methods, has been developed by geographers, planners, and scholars, and it has shown great potential for representing and simulating the complexity of the dynamic processes involved in urban growth and land use change[2]. Cellular automata (CA) is particularly well suited for this sort of simulation. In the past ten years, CA has witnessed significant technological advancements, as many CA-based urban models have been developed[3-7]. These CA-based dynamic spatial urban models provide an improved ability to forecast and assess future urban growth and to create planning.
scenarios, allowing us to explore the potential impacts of simulations that correspond to urban planning and management policies [8-9].

The SLEUTH (Slope, Land use, Exclusion, Urban extent, Transportation, Hillshade) model is a well known CA-based urban growth model coupled with a land-cover-change model [4, 10], which can project urban growth based on historical trends with urban/non-urban data or with detailed categorized land use data under different development conditions [11-12].

The SLEUTH urban growth model has been widely applied in the world and has shown its robust capabilities for simulating and forecasting landscape changes [1-2, 9, 13-14]. The model can generate alternative urban scenarios that may reveal the risk associated with certain development policies, thus allowing us to take the necessary precautions against disastrous consequences.

Shenyang City in China has continuously expanded its borders along with the growth of its population and the construction of economic development zones, especially after 2000. In 2004 the urban built-up area was up to 291 km², 2.5 times bigger compared to the early years of the establishment of the republic in 1956. This rapid urban expansion has occupied much of the surrounding arable land and created substantial changes to the region’s landscape and ecosystems. Therefore, it is impending for local planners and decision-makers to monitor this rapid urbanization process and develop effective policies to minimize the detrimental impacts of rapid urbanization [15].

The purpose of this paper is to simulate future urban spatial development under different conditions of development using SLEUTH model and to explore the potential environmental impacts of different land use and urban development policies in Shenyang City.

1 Material and methods

1.1 Data preparation and processing

In this study, many data sets have been collected, including multi-temporal city maps, historical traffic/tourism maps, aerial photographs, a time series of Landsat Thematic Mapper (TM) data, population census and statistical data. The TM image in 1997 was geometrically corrected by using the topographic map (1:100000) of 1981 with the total root mean squared (RMS) error of less than one pixel. Then the image-to-image method was used for the geo-referenced registration of other images with the total RMS error of less than 0.5 pixels. The visual interpretation from Landsat TM images for the years 1988, 1992, 1997, 2000 and 2004 was carried out to form a binary map of urban/non-urban classes, with the help of ancillary data including the aerial photographs of the central city in 1997 and 2001, the topographic map and the ground survey information. In this study, the urban extent included not only all built-up land use types but also the unattached transportation and industrial land outside of the central city which had played a role in urban development. The multiple-temporal urban extent images, called observed maps, were used to perform the calibration and evaluation of the model.

We mapped the 1981 and 2004 road layer based on the topographic map of 1981 and a 2004 map of Shenyang’s (1:210000) detailed transportation network, respectively. These roads were then weighted according to their relative urban attractiveness. The expressways, national and provincial highways and local primary roads were given a value of 100, while non-road cells had a value of 0. The secondary roads, including local roads and those reserved for special use, were given a value of 50. We then created 1988, 1992, 1997 and 2000 transportation networks by overlaying the 2004 and 1981 roads with 1988, 1992, 1997 and 2000 TM images and removing the roads that did not appear in these years or modifying the weight values by referencing the transportation construction data and the historical maps.

Designated excluded layer areas are partially or wholly excluded from urban development with a range of values (0 to 100). In the excluded layer, the large river and lakes or reservoirs had a 100% probability of exclusion, while primary parks had an 80% probability of exclusion according to local environmental characteristics and correlated applications of the SLEUTH model. These exclusion factors were derived from the 1988 TM images, the topographic map and Shenyang map. The percentage slope and
hillshade maps were computed from the DEM with 25 m resolution in GIS. The hillshade layer was used as a background image for model image output. All the input data layers were geo-referenced to the local coordinate system and clipped to the same map extent and then transformed to raster grids at 60 m resolution. Then, for model calibration, we resampled each data layer into 120 m and 240 m spatial resolution.

In addition, the land use information of 2004 classified from Landsat TM image with an accuracy of 80.2% was used to analyze resources loss from urban expansion under different policy scenarios. The land use types included urban land, farmland, forest land, water body, other built-up land, and unused land.

1.2 Scenarios design and urban growth simulation

We calibrated SLEUTH with the historical urban extent maps for the years 1988, 1992, 1997, 2000 and 2004, all of which were extracted from a time series of TM images. Because of time and computational constraints, we have adopted the “Brute Force” calibration method to refine the model parameters in the three sequential calibration phases suggested by the above website. This allowed us to find the optimal coefficient sets that could effectively simulate growth during the historic time period. The composite metric of the comparison, population, edges, clusters, and Lee-Sallee statistics was used in narrowing the range of parameter values from the calibration.

Then, based on the optimal coefficient sets, the model was used to simulate the urban growth from the past to the present (1988-2004) and to project future changes to year 2030 for different policy scenarios. The model results for the 1988-2004 periods were compared against observed data of urban growth for the same period using relative operating characteristic (ROC) curve statistics[16] and Kappa coefficients in order to assess the accuracy of the SLEUTH model.

We initialized SLEUTH with the map of urban extent for 2004 and simulated the spatial consequences of urban growth under different policy scenarios. The excluded layer served as the primary instrument to reflect alternative future policy orientations (Fig. 1). First, the current trends scenario (Scenario CT) reflected the continuation of past development trend assuming no significant regional constraints on urban growth. For prediction, according to 2004 TM image, a second layer of updated excluded areas was produced (Fig. 1(a)), which come with a range of values (0-100) indicating level of exclusion. All excluded areas in the first layer for model calibration were still preserved. Second, the regional development policies and urban planning scenario (Scenario PP) not only considered the regional development policies from local government and newly updated master urban planning (2006-2020), but also the optimization of regional spatial structure from the idea of economic geography. We designed six radiated development corridors from the central urban area that represented the directions of regional incorporation to different cities of urban agglomerations in the middle part of Liaoning Province (Fig. 1(b)). These corridors of about 20 km wide passed main transportation networks and satellite towns and served as main urban development spaces. According to the urban master planning, the planned urban area and greenland were assigned a value of 0 and 60, respectively. Other areas were assigned a value of 100. The third scenario, i.e., environmental protection scenario (Scenario EP), reflected a set of policies targeted toward limited growth and natural resource protection, as expressed through exclusion probabilities on different types of resource lands (e.g., forest, riparian buffer zones, etc.) (Fig. 1(c)). It would prohibit new development on designated prime farmland and hillsides having slopes in excess of 15 percent. Also, different probabilities of exclusion for urban development were assigned for these buffered zones.

All scenarios based on historical trend were predicted out to year 2030. A new road layer was prepared for the year of 2008 according to the transportation plan and construction and rebuilding of new roads. In order to compare simulated patterns of growth with mapped patterns, the probability image was reclassified into a binary representation of urban extent using a probability threshold of 50%.

1.3 Scenarios analysis and comparison

The spatial pattern of urban growth and resources loss under the three policy scenarios would be compared by using spatial analysis methods. A basic
Fig. 1  Excluded layers for urban growth scenarios for Shenyang City

impact assessment on land-cover change for each future scenario was performed using the land cover map for 2004 classified from the TM images. The resource losses under each scenario were computed by GIS zonal statistics method. The spatial distribution of resources losses pinpointed areas at risk for future urban development.

The landscape metrics can help improve understanding and representation of urban spatial structure, urban dynamics and urban modeling. In this study, we use four metrics to evaluate and compare the urban spatial pattern under different policy scenarios. They are mean patch size (MPS), largest patch index (LPI), mean perimeter-area ratio (PARA_MN) and compactness index (CI), whose expression can be found in the technical report of the Fragstats software program and correlated literatures [17-18]. In this study, the LPI metric describes the percentage of the total urban land represented in the largest urban blob [8]. The revised compactness index (CI') is given as follows:

\[
CI' = \frac{CI}{n} = \frac{\sum_j 2\sqrt{S_j \pi / P_j}}{n^2}
\]

where CI is the value of the compactness index, \(S_j\) and \(P_j\) are the area and perimeter of urban patch \(j\), and \(n\) is the total number of urban patches.

2  Results

2.1  Accuracy evaluation of SLEUTH model

The dashed line in Fig. 2 illustrates the expected ROC (50%) for a model that selects grid cells at random [16]. The ROC value assessing urban growth of Shenyang City between 1988 and 2004 equals 76.5%, demonstrating that the performance of SLEUTH is better than random and that it, therefore, has a credible precision. Also, the Kappa coefficient comes out as 0.782, which shows the better agreement of simulated and observed urban extent in 2004. Therefore, we can use the SLEUTH model to simulate future urban growth in study area under different development conditions.

Fig. 2  ROC curve to assess simulation accuracy for urban growth in Shenyang City between 1988 and 2004 based on the SLEUTH model

2.2  Urban spatial development under different policy scenarios

2.2.1  The overall trends of urban growth under different scenarios

According to past urban development trends, the urban expansion under all policy scenarios would continue in the near future. The urban area under scenario CT would show rapid growth, compared with scenario PP and scenario EP (Fig. 3). The simulated urban area for 2030 would be 771.3 km² under scenario CT, an increase of 66.8% for the entire period, accounting for 22.2% of the total land area (Ta-
ble 1). The net increment in urban land would be 309.0 km$^2$, 11.9 km$^2$ per year, which would be higher than the growth speed under the other two scenarios. Also, the urban growth under the scenario CT after 2016 will accelerate and show obvious differences between the three scenarios, as shown in Fig. 3. The urban area under scenario PP and EP by 2030 would be up to 646.4 km$^2$ and 677.7 km$^2$, respectively (Table 1). The net increment under the two scenarios would only account for 59.5% and 69.7% of growth area under scenario CT, respectively. Compared with scenario CT, the growth rate after 2016 under the latter two scenarios would show no obvious increase, indicating the constraint effects from environment protection and urban planning policies.

As shown in Fig.4, the majority of new urban land under all policy scenarios will develop around existing urban centers, especially the Shenyang Economic and Technological Development Area, Hunnan New Zone, and Shenyang New & High-Tech Agricultural Development Zone concentrated around a central urban area. The urban development pattern under scenario CT would be more dispersed than scenario PP and EP. The urban expansion shows obvious development along the road in the northeast direction of the central urban area. In contrast, the spatial development under scenario EP will be restricted because of environmental protection policies. However, the distribution of natural elements that are protected would be conducive to a relatively dispersed pattern than scenario PP during the prediction period. The urban pattern under scenario PP is most compact in three policy scenarios. The urban expansion would concentrate around the central urban area and main transportation corridors under the guide of urban planning and regional development policies.

### Changes of urban landscape pattern under different policy scenarios

The variation of landscape metrics further illustrates changes of urban spatial pattern under different policy scenarios (Fig.5). During the overall simulation period, the MPS and CI’ values first increase, and then decrease under three policy scenarios. The

| Items                      | Time phases | CT    | PP    | EP    |
|----------------------------|-------------|-------|-------|-------|
| Urban area (km$^2$)        | 2015        | 572.6 | 538.2 | 551.1 |
|                            | 2030        | 771.3 | 646.4 | 677.7 |
| Percentage to total land area (%) | 2015    | 16.5  | 15.5  | 15.8  |
|                            | 2030        | 22.2  | 18.6  | 19.5  |
| Urban growth area (km$^2$) | 2005-2015   | 110.3 | 76.0  | 88.8  |
|                            | 2016-2030   | 198.7 | 108.1 | 126.6 |
|                            | 2005-2030   | 309.0 | 184.1 | 215.4 |
| Growth area per year (km$^2$) | 2005-2015 | 10.0  | 6.9   | 8.1   |
|                            | 2016-2030   | 13.2  | 7.2   | 8.4   |
|                            | 2005-2030   | 11.9  | 7.1   | 8.3   |
LPI values show a decreasing trend on the whole, however, the values of mean shape index reverse this general trend. The changes of the four metrics indicate that the urban landscape patterns in 2030 under all policy scenarios become more dispersed and complex with decreasing dominance of the central urban area. From 2004 to 2016, the urban landscape patterns under all scenarios are relatively compact. The urban land conversion is concentrated as infill development adjacent and/or within pre-existing heavily urbanized areas. After 2016, the landscape patterns begin to become more dispersed and complex under different growth scenarios and show the significant differences. The urban landscape pattern under scenario CT is most dispersed and complex than the other two scenarios. During the simulation period, the change of urban pattern under scenario EP shows similar trends with scenario CT; however, the spatial pattern under scenario PP is relatively compact and regular. This can be attributed to the low growth rate of urban development and the constraint of urban planning and environment protection policies. After 2028, the compactness of the urban landscape under scenario PP would decline and possibly show high degrees of spatial landscape homogeneity.

2.3 Resource losses under different policy scenarios

This expansion of imperviousness will result in great resource loss, which can be expected to have serious environmental consequences throughout the study area. Not surprisingly, the scenario CT will result in the largest resource loss, including farmland loss of 969.9 ha per year, forestland loss of 54.2 ha per year, and waterbodies and unused land loss of 42.2 ha per year. Therefore, the area percent of forestland and water bodies and unused land loss is also the largest and are up to 4.6% and 3.6%, respectively. However, the area percent of farmland loss is less than the other two scenarios, which can be attributed to a high growth rate of urban development under an uncontrolled growth policy condition. Under the constraint of environmental protection policies, the prime farmland, eastern forestland and partial water bodies will be protected from the expansion of urban land under scenario EP. Therefore, the rate of resource loss will greatly decrease, compared with scenario CT (Table 2). However, because the forestland includes orchards and nursery gardens in this study, mainly distributing around existing urban patches and occupied by urban built-up land, the area percent of forestland loss under scenario EP is more than scenario PP. The scenario PP reflects a much slower process of urban land conversion and corresponding slower decline in the amount of resource land under spatial constraint of urban planning and regional development policies (Table 2). The nursery garden and ponds and

![Image of graphs showing landscape metric comparison of three different growth scenarios for Shenyang City forecasted for the year 2030](image-url)
puddles around existing urban patches and riverside area of Hun River in the urban planning zones will be occupied by urban land under scenario PP.

Table 2  Resource loss under different policy scenarios

| Land use types                  | Area percent (%) | Rate of resource loss (ha/yr) |
|--------------------------------|------------------|-------------------------------|
|                                | CT   | PP   | EP   | CT   | PP    | EP    |
| Farmland                       | 81.6 | 88.0 | 85.7 | 969.9 | 622.8 | 709.8 |
| Forest land                    | 4.6  | 2.0  | 2.6  | 54.2  | 14.0  | 21.4  |
| Waterbody and unused land      | 3.6  | 2.5  | 1.5  | 42.2  | 17.6  | 12.2  |
| Other built-up land            | 10.3 | 7.6  | 10.3 | 122.3 | 53.6  | 85.0  |

The incorporation of other built-up land into urban land is the second source of urban growth under all policy scenarios. The other built-up land near existing urban patches tends to convert into urban land under the attraction of urban centers. However, under scenario PP, the urban growth concentrates around the central urban area and economic development zones in the planned urban area and development. Therefore, the other built-up land makes up less proportion under scenario PP than that of the other two scenarios (Table 2).

On the whole, urban growth under scenario CT would consume more resource land than scenario EP and PP. We need to pay more attention to the loss of eastern forest land and water body around the central city under scenario CT and PP.

3 Conclusion

Urban growth has a great uncertainty resulting from the complexity of urban systems. This uncertainty should reinforce the view that the scenarios are best viewed as providing a comparative insight about alternative futures rather than precise forecasts of any specific future\(^{[19]}\). Scenarios help manage the inherent uncertainties of decisions based on assumptions by examining several alternatives of how the future might unfold and compare the potential consequences of different future contexts\(^{[20]}\). The SLEUTH model is a useful tool for assessing the impacts of alternative policy scenarios on urban land use changes to a certain extent. The excluded layer of the SLEUTH model is ideal for simulating the effects of conservation or regulatory policies and illustrates the advantages of linking the modeling process to a GIS\(^{[9]}\). In this study, we adopted the SLEUTH model with scenarios method to explore the spatial sensitivity and environmental impact of future urban development under different land use and urban management policies. These results show that urban expansion under the development with current trends will lead to substantial loss of resource lands, and the urban landscape pattern would be increasingly complex and dispersed. In contrast, urban growth under the guide of existing urban planning and environmental protection policies will consume less natural resource land and show a relatively compact urban development pattern during the prediction period. These results will provide much valuable decision-making information for future urban planning and urban ecological construction in Shenyang City. This study suggests that it is crucial to take stringent urban management measures to control future urban spatial development and protect primary farmland and eastern water resource areas, and to optimize urban morphology and regional spatial structure during the process of urbanization in Shenyang City.

However, there are many problems in this case study that makes it worth discussing further. The model is inclined to simulate the compact development pattern. It considers few socioeconomic factors and does not have an adequate mechanism to simulate the potential impacts of incentive policies. These disadvantages compromise the significance of these scenarios for the choices of future urban planning schemes and urban growth management policies in the study area. Therefore, in the near future, we will enhance the practicability of scenario designs by improving the design and simulation methods of policy scenarios, or considering the impacts of more anthropogenic driving factors on the urban growth process.

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