The spatiotemporal transition of China's JingJinJi Metropolitan Area: Detection, modeling and projection

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Abstract: It has long been recognized that cities are significant drivers of local economic development, however, their importance to regional development is not yet fully appreciated. Though many models have been developed to depict the dynamics of cities at local scale, few can be applied to a larger spatial scale. A Cellular Automata (CA) model is one that can be used on a regional scale to reflect urban evolution in terms of local interactions, where space and time are considered as discrete units, and space is often represented as a regular lattice of two dimensions. CA offers a unique and innovative approach to the study of urban systems and there has been a wide application of CA-based models to urban systems at local scale. This article explores the applicability of the CA-based SLEUTH model to the area of regional urban growth management. In general, SLEUTH model only incorporates physical factors that shape urban development, and the failure of incorporating socioeconomic factors would limit the utility of the model, both in terms of simulating historic growth patterns and in predicting future scenarios of where the new urban. This articles also attempts to overcome this limitation by including socioeconomic variables into the model.

Taking the JingJinJi Metropolitan Area (Beijing-Tianjin-Hebei) in China as the area of study, this article simulates the dynamics of urban growth, as well as future development scenarios by integrating remote sensing, GIS, and dynamic spatial modeling technologies. Primarily, this article attempts to examine the urban spatial growth and landscape changes of the JingJinJi Metropolitan Area since the late 1970s using a time series of satellite images. The SLEUTH model is then applied to simulate urban growth and analyze the major driving forces behind the observed growth and change. Finally, three potential urban growth scenarios are proposed under different environmental and development conditions to predict the urban growth of this cluster over the next decade. Through the calibration with historical data, these results prove SLEUTH's ability to explain the spatial pattern of urban growth, as well as to simulate urban dynamics, and forecast developing tendencies at regional scale. In order to interpret the urban growth mechanism of the JingJinJi Metropolitan Area under China's social, economic and political environment, four factors (Urban policies, Industry restructuring, Rural-urban migration, and Reclassification of urban boundaries) are further discussed to understand their driving forces in the urban transition.

Keywords: SLEUTH; Simulation; JingJinJi Metropolitan Area; ANFIS classification

1. Introduction

1.1 Need for regional studies

Cities are self-organizing systems, in which emergent bottom-up processes create distinct neighbourhoods, in addition to unplanned demographic, socioeconomic clusters (Kitchen and Williams 2009, Knox and Pinch 2006). In this emergent phenomenon, each component contributes to, but does not control, the form and pattern of the whole (Alberti 2008, Alberti et al. 2003). Traffic congestion, air pollution, and urban sprawl emerge from local-scale interactions among variables such as topography, transportation infrastructure, individual mobility patterns, real estate markets, and social preferences (Cheng and Masser 2003, Skinner and Henderson 1999, Tian et al. 2007).

Scale has always been the focus of discussion in the social sciences, particularly in geography. The main issue for attempted research projects is the difficulty of reconciling patterns and processes that operate and manifest at the local level, with those on larger scales (Torrens 2000). Contemporary urban models usually treat space in a metaphysically manner, (e.g., spatial interaction and gravity models, econometric models, location-allocation models, and core-periphery models), tending to derive an abstract pattern from spatial complexity (Couclelis 1997). Cities, however, are complex systems with many sub-systems that interact with one another at different scales.

According to the Ecological Fallacy[1], the processes that create macro-scale patterns cannot always be understood by simply aggregating up or extrapolating from the individual. A comprehension of the interactive dynamics that link local-scale and larger-scale phenomena are necessary in order to reach an understanding of these processes (Torrens 2000). Since the reductionist approach is disadvantaged due to its potential to miss the emergent phenomena of the interactive dynamics of individual elements, a synthetic approach would be more appropriate for studying urban systems[2].

1.2 China's regional urban studies

Since the mobility of people and goods extends the influence of cities well beyond their borders, it is essentially inadequate to study a city in isolation, without taking into consideration its relationship to the surrounding area (Semboloni 1997). Studying the development of a group of cities that are closely connected sheds light on the crucial role of cities in the structuring of urban space.

As a developing economy, China has been urbanizing at rapid rate since the economic reforms (Cao 2010). In retrospect, however, there were drastic fluctuations in its progress until the end of 1970s, which was followed by a period of sustained development. Furthermore, the development is uneven between regions: the urbanization rate of the

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[1] The ecological fallacy is an error in the interpretation of statistical data in an ecological study, whereby inferences about the nature of specific individuals are based solely upon aggregate statistics collected for the group to which those individuals belong. This fallacy assumes that individual members of a group have the average characteristics of the group at large.

[2] A reductionist approach analyzes the nature of complex things by breaking them down to fundamental components, and understands that by the interactions of their parts. On the contrast, a synthetic approach studies a phenomenon by experimenting with simple rules for behavior and allows components to interact dynamically until the macro scale phenomenon emerge (Knox and McCarthy, 2005)

eastern region is higher than that of the central region, and substantially higher than that in the west. It was not until the late 1990s that urban clusters began to emerge in the eastern regions (Han 2012). Also, urban development has also been inconsistent in terms of the size of cities. The central government's policy of controlling the development of large cities has gradually faded out, which has resulted in an increasing number of large cities. Following the implementation of economic reforms and an open door policy in the late 1970s, China's cites have been increasingly influenced by a market economy. Today, China's urban system is a hybrid product of a traditional planned economy and the market system. Therefore, the study of such an urban system would be a significant contribution to the field of urban studies, which continues to be dominated by Western-oriented theories. Furthermore, the application of such theories to China's urban development would also help to better understand the history, present and future trends of urban development.

The studies on China's urban development falls into two general categories of interest in terms of scale: the city level and the national level. In regards to the former, the morphological expansion of cities has been studied extensively by detecting and observing the land cover change (Deng and Huang 2004, Gaubatz 1999, Xie et al. 2007). Also, the study of social spaces has attracted a lot of interest (Gu and Shen 2003, Wu and Luo 1999, Wu 2008, Xu et al. 1989, Yeh et al. 1995). More attention, however, has been paid to urban growth, structural change, regional distribution, and rank size distribution in studies conducted on the national scale (Lin 2002, Pannell 2003, Qi 2002, Song and Zhang 2002, Wu and Yeh 1997). Despite the extensive nature of these researches, the functional structure, the interaction mechanism among cities, and the relationship between socioeconomic and biophysical factors in the urban system have largely been ignored. By studying all the cities on mainland China as a functional geographic system, the paper by Han (2012) successfully investigates the socioeconomic developmental mechanism of China's national urban system, and also depicts the spatial interactions within it. In this study, both socioeconomic and topographical factors were taken into account to study the evolution of the Chinese urban system since the mid-1990s, which was then presented by the development of a hierarchical structure and spatial development tendencies. Special attention was given to the unique nodal structure of China's urban system, the evolution of its hierarchical structure, as well as the relationships between the nodal structure and various socioeconomic factors.

1.3 Research Questions

While the two previously discussed areas of study of urban China (city and national level development) have been widely examined, regional development has been largely overlooked. Although urban clusters are emerging and developing at high speed on the regional scale in China, the existing urban clusters lack an overall developing strategy that covers both their urban and rural areas. Urban clusters are usually distinguished based on the spatial interactions between cities, but the development process and patterns inside a cluster are often overlooked. Inter-city relations, the relationship between cities within a region, are necessary for cities and the areas that fall within the radius of their impact to achieve sustainable development. Hence, there is need to study cities on the regional scale in order to fill in the gaps between studies conducted on the national and local city scales.

Located in the north of China, The JingJinJi Metropolitan Area is one of the largest subsystems in China's urban hierarchical structure and has demonstrative history of

Chinese urban development, and as a result is demonstrative of many of the distinctive characteristics of this process. The development of urban patterns is mainly due to geographical and historical factors. Since urban feedback on these factors is usually phase-lagged, often by decades (e.g., as a result of decisions about highway development), the study of urban changes over time is indispensable (Alberti et al. 2003, Cao et al. 2005, Cohen 2004). The following study of the JingJinJi Metropolitan Area's urban development will focus on providing answers to the following questions: On a regional scale, what specific processes and patters are discernible in terms of this area's urban development? More specifically, how the JingJinJi Metropolitan Area develop in the context of the surrounding area? How can its expansion mechanism be accurately represented, simulated, and projected as a potential development pattern for other urban areas?

The transition from the spatial interaction-based national scale modeling give rise to the regional scale based modeling, which is supported by new scientific approaches (Han and Cao 2012). Regional scale studies focus on the relationship between cities in any given urban cluster that has developed based on reciprocal interactions of dependency and competition. These relationships connect cities in two ways: the physical flows of goods and people, and the non-physical flows of information and capital. To depict the evolution of a whole system, a Cellular Automata (CA) model can be used, which is a dynamic model where space and time are considered as discrete units and space is often represented as a regular lattice of two dimensions (Batty 2003, Clarke et al. 1997, White and Engelen 1993). Due to its ability to represent nonlinear, spatial, and stochastic processes (Ward et al. 2000), the CA model is extremely useful. Therefore, this research applies a CA model to a simulation of the urbanization process, present transition patterns, and project future development patterns within an urban cluster —the JingJinJi Metropolitan Area.

2. Research Methodology

2.1 JingJinJi Metropolitan Area and data acquisition

Today, the JingJinJi Metropolitan Area plays a significant role in promoting the economic development of northern China. The study area is located between the latitudes of 38º05´N and 41º04´N, and the longitudes of 115º14´E and 118º54´E. It is comprised of Beijing and Tianjin, which are the dominant cities in this cluster, as well as 13 smaller cities from Hebei province, a total area of 64,022 km^2, and a total population of 94.32 million. There are totally 73 county-level units including counties, county-level cities, and city districts in the Area. Beijing is the capital city of China with an area of 16,300 km^2 and a population of 17.55 million as of 2009. Tianjin is a municipality direct under the Central Government, as well as an expanding city. It is one of the largest cities in North China with an area of 11,700 km^2 and a population of 12.28 million in 2009. Other important cities of this region include Tanggu and Tangshan. Some cities like Shijianzhuang and Handan in southern Hebei were recently integrated into this cluster in order to increase its competitiveness. The urbanization rate of Hebei province is 37.70% (2005), while Beijing and Tianjin have much higher levels of urbanization (83.62% and 72.11%, respectively) in comparison to the national average of 42.99% (2005). Also, the GDP of the Jingjinji area has been steadily increasing by an annual rate of 11.4% since 1995 (Dong et al. 2008).

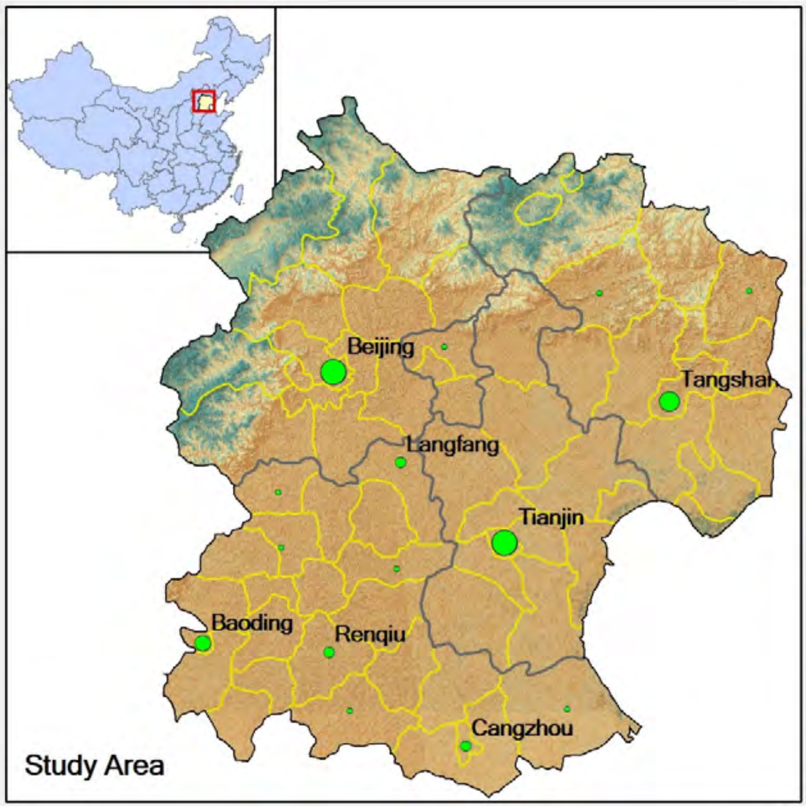

Figure 1 Study area of JingJinJi Metropolitan Area

To conduct a temporal analysis of the study area, three sets of remote sensing images from 1992, 2000, and 2009 were obtained. Each set of images is composed of 4 scenes of Landsat images that cover the whole study area (Figure 2). Landsat Thematic Mapper (TM) 5 and Landsat Enhanced Thematic Mapper Plus (ETM+) 7 images (downloaded from US Geological Survey) were selected for their spatial and spectral resolution. The specifications of each satellite are displayed in Table 7 from Appendix.

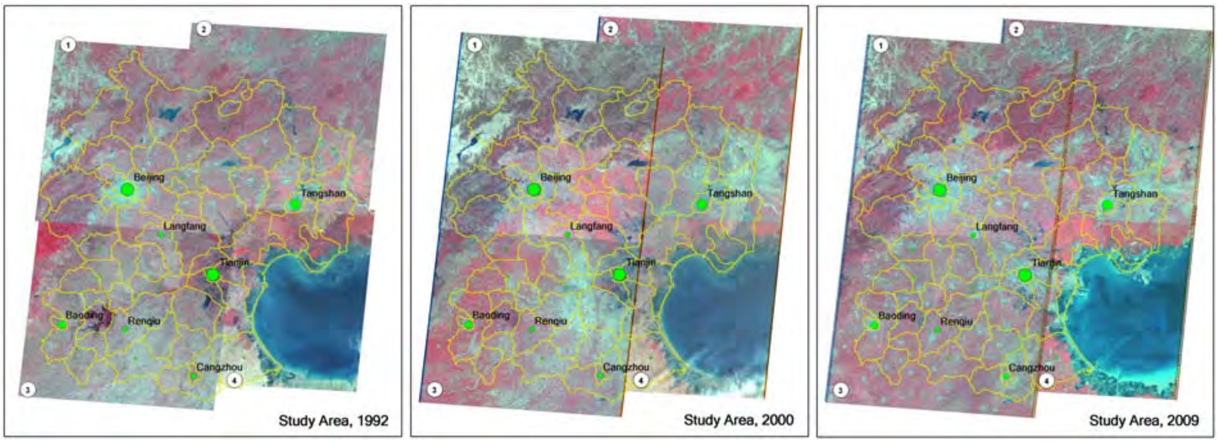

Figure 2 Landsat TM mosaics of 1992, 2000, and 2009 (RGB= Bands 4, 3, 2)

Since 4 scenes of Landsat images are necessary to cover the entire study area, the resulting mosaic of multi-date images is unavoidable because of the minimum 7 days overlap between neighbouring scenes (Landsat Project Science Office 2009). For the scenes where cloud-free coverage is not available, the scenes that were closest to the anniversary date were selected to minimize the variation of environmental factors (Jensen 2005). As no cloud-free images exist around the anniversary date in 2000, Landsat 7 ETM+ was used as a substitute since it provides spectral and spatial information that is as consistent as Landsat 5 TM (Table 7 and Table 8 in Appendix). The measured wavelength locations of the ETM+ spectral bands are compared to Landsat 5's TM in Landsat-7 Science Data User's Handbook (Landsat Project Science Office 2009).

Upon retrieval, all Landsat scenes were processed with the Standard Terrain Correction (Level 1T) by USGS. This Level 1T processing includes radiometric correction, systematic geometric correction, and precision correction by using ground control points (GCP) and digital elevation models (DEM) to correct parallax error due to local topographic reliefs (Roy et al. 2010). The WGS84 ellipsoid is employed as the Earth model for the Universal

Transverse Mercator (UTM) coordinate transformation (Landsat Project Science Office 2009).

Spectral bands 1 to 5 and 7 of the Landsat satellites are delivered at 30m's resolution, while the thermal band (Band 6 on TM and ETM+) provides spectral information at different resolutions (Table 7 in Appendix). The thermal band is omitted from the analysis process in order to obtain a consistent resolution for use in subsequent processing. Before the Level 1T processing begins, the pixels with a value of 255 that exceed the sensor's detection limit are identified as "saturated." As these pixels are "saturated" they do not provide useful data for subsequent analysis. Furthermore, the cloudy areas are also identified, which generally coincided with the location of the "saturated" pixels. Then, for each band, a NO DATA "mask" for all areas with "saturated" pixels or cloud cover was created.

2.2 CA-based SLEUTH model

Cellular Automata (CA) modeling was developed with the explicit purpose of representing emergent properties that originate from sets of simple behavioural rules operating over a cell-based pattern (Pinto and Antunes 2007). Therefore, the CA-based model's usefulness derives from its capacity to combine subsystems, which reveals the emergence of large-scale patterns from the interactions of local elements (Torrens 2000). It works interactively with space, time, and system attribute, where a change in one element has profound effects on its neighbours along the spatial and temporal scales. Essentially, CA allows users to model configuration and function, and pattern and process simultaneously.

CA offers a unique and innovative approach to the study of urban systems and there has been a wide application of CA-based models to urban systems in urban studies. Factors such as urban growth and sprawl, segregation and gentrification, population dynamics, economic activity and employment, historical urbanization, and land use evolution can all be examined using CA (Clarke et al. 1997, O'Sullivan and Torrens 2000, Pinto and Antunes 2007, White and Engelen 1997). As such, this extensive method gives researchers valuable insight into the development of urban systems. Cellular Automata consist of five essential elements: cells arranged evenly on a tessellated grid-space, states of the cells, neighbourhoods, transition rules, and time, which are explained in detail in the Appendix.

SLEUTH's name is an acronym that is derived from the model's required inputs of image data: Slope, Land cover, Exclusion, Urbanization, Transportation, and Hillshade. SLEUTH runs under UNIX system or UNIX environment built in Windows (such as Cygwin using a GNU C compiler) and is composed of the urban growth model (UGM) and the land cover deltatron model (DLM), which is optional. After the these inputs are correctly prepared, SLEUTH will be verified to ensure the model functions, then the model is calibrated, and finally changes are predicted and the products are built. Five coefficients are calculated while the model is being implemented, including diffusion (dispersion) coefficient (DI), breed coefficient (BR), spread coefficient (SP), slope resistance coefficient (SR), and road gravity coefficient (RG).

One of SLEUTH's main tasks is to express dynamic urban growth by the four growth rules (Candau, 2002). First, spontaneous growth, controlled by diffusion coefficient, simulates the process of urban growth in a new area, without being affected by pre-existing urban areas and infrastructures. The Dispersion coefficient effectively limits how often a particular cell is selected to be urbanized during the application of spontaneous growth law, and it also determines the overall outward dispersive nature of distribution.

Second, new spreading centre growth, measured by breed coefficient, defines the likelihood that a spontaneous occurrence of urban growth will develop into a centre of continued growth. The Breed coefficient determines the probability of an urbanized cell become a new urban core with the possibility to evolve and begin its own growth cycle (new spreading center) during the spontaneous growth phase. Moreover BR is used in the road-influenced growth phase to determine the spread alongside a road.

Third, edge growth, controlled by spread coefficient, estimates the extent to which urban growth has moved outwards from the city, and also how much urban infilling has occurred. Spread coefficient defines the probability that a cell in a spreading centre will trigger another urbanized cell within its neighbourhood, so it controls how much diffusion expansion occurs from existing settlements.

Fourth, road influenced growth, measured by road gravity coefficient, represents the tendency of new settlements to develop along existing transportation lines. Road gravity coefficient defines the maximum distance over which each road can exert its influence on urbanization probability. Slope resistance coefficient determines likelihood of a settlement extending up steeper slopes, which captures the effect of steep slopes on restricting development, therefore this coefficient functions in all the previous four rules. Users can also define an excluded layer, which specifies areas that are wholly (e.g. water or parks) or partially (e.g. restrictive zoning) excluded from development.

In an urban growth simulation, time units are referred to as a growth cycle. For the purposes of this research a growth cycle corresponds to one year. These four growth rules can be visualized as four steps in a cycle (Figure 3). These growth rules are implemented in both of phases of the model. During the calibration phase, SLEUTH replicates historical trends and patterns in urban development to attune the coefficients. Then during the prediction phase, those growth rules controlled by the calibrated coefficients are employed to project the future in a probabilistic way.

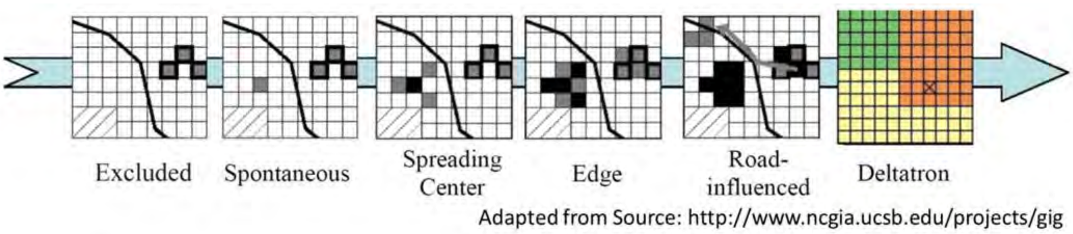

Figure 3 The behavior rules of a growth cycle year

2.3 Modifications to the SLEUTH model

SLEUTH model only incorporates physical factors that shape urban development (Jantz et al. 2004). Urban settlements are the result of human activities in a physically restrained setting. However, after an urban settlement has been formed, it is the socioeconomic factors that play a substantial role in propelling urban growth. Therefore, failure of incorporating socioeconomic factors would limit the utility of the model, both in terms of simulating historic growth patterns and in predicting future scenarios of where the new urban growth is going to take place.

The Exclusion layers in the SLEUTH model was originally designed to be a binary layer to exclude those land cover types that are not suitable for urban use. Areas where urban development is restrained or impossible, open water bodies or reserved park space for example, are simply ignored in the growth model. However, by adopting a multi-criteria analysis, an Attraction layer is generated based on the socioeconomic and demographic factors that promote urban growth. 17 Variables covering domains of demography, economy, industry and infrastructure are collected for the 73 county-level (counties, county-level cities, and city districts) units in JJJ Metropolitan Area (Table 1). These variables are then processed using Principal Component Analysis to generate a comprehensive indicator: the areas with higher values are more attractive for potential urban growth, vice versa. Variable including proximity to metropolitan centers and proximity to roads are calculated at a pixel level. These factors are then reclassified to a standardized scale and combined into a layer indicating the suitability of a location to be developed. For example, areas with higher population density are more likely to be urbanized; areas closer to an economic or industrial development are also favorable to build settlements. By overlaying the Attraction layer and the Exclusion layer, a composite Exclusion/Attraction is created.

Table 1 Socioeconomic factors included in the SLEUTH model

Domain	ID	Variables
Demography	1	Population Density
Economy	2	Urban Employment Rate
	3	Average Wage of Staff and Workers
	4	Gross Domestic Product (GDP) Per Capita
	5	GDP Growth Index
Industry	6	Share of Primary Industry's Product in GDP
	7	Share of Secondary Industry's Product in GDP
	8	Share of Tertiary Industry's Product in GDP
	9	Gross Industrial Output (GIO) Per Capita
	10	Share of GIO from Domestic Funded Enterprises
	11	Share of GIO from Enterprises Funded by Hong Kong, Macao and Taiwan
	12	Share of GIO from Foreign Funded Enterprises
Infrastructure	13	Investment in Fixed Assets Per Capita
	14	Local Expenditure Per Capita
	15	Local Revenue Per Capita
	16	Number of Beds in Health Care Institutions per 1000 people
	17	Number of Certified Doctors and Nurses per 1000 people

2.4 Data input preparation

Urban layers were derived from the reclassification of detailed land cover classified maps. We applied an adaptive-neural-based fuzzy inference system (ANFIS) with training sites purification to Landsat TM, ETM images to map land cover for the following years in the JJJ urban area: 1978, 1984, 1992, 2000, and 2009. These images were co-registered with an acceptable RMSE using the nearest neighbourhood algorithm. The maps were then converted into binary urban/non-urban layers to depict the JJJ Metropolitan Area's profile.

Transportation layers were derived from visual image interpretation and on-screen digitization of the satellite data and the thematic transportation maps from different periods. The Slope layer was created from ASTER Global Digital Elevation Model (GDEM), which was subsequently transformed to percent slope. All values beyond 100% in the slope layer were changed to 100 and the layer was re-sampled to a 30 m resolution using the bilinear algorithm. The Hillshade layer was also created from the same GDEM for the study area. The Exclusion layer encompasses any sites that cannot be developed: water bodies, wetlands, historical sites, airports with a 1 km buffer, railway stations, and local green spaces. These spaces within the JJJ Metropolitan area were identified and classified from satellite images. The Attraction layer is the direct result of reclassifying the multi-criteria analysis of the socioeconomic factors discussed in the previous section. The combined Exclusion/Attraction factor is the spatial overlay of both the Exclusion layer and the Attraction layer. Each piece of the input data required for SLEUTH's calibration was clipped to the same boundary, and then converted to 30m resolution raster grids in grayscale gif format. Table 2 lists the data requirements and generation methods for the SLEUTH model.

Table 2 Data requirement and generation methods

Input layers	Data requirement	Extraction methods
Slope	One Slope map in percentage rise	Generated from ASTER Global Digital Elevation Model
Land use	At least two land use maps were required for the model. Five land use maps were used to increase the calibration accuracy	Classification from Landsat images of 1978, 1984, 1992, 2000, and 2009
Exclusion/Attraction	One map showing the areas that cannot be developed and are more likely to be developed	Overlay of rasterized from vector of protected areas and multi-criteria evaluated result
Urban extent	At least four periods of urban extent for calibration. This research employed five.	Extracted from Landsat images through image classification
Transportation	At least two road networks. This research employed five roads networks maps	Transportation maps, updated with Landsat images
Hillshade	Background for display purpose	Generated from ASTER Global Digital Elevation Model

2.5 Dynamic spatial modeling

Since SLEUTH operates under the assumption that the way in which a region has developed in the past will play a role in determining how it will continue to develop in the future. As such, SLEUTH uses past developmental patterns to shed light on probable future changes in the study area's urban development (Clarke et al., 1997). In order to forecast future change urban growth during a given historical period must be effectively simulated during the calibration phase. To achieve this end, the model is calibrated by fitting simulated data to real historical data collected from the study area. In the case of the JJJ Metropolitan area, this procedure was completed using a large number of Monte Carlo iterations. SLEUTH employs Monte Carlo iterations stochastically to generate multiple growth simulations in three phases: Coarse, Fine, and Final. Furthermore, the five coefficients may independently take values between 0 and 100 in each phase.

In the Coarse phase, we applied the widest range of parameters (0-100), a large value (25) for incrementing the parameters, and the lowest spatial resolution through a resampling of the images to 1/4 of the original sized (120 m). By using the fit statistics that were generated during the model run, the coarse calibration phase's results were evaluated, which resulted in a narrower range in the best-fit set. In the Fine calibration phase, the range was further narrowed, and the increment size, the number of Monte Carlo iterations, and image resolution were all increased to improve the results of this modeling process. The Monte Carlo iteration was set at as seven with a half resolution (60m) for input data in accordance with SLEUTH's standard calibration method. In the Final phase, we used the best-fit results of the Fine phase, again narrowed down the ranges of possible parameters, and used eight Monte Carlo iterations for full-resolution (30) inputs.

3. Results and discussion

3.1 Result of Calibration Phase

During the SLEUTH model's implementation, coefficient values are constantly altered due to the model's process of self-modification. Therefore, the best calibrated parameters of the stop date are selected and their use will ultimately produce a single set of stop date parameters that allow us to initialize forecasting future changes. Since there is a certain degree of random variability during SLEUTH's running, using the averaged parameter results of more Monte Carlo iterations will ultimately produce a more reliable set of parameters for the forecasting process. Therefore, the best parameter values in final Monte Carlo iterations with one step increment were used to derive an average for each parameter. The result of the calibration phases for modeling JJJ Metropolitan Area is presented in

Table 3, and the coefficients used during the predication process are also represented in this table.

Table 3 The optimum of the coefficient set trough calibration phases

Coefficients	Calibration Phase			Predication Phase
	Coarse	Fine	Final	
Diffusion	85	80	80	80
Breed	75	95	97	98
Spread	100	95	95	97
Slope	25	25	25	25
Road gravity	50	85	85	90

The JJJ Metropolitan Area has a high diffusion parameter (80), which is reflexive of the fact that its urbanization mainly occurs outwards from existing urban areas and urban cores. The JJJ area's high spread coefficient (95 from the final phase) represents the likelihood that urbanization will continue to occur outwards from the existing urban centre's outskirts. Moreover, the breed parameter for this area is also quite high (97), which indicates that there is a high probability that new urban centres will be established. Both this probability of new urban centres and the likelihood of spreading are responsible for the majority of the dispersive urban growth in the JJJ Metropolitan Area.

Slope resistance was extremely low (25 from the final phase), demonstrating that topography was not a significant factor in limiting urban sprawl. Due to the topographic profile of the area, there are no restrictions to constrain the growth spatially as it sits on the North China plain. On the other hand, the road gravity factor was quite high. This score shows that road networks attract a substantial amount of urban growth, and thus heavily influence the study area's development patterns. Ultimately, it can be concluded that there is a high probability that new urban centres will be established near the main city centre through spontaneous growth, and also be attracted by the development of transportation lines.

3.2 Land use/land cover change during the Calibration Phase

Land use/land cover change focuses on the nature of urban growth and the changes of other land use/cover types that necessarily accompany this process. In the context of this research, the process of urban expansion in the JJJ Metropolitan area was analyzed by extracting the spatial distribution of the urban use/urban cover classes from each map in the time series. Then, the GIS minimum dominate overlay method effectively summarized the changes that occurred in urban areas. The GIS method is uniquely suited to this task because it maps urban land use in the 1970s as the point of reference which is then overlaid by the time sequence: the net addition in the following time period. By assigning a unique colour scheme to each year's net addition on the overlaid map, the progression of urban growth in the study area can easily be perceived visually, thus allowing for a statistical summary of urban expansion for each period.

The nature of urban change was analyzed by representing land conversion using a two-way cross-tabulation (a matrix analysis) that assigns a unique class to each coincidence between any two input layers. This assignment process captures the different combinations of change, such the conversion from farm land to urban land. Although there are a total of 36 possible combinations for each period due to the given number of land use and land cover classes, in order to focus on the process of urbanization, only combinations that involved conversion from non-urban to urban were selected.

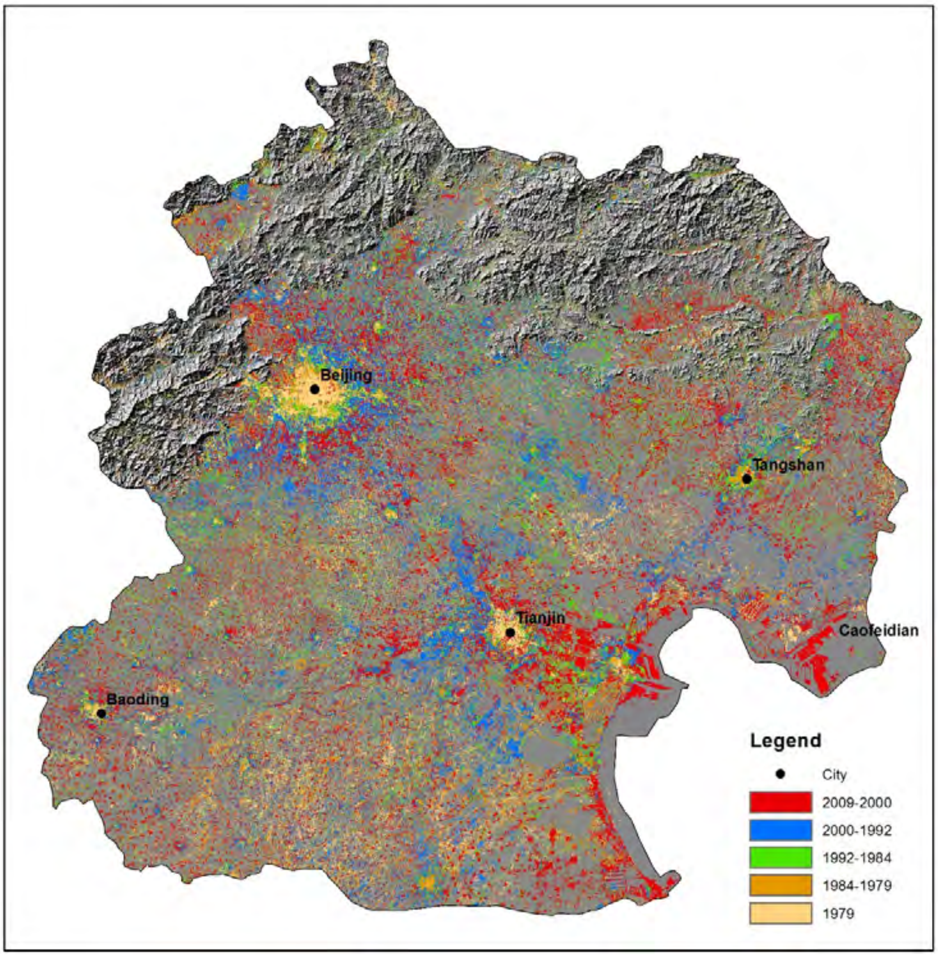

Figure 4 Urban expansion from 1979 to 2009

Figure 4 shows the spatial trends of urban expansion within the JJJ Metropolitan Area. Between 1978 and 1984 the annual urban growth rate was relatively slow at 106 km^2 per year, and during this period the majority of new urban development took place in the areas surrounding large cities. The pace of urbanization accelerated from 1984-1992, reaching doubled rate at 213 km^2 per year compared to last period, which led to an additional 1705 km^2 of built-up areas. In 1978, only 8% of this region could be considered urban (Table 4), and most of the newly developed land was located in the regions around highly-developed cities, like Beijing, Tianjin, Tangshan, and Baoding.

Table 4 Land and land cover statistics for JingJinJi Metropolitan Area

No.	Land use/cover	1978		1984		1992		2000		2009	
		Area (km^2)	%	Area (km^2)	%	Area (km^2)	%	Area (km^2)	%	Area (km^2)	%
1	Urban land	5325	8.0%	5963	9.0%	7668	11.6%	9856	14.9%	12590	19.0%
2	Cropland	36154	54.5%	35563	53.6%	33908	51.1%	32120	48.4%	29963	45.2%
3	Forest land	19471	29.3%	19216	29.0%	19061	28.7%	18534	27.9%	18179	27.4%
4	Bare land	576	0.9%	704	1.1%	652	1.0%	821	1.2%	695	1.0%
5	Wetland	1367	2.1%	1298	2.0%	1206	1.8%	815	1.2%	473	0.7%
6	Water	3039	4.6%	2863	4.3%	3286	5.0%	4062	6.1%	4399	6.6%
7	Seashore	431	0.6%	754	1.1%	580	0.9%	153	0.2%	62	0.1%
	Total	66362	100.0%	66362	100.0%	66362	100.0%	66362	100.0%	66362	100.0%

JJJ's urbanization began to take off after 1992, as can be seen by the significant increases in its growth rate. Between 1992 and 2000, the growth rate reached 273 km^2 per year, and 14.9% of the total study area was urbanized (Table 5). Much of the growth in the 1990s took place in small towns and cities as a direct result of the implementation of the Chinese government's two Five-Year plans (the Eighth and Ninth Five Year Plans of 1991-1995 and 1996-2000 respectively). These Five-Year plans strictly controlled the development of large cities' and that encouraged the growth of small cities between 1990 and 2000 (Kamal-Chaoui et al. 2009). As indicated by Figure 4, the urban growth in the 1990s (blue) was largely distributed along major roads and railways and at a distance from large cities.

Table 5 Land use and land cover conversion statistics

Land use/cover		**Land conversion statistics**			
Year A	Year B	**1992-2000**		**2000-2009**	
		Area(km^2)	**%**	**Area(km^2)**	**%**
Cropland	Urban	3516	45.9%	5658	44.9%
Forest land	Urban	534	7.0%	381	3.0%
Bare land	Urban	272	3.5%	429	3.4%
Water	Urban	477	3.2%	971	7.7%
Wetland	Urban	20	0.3%	11	0.1%
Seashore	Urban	6	0.1%	48	0.4%

In the most recent decade, the urban development is featured by a higher urbanization speed and more centralized pattern, resulting in 19% of the area being urbanized (Table 5). Large cities regained stage for fast spatial sprawl. Early stage of suburbanization began to take shape in these cities due to growing automobile ownership and ever-increasing cost in inner-cities. Another noticeable change in spatial patterns is the emerging developed areas along the coastline (Figure 4). China's entry into the World Trade Organization in 20001 brought about the prospect of international trade and communication. As a major port for exporting and importing, capacities of harbors were greatly extended to accommodate fast-growing business. Caofeidian, which used to be a small unpopulated island located 80 KMs south of Tangshan, is being converted to a gigantic economic development zone through land reclamation. Caofeidian has been mapped to become China's largest steel production base by 2010 and the area is expected to have a population of 300 000 by 2010 (http://www.caofeidian.us/). Moreover, Binhai New Area in Tianjin is being developed as a new special economic zone in Northern China, functioning as the Pudong New Area in Shanghai. Besides, robust industrial economy requires raw materials like salt, which is obtained from sea water through evaporation. The production of sea salt in this method led to increased built-up areas along the coastline. Although the areas of sea shores distinguished from remote sensing images varies due to the tidal effect, the areas that were converted to built-up surfaces increased significantly in the past decades (Table 4).

3.3 Future growth scenario simulation

Following the model's successful calibration, prediction mode used the average values, the full resolution data, and final Monte Carlo iterations to simulate the JJJ Metropolitan Area's future growth. A map showing the probability of grid cells being urbanized in the future is produced for every year from the first to the last, which is 2050. Insight into the cut-off point for urbanization in this area is provided by an examination of 2050's probability map's frequency histogram. Aside from the frequency histogram, a second popular method of determining the threshold of urban development using a probability map is to use demographical and statistical methods to project increases in population and the accompanying urban growth. The second method assumes that mathematic relationships exist between urban land use and urban population. In the context of JJJ's metropolitan area, regression models were run to verify the relationships between Built-up Area and Urban Population (Figure 5). Apparently, strong linear relationships do exist between these variables, which further validate the feasibility of this method. Therefore, the second method was adopted in this research.

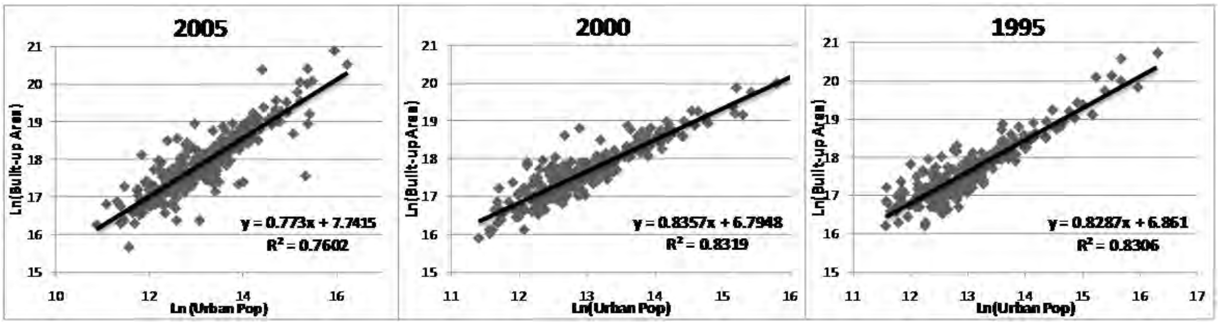

Figure 5 Linear regression between the logarithm of Built-up Area and Urban Population

The SLEUTH model provides a simulation environment that allows researchers to explore the potential consequences of policy changes. In this study, we simulated the JJJ Metropolitan Area in three different scenarios to maximize its practical application potentiality. First, the Historical Urban Growth (HU) scenario furthered the area's historical growth trends while also allowing for limitless expansion. Second, in the Environmental Protection (EP) scenario, various environmental considerations placed limits on urban growth. Third, the simulation of a specific form of urban growth (SUG) allowed for urban growth that was based on the historical growth tendencies and also limited by the logistics of constructing new infrastructure in steeper areas. Xiang and Clarke (2003) suggest three criteria for the defining and application of each set of acceptable scenarios: plausible unexpectedness, informational vividness, and cognitively ergonomic design. The application of these criteria to the three scenarios used in this study, demonstrated the modeling method's usefulness and provided a coherent context for city planners' use.

Using the SLEUTH model, there are three separate methods that can be used to simulate different growth scenarios. The first methods works by altering the parameter values that affect urban growth rules. Since these rules determine the form of any new urban growth in a given area, their alteration also alters the shape that this growth can take on (e.g. Leao et al., 2004). In the second method, different levels of protection values are assigned to specified areas within the excluded layer (e.g. Oguz et al., 2007). During the third method's application self-organization constraints are manipulated (e.g. Yang and Lo, 2003). We chose to use the first method in our research to benefit from the flexibility of changing the parameter values.

For the first scenario, we set the diffusion, breed, spread, slope resistance, and road gravity parameters at 87, 98, 97, 1, and 90 respectively. These parameters create the assumption that the current status quo will be maintained and that future growth will occur in accordance with the historical growth trends. In the second scenario, we reduced the spread and breed parameter values by half. These two parameters correspond with the urban sprawl pattern and the gravity effect of road networks on the location of new urban settlements. Historical trends reveal that despite land use planning protocols that limit construction in areas with a grade steeper than 9 degrees, the Beijing metropolitan area has expanded into steep regions in both the north and the west. To take this into account, we explored the urban-future under increased limitations with respect to urbanization in steeper areas during the third scenario. For this third scenario, we used the same parameters for the historical trend, while increasing the slope resistance to 8, which could also be achieved using other methods, such as masking out steep areas or resetting the critical slope parameter in the calibration files. Figure 6 compares the results of these three scenarios for urban future predictions.

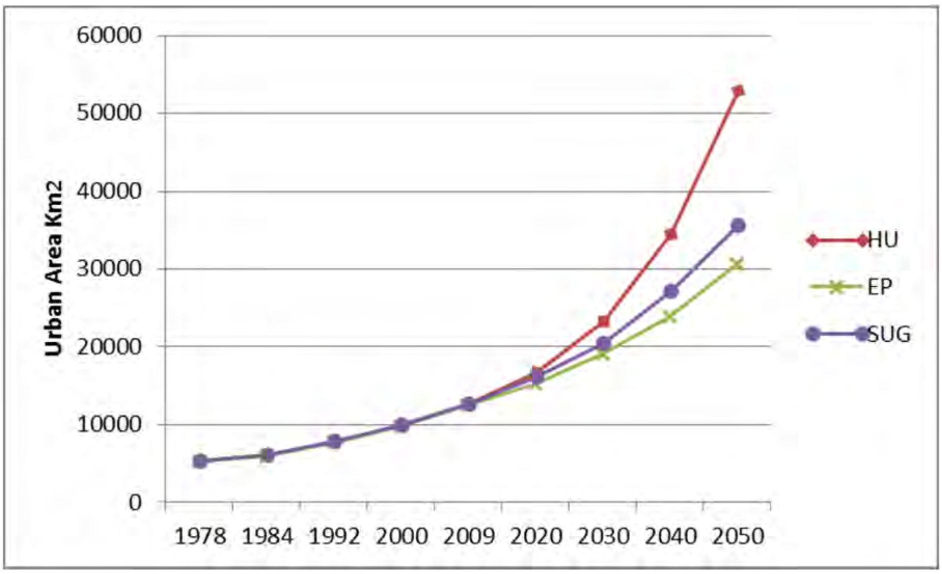

Figure 6 The urban area of JJJ up to the year 2050 under three scenarios

The HU scenario shows that there is no major limitation against urban expansion. The area of the study area expanded about 200% from 2009 to 2050 where 2.7% of urbanization was occurred in unsuitable areas with regards to slope. This scenario showed the highest expansion causing degradation of land and its natural resources. The EP scenario showed the smallest increase of the urban extent in the future as compared to the historical scenario. Under this scenario, the city area was expanded 40% from 2009 to 2050 and of this, only

0.8% occurred in unsuitable areas with respect to slope. This form of urban expansion showed compact city growth which saved thousand km^2 of lands from development. We predicted that urban area in the third scenario will cover approximately 35688 km2 by 2050, an 80% increase in the city extent with only 1.4% of urbanization in unsuitable areas. Given these findings, the EP scenario saved large areas of land and resources and also dictated a compact form of growth which facilitates provision of urban services by stake holders. Hence, the EP scenario was preferred against other forms of growth for a sustainable future.

However simple they may be, these scenarios are based on China's past urban development since urban development is partly controlled by the master plans derived from regional land use planning. Also, municipalities set upper boundaries for each city's area of development. In practice, a mixture of the results of land use planning and the controls exerted by the municipality and, in some cases unharnessed housing, is shaping some of the major cities and towns in China. These factors create a complex situation in which defining accurate or plausible scenarios is quite difficult. Hence, the three scenarios presented in this study serve only as a general guide to help city managers realize the potential of the modeling approach and the potential results of different development policies. It also reaches a larger audience composed of influential parties in city development, and helps them reach a common ground in regards to urban growth, through conducting 'what-if?' experiments.

3.4 Driving forces

It is difficult to determine trends for land cover and land use, as well as of social, economic, and demographic characteristics, as they are constantly in flux. These spatial structures are inherently unstable, and since they are exposed to external phenomena on a regular basis, they are subject to frequent change. In the context of JJJ, the dynamics of urban transition can attribute to the following four factors.

3.4.1 Urban policies

The regional urban development of the JJJ area is also the result of the urban policies that were formulated and renewed every 5 years and implemented to the national scale.

In the first decade of opening up, from 1978 to 1988, China's national urbanization strategy was stated as: "controlling the large cities, moderating development of medium-sized cities, encouraging growth of small cities" (National Urban Planning Law,1989), which was later codified in the National Urban Planning Law in 1989. In 1994, the central and local government rearranged the fiscal liaison, ending up the local government's reliance on inter-governmental transfer as the main revenue income; partly result from a common recognition for the urbanization financial demand. The local government profited, and made land-leasing become the principal source of off-budget revenues, leading to massive redevelopment of inner-city neighborhoods, and to new residential and industrial park development in outer urban and suburban areas in many cities. In 1990s, large volume of foreign investment in manufacturing poured in to many coastal cities, resulting real estate boom which has largely driven China's economic growth up to today.

The national Eighth Five Year Plan (1991-1995) explicitly addressed the "urbanization" issue for the first time, however, it retained the policy "control the large cities, moderate development to medium-sized cities, and encourage the growth of small cities". The national Ninth Five Year Plan (1996-2000) again repeated the central government's urban policy, but strengthened the emphasis on controlling large cities: “strictly control the growth of big cities, reasonably develop medium-sized cities and small cities”.

At the end of the 1990s, the two most critical issues for the government are: 1) regional and rural-urban disparities; and 2) stagnation and low consumption in domestic market. These challenges formed the backdrop for the government’s adjusting urbanization policy.

The Tenth Five Year Plan (2001-2005) explicitly put city and town-based urbanization as one of five key policy thrusts. Three key policy measures were designed to promote towns-based urbanization: 1) allowing conversion of agricultural to non-agricultural hukou for rural residents permanently relocating to towns within their counties; 2) land reforms designed to create secondary markets in farming rights by allowing farmers to permanently sell off their rights to other farmers to encourage economies of scale in production; and 3) promotion of industrialization in towns with implied approval of conversion of agricultural land to town construction land (largely for industrial parks). The third policy measure, industrial development of rural towns, however was largely unsuccessful, and as a result, waves of rural surplus labours were forced to cities to find employment.

The Eleventh Five Year Plan (2006-2010) placed much stronger emphasis on the development of metropolitan regions across the country, and promoted an urbanization process through “balanced development” of cities and towns regardless of their size. Governments at both central and local levels appear to be now trying to plan and control development at a scale that encompasses both rural and urban focused developments.

The Twelfth Five Year Plan (2011-2015) addresses urbanization as a central issue, and emphasizes on "inclusive growth", aim at reducing urban-rural income gap. In his report to kick-off the NPC and CPPCC, Premier Wen Jiabao emphasized to continue with the "Chinese characteristic urbanization", and guaranteed to gradually assimilate migrant workers into urban society, on the condition that they have stable employment and have lived in the urban area for some years (not detailed). This plan projected that from 2011 to 2015, the population living in urban areas will continue to grow and is likely to reach 51.5%. This plan targets at creating 45 million jobs in urban areas, keeping registered urban unemployment below 5% and boosting domestic consumption. As part of the drive to realize these goals, the government will boost investment in "improving people's livelihood", for example to build and renovate more apartments for low-income families, and extend the current urban pension schemes to including the 357 million urban residents. The Twelfth Five Year Plan aims at 16% cut in energy intensity, corresponding to 17% cut in carbon intensity.

3.4.2 Industry restructuring

The Modernization Theories developed in the 1950s believed that urban development in less developed countries would follow the European or American style. According to this developmental approach, cities in JJJ area would undergo an economic transition along a "continuum of progress from a traditional rural society toward a modern urban industrialized one" (Knox and Pinch 2006). Although the socialist marketism with Chinese characters is not exactly the same as capitalism, the development and industrialization steps share common characteristics.

The development of the two mega-cities, Beijing and Tianjin, has been transiting from centralization to decentralization. The increasing environmental and economic pressure and induced the centrifugal movement of secondary industries. Heavy industry and manufacturing sectors were relocated to suburban areas and more land became available for service sectors. The outward movement of industries led to the following movement of employed or related residents. Meanwhile, the soaring housing price and the revitalization of inner cities also forced the suburbanization of residents.

As explained in core-periphery model, economic growth in one region would trigger strong demand for life and economy necessities that local producers could not satisfy. This demand would create the opportunity for investors in peripheral regions to establish a local capacity to meet the demand. Due to the agglomeration diseconomy in inner cities, entrepreneurs would take advantage of the cheaper land and labor in the hinterland. If this spread effects is strong enough to be trickled down to the peripheral areas to stimulate their growth, these regions can develop an upward spiral of cumulative causation as in Myrdal's model. A growth pole is formed with the urban core and its periphery, which is usually characterized by a key industry whose economic influence causes linked industries to develop in the vicinity, As this key industry expands, there is an increase in the output of employment, related investments, new technologies and new industrial sectors. However, because of the theory of Scale and Agglomeration Economies near the growth pole, regional development is usually unbalanced. Meanwhile, the "trickle-down" of innovations and investments usually take decades. In the short-term, this strategy has more negative than positive effects. More specifically, the hinterlands will suffer because industries will overwhelmingly choose to locate themselves in the growth center. The hinterland effects that dominate the early years of the growth center policy is also called the "shadow effect:" large cities expand at the expense of smaller ones, much as a larger tree can stunt the growth of the ones below it by blocking their access to sunlight (Evans 1985).

Beijing is the dominant city in JJJ area, and its development has long been prioritized due to its political status as China's capital city. Due to this political privilege, other cities were unable to compete with Beijing, and the collaborative development relationship between Beijing and its surrounding cities became a conceding and concessive one. Essentially, the spreading effect of Beijing's development was outweighed by the siphoning effect. By examining the socioeconomic and biophysical contexts that delineate regional urban clusters, a noteworthy pattern appears from the perspective of spatial interaction (Han and Cao 2012). In terms of the variation of heaviest linkages and the Influential Factor discerned from previous study, the difference between Beijing and Tianjin was enlarged in the decade after 1995 (0.55 vs. 0.22 in 1995; and 0.89 vs. 0.33 in 2005) (Table 6). The development of Tianjin was greatly constrained by Beijing's "shadow effect," resulting in the loss of the heaviest linkages of interactions (Figure 7). The heaviest linkages that Beijing retained increased from 18 in 1995 to 45 in 2005; while the number of cities with heaviest linkages to Tianjin was reduced from 11 in 1995 to 5 in 2005 due to Beijing's overwhelming influence (Table 6).

Table 6 Variation of heaviest linkages and Influential Factor

Urban cluster	City	Linkages		Influential Factor	
		1995	2005	1995	2005
JingJinJi	Beijing	18	45	0.55	0.89
	Tianjin	11	5	0.22	0.33

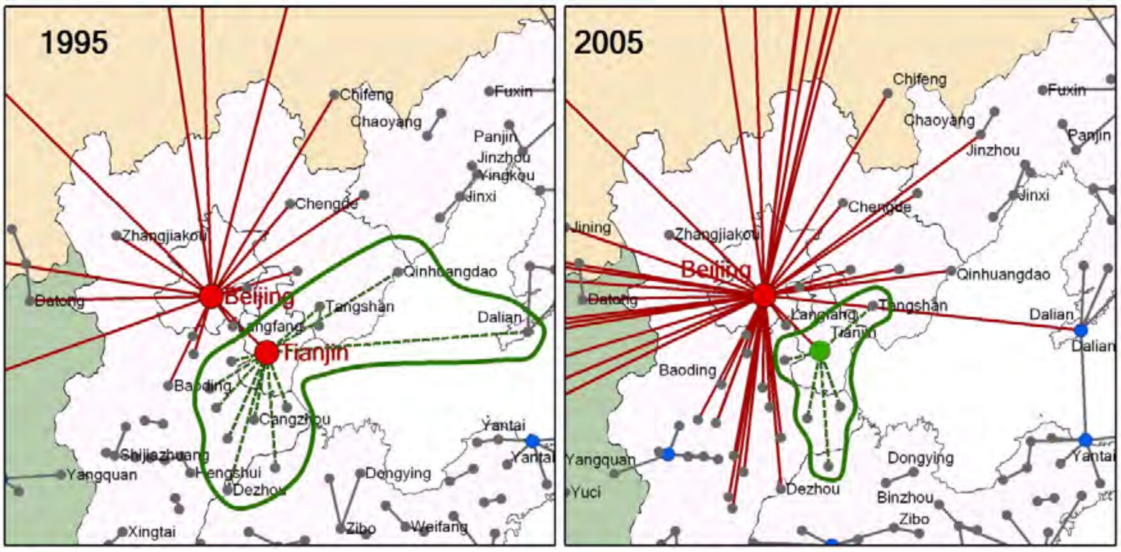

Figure 7 Evolution of the JingJinJi Metropolitan Area

3.4.3 Rural-urban migration

Natural growth, rural-urban migration, international migration, and the reclassification of urban boundaries are the main contributing factors to urban growth. In the case of the JJJ Metropolitan Area rural-urban migration is the most significant factor influencing its continuing urban development.

China's overall development strategy has relied on secondary industry before the economic reforms, which had a low-labour absorption rate, fewer opportunities for urban employment, and consequently lower levels of urbanization (Lin and Chen 2011). With this reduction in urban employment comes an increase in agricultural workers, and this saturation of the agricultural market results in a drop in agricultural wages, ultimately increasing urban-rural inequality (Cao et al. 2000). It is this disparity between the living conditions in urban and rural areas that prompts those born in the countryside to migrate to urban centres, like Beijing, in the hopes of securing employment and a better standard of life.

However, the issue of rural-urban migration is a difficult one. While the *hukou* system makes it extremely hard for rural residents to establish themselves in urban areas, China's one-child policy has led to little or no natural growth in urban centres, and so these mega-cities depend on such migration in order to further develop (Cao et al. 2011). Statistics on Beijing's growth patterns put this situation into perspective: Beijing's natural growth has remained steadily at zero since 2001, and according to the 2000 census, migrants accounted for 24.4% of the population, 46% of which were rural migrants according to Cao et al. (2011). Furthermore, without this influx of rural migrants Beijing's population will decrease from 10.5 million to 9.8 million between 2000 and 2030. However, if Beijing chooses to relax its migration policies, then its population could reach 21.2 million by 2030 (Cao et al. 2011). In summation, the future growth of JJJ's cities is largely dependent upon encouraging rural migrants to seek employment in urban centres. Some of the complications that these cities will have to rectify in order to continue attracting rural migrants include: labour market segregation, unequal urban and rural pay, exclusion of rural migrants from the urban welfare system, and migration restrictions like the *hukou* system.

3.4.4 Reclassification of urban boundaries

Like the factor listed above, reclassification of urban boundaries is another contributor for JJJ's urban growth. As part of the effort to promote rural-urban development, many counties since 1983 have been allowed to be reclassified as cities or be agglomerated into metropolitan cities as a district under certain conditions. A revised State Council directive that was promulgated in 1986 and is still in use stipulates the specific requirements that must be met in order for this reclassification to occur. For instance, a county with a total population of less than half a million would qualify for city designation if it has a town with a nonagricultural population of at least 100,000 and an annual output of at least 300 million yuan. Prior to this State Council directive only the town would have been reclassified as a city, but with its implementation the entire county can now be reclassified, As expected, these newly designated cities at the county level, contain large rural areas as well as a vast rural population within their administrative area.

Beijing has 18 administrative units including Districts, whose residents are all counted as urban population, and Counties, only a small portion of whose residents have non-agricultural *hukou* and thus counted as urban population. In 1992, eight of the 18 units are counties, and the rural population accounts for 32.1% of Beijing's total population. By 2009, six of the counties have been incorporated in the urban boundary of Beijing, leaving only two as counties and accounts for 4.2 % of the total population. This expansion of administrative urban boundaries exits in every large cities in the JJJ metropolitan area.

4. Conclusions

Today's metropolitan cities depend upon a series of regional-level socioeconomic inputs to develop, while simultaneously, their influence is required to support an urban field. Since an urban field is defined as an area 100 to 300 times larger than the urban region itself, the way in which these modern metropolises interact with their surrounding regions has an impact on an extremely extensive area (Alberti et al. 2003). Therefore, while the changes that accompany urban development are most noticeable on a local level, urbanization also leads to regional environmental and socio-cultural changes. The reciprocal nature of this relationship between metropolises and their outlying regions can be summarized as such: a city's need for resources to develop is affected by its spatial organization and location, as well as its degree of influence on the surrounding region. While these large cities have long been recognized as drivers of local development, their importance on a regional scale has often been overlooked (Alberti et al. 2003, Friedmann 1966, Pickett et al. 2001). As such, this study of cities at a regional level has taken this gap in the knowledge into consideration to establish a more complete understanding of China's urban hierarchy.

When conducting research on regional urban development, a dynamic Cellular Automata (CA) model is ideal because it analyzes local interactions to produce a representation of the entire urban system's evolution. As it considers space and time as discrete units and often represents space as a regular lattice of two dimensions it is well-suited to represent nonlinear, spatial, and stochastic processes (Batty 2003, Clarke et al. 1997, White and Engelen 1993).

In this research, the SLEUTH model was successfully calibrated for the JJJ Metropolitan Area using historical data from 1978 to 2009. SLEUTH's ability to predict future urban growth was demonstrated by the accuracy of the coefficient values derived for each of its metrics. Ultimately, SLEUTH generated three future growth scenarios that were used to evaluate the potential consequences of continuing urbanization. While these scenarios have a unique importance to developers and planners, it must be noted that urban growth is a complex process that is also affected by population increase, infrastructure, and socioeconomic factors. Furthermore, in the case of the JJJ Metropolitan Area, development is not only controlled by land use planning results, municipality decisions, and the sparse unharnessed development of built-up areas, but also by the particular development environment in China. The SLEUTH model is also limited in that it only considers road networks when analyzing the effect of infrastructure on urban expansion. While the results generated by SLEUTH and other models are approximations, SLEUTH's accurate modelling method produces scenarios that are extremely useful for comparing potential consequences.

Finally, this research brought to light the extremely useful link between the GIS and the CA in in obtaining the best possible results from SLEUTH's application. By effectively utilizing this connection, the input data was more easily prepared for modeling in a raster based GIS environment and the model's results were then straightforwardly imported into the same GIS environment for presentation purposes. As this model is readily available to efficiently produce possible results of different development scenarios it serves as a support tool for city planners during the decision making process.

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6. Appendix:

Table 7 Specifications for Landsat 5 TM and Landsat 7 ETM+ satellites (Source: Jensen, 2005)

	Spectral bands	Landsat 5 TM	Landsat 7 ETM+
Spectral Resolution (µm)	Band 1	0.45 – 0.52	0.45 – 0.515
	Band 2	0.52 – 0.60	0.525 – 0.605
	Band 3	0.63 – 0.69	0.63 – 0.69
	Band 4	0.76 – 0.90	0.75 – 0.90
	Band 5	1.55 – 1.75	1.55 – 1.75
	Band 6	10.4-12.5	10.4-12.5
	Band 7	2.08 – 2.35	2.08 – 2.35
Spatial Resolution		30 m × 30 m for Bands 1 to 5,7 120 m × 120 m for Bands 6	30 m × 30 m for Bands 1 to 5,7 60 m × 60 m for Bands 6
Altitude		705 km	705 km
Swath Width		185 km	185 km
Inclination		98.2°	98.2°
Revisit		16 days	16 days

Table 8 Acquisition date for each scene

Scene ID	Path	Row	1992 (Landsat 5 TM)	2000 (Landsat 7 ETM+)	2009 (Landsat 5 TM)
1	123	32	September 07, 1992	April 30, 2000	September 22, 2009
2	122	32	July 30, 1992	May 25, 2000	September 22, 2009
3	123	33	June 17, 1991	May 16, 2000	September 15, 2009

4	122	33	June 15, 1993	May 25, 2000	August 30, 2009

Elements of Cellular Automata:

Cellular Automata consist of five essential elements: cells arranged evenly on a tessellated grid-space, states of the cells, neighbourhoods, transition rules, and time.

6.1.1 Cell space

In an urban context, cell space is constrained to the grid finite dimension. Since the structure of cities is anisotropic in terms of internal configuration, the space is marked as irregular. The cell size is set to the multiples of the cell resolution of the original imagery when remotely sensed imagery is included to derive base maps such as land use and land covers.

6.1.2 Cell states

In an urban context the cell state can represent any attribute of the urban environment, land use or cover types, population density, etc., and cellular models of urban systems often contain several cell states simultaneously. Recent research into urban CA models has introduced a greater degree of flexibility for cell-state design by allowing cells to take on a variety of forms concurrently. For example, cells can now adopt binary states such as developable or non-developable continuous values that represent proximity to urban characteristics, and also discrete values like land cover types (Wu and Webster 1998). With the introduction of cell-state fixture, researchers are now capable of restraining urban development and distinguishing between cell states that are “fixed” and those that are “functional” (White and Engelen 1997). “Fixed” sites, such as bodies of water or reserved forest land, are generally exempt from the urban development process, whereas “functional” sites, such as farmland or bare land, are suitable for urban expansion.

6.1.3 Neighbourhood

Urban neighbourhoods can be represented in a variety of shapes, sizes, and configurations. Based on the Moore (the central cell and its eight bordering cells) and von Neumann (the central cell and its four cardinal neighbors) neighbourhoods that restrict the level of spatial variation that cellular automata models can generate, many researchers have developed custom neighbourhoods that include the notion of “action-at-a-distance” (Torrens 2000). Neighbourhoods have been extended to cover larger areas, and distance decay effects, as weights applied to neighbourhoods, have been introduced (He et al. 2008). In a specific CA model, different types of neighborhood can even be applied to different states of cells (Qi et al. 2009).

6.1.4 Transition rules

In the context of an urban system, transition rules can be constructed to represent any process affecting said system. For instance, if all cells in a given vacant cell’s neighbourhood have states corresponding to “extremely high land value,” then it is suitable for conversation from “vacant” to “developed.” If this condition is not met, then the cell remains vacant.

Perhaps the greatest potential for adjusting cellular automata models comes in the formation of transition rules, and it is during this process that cellular models of urban systems are generated in adherence to what we theoretically know about cities. Urban studies that use cellular models have introduced an innovative range of parameters into transition rules in a bid to enhance their realism. These parameters have included probabilistic functions, utility-maximization, accessibility calculations, exogenous links and constraints (linking cellular models to other models), weights, hierarchies, inertia, and stochasticity.