Article:

Xu, J. and Kang, J. (2017) Comparison of Ecological Risk among Different Urban Patterns Based on System Dynamics Modeling of Urban Development. Journal of Urban Planning and Development, 143 (2). ISSN 0733-9488

https://doi.org/10.1061/(ASCE)UP.1943-5444.0000365

Comparison in ecological risk among different urban patterns based on system dynamics modelling of urban development

Jian Xu[1, 2,3], Jian Kang[2, 3]*

[1] School of Economics and Trade, South China University of Technology, Guangzhou 510006, China

[2] School of Architecture, University of Sheffield, Sheffield S10 2TN, UK

[3] School of Architecture, Harbin Institute of Technology, Harbin 150001, China

Jian Xu, BSc, MSc (Northeast Forestry University), PhD (Harbin Institute of Technology & University of Sheffield), has been lecturer at the South China University of Technology since 2016. Her research field is landscape, planning and architectural technology. She has published 10 journal and conference papers.

Jian Kang, BEngArch, MSc (Tsinghua University, Beijing), PhD (University of Cambridge), has been Professor at the University of Sheffield, UK, since 2003. His field is built environment sustainability, with 70+ engineering projects, 80+ research projects, and 800+ publications.

* Corresponding author. Email: j.kang@sheffield.ac.uk

2016 Journal of Urban Planning and Development

Date Received: 2 October 2015 Date Accepted: 18 July 2016

Publish online: 23 September 2014

Abstract: In this study an urban development model has been developed based on system dynamics, in order to compare four urban layout patterns, in terms of their effects on landscape ecology risk and environmental pollution. The four patterns are: centralised urban model, green corridor urban model, decentralised urban model (satellite city model) and resource-based city model. Landscape ecology risk assessments based on simulation results show that: the decentralised urban model is superior to the centralised urban model in terms of long-term landscape ecological development and environmental protection. In the meantime, the relationships between the patch spacing and evaluation index have been revealed.

Keywords: Urban development; Landscape ecological risk assessment; City patterns; System dynamics model; GIS;

Introduction

Centralisation and decentralisation are two basic urban spatial evolution patterns that occur throughout the entire process of urban development (Hoyt 1941). Decentralism is represented by the “Broadacre City,” which was proposed by Wright in 1930s (Wright 1935), and centralism is represented by the “Radiant City,” which was proposed by Corbusier in 1967 (Corbusier 1967). Thus, centralised and decentralised urban layouts and development have been discussed throughout the western industrial revolution period and highly debated. Currently, urban spatial patterns have become increasingly diverse and complex. The formation of complex spatial “hybrids," such as metropolitan expansion, urban industrial relocation and urban regional integration, result in unchecked urban expansion beyond the original framework (Al Rawashdeh and Saleh 2006). Negative consequences that include various degrees of landscape ecological corridor breakdown and aggravated urban pollution have attracted increasing attention throughout society (Botequilha Leitão and Ahern 2002). To achieve sustainable and healthy urban development, researchers have used numerous tools, including cellular automata (Torrens and O'Sullivan 2001; He *et al.* 2013; Leao *et al.* 2004) and neural-network models (Xia and Gar-On 2002), in predictive and simulative studies of urban layouts. Although such discussions include land-use, economy and employment relationships, they lack quantitative simulations of urban landscape ecology and cannot be used to evaluate the ecological sustainability of a complex, diverse and dynamic urban system (Anas *et al.* 1998). Currently, studies on the relationship between urban layout patterns and overall urban systems are scarce, especially with regard to dynamic simulation studies and quantitative analyses of landscape ecological risk.

In this study, therefore, a historical industrial city, Harbin, is used as an example to determine the environmental pollution index, industrial characteristics index (ICI), green-land distribution index and landscape ecological risk index (LERI, based GIS landscape index calculations) by simulating the effects of four urban layouts: 1) centralised city model, 2) green corridor urban model, 3) decentralised city model (satellite city model) and 4) resource-based decentralised city. The simulation results are used to identify superior layout plans for urban development, facilitate the improved implementation of macro-control over current urban development and provide planning guidance for future urban layout and construction. This study assumes that economic policy of urban development is stable, and the urban population is under the typical state of changes without the influence of natural disasters and major communicable diseases.

City distribution patterns

Researchers and other interested parties have been investigating urban development patterns and criteria for sustainable urban layouts. Studies on urban spatial layouts date back to studies on living spatial models of Manchester society by Engels in the 19th century and studies on urban expansion patterns and orientations by Hurd (1904) and Garpin (1918). “Cities in Evolution” by the biologist Geddes (1915) placed urban and rural economies and ecological planning into one system, and urban spatial and structural orientations based on this theory are divided into two major groups, including centralism as represented by “The Athens Charter” , which was proposed by Corbusier in 1933, and decentralism as represented by “Broadacre City” , which was proposed by Wright in 1935. After the 1930s, the Chicago school built three classic models of urban spatial structures by an ecological approach: the zonal model, the sectoral model and the multiple nuclei model.

In modern ages, urban development and frequent corrections and updates of the three classic models by various scholars have led to the creation of multiple new urban spatial layout models, such as the eclectic theory by Ericksen in 1955 and the concentric sector theory by Mann in 1965. These theories laid the foundation of centralised multiple sectors and multiple-nuclei urban development, and this “urban sprawl” pattern is the basic pattern for the majority of cities. The theoretical model is shown in Figure (a), and a conventional urban layout model exemplified by Beijing in China is shown in Figure (e), and it represents the basic layout pattern of conventional metropolises under typical development. In 1966, Münster City Council built the “Münster Green Space Ordinance” with seven green corridors and three green rings in a single system, which was the first example of continuous green lands between construction blocks in a centralised city. Then, many urban designers began a bold attempt, such as Unwin's and Abercrombie's plans for London, and the concept of an “urban green corridor” planning model was fast developed in many rapidly expanding cities. The theoretical model is shown in Figure (b), and it ensures the connectivity of ecological corridors during planning and is an ideal planning pattern (Figure (f)) to guarantee sustainable development of urban ecosystems and haze control in developing countries (Douglas 2012). In 1924, Unwin clarified the definitions of decentralised and satellite cities in the International Urban Conference in Amsterdam, and the theoretical model is illustrated in Figure (c). This model has been widely adopted by numerous major cities, and from 1912 to 1920, 28 dormitory towns were constructed according to a suburb living construction plan 16 km away from the centre of Paris, which effectively mitigated the problems of highly concentrated populations and land shortages in urban central areas. In 1938, Finnish architect Eliel Saarinen planned the decentralisation of Greater Tallin, Estonia, Greater Helsinki and the Netherlands in the Greater Helsinki plan (Saarinen 1943) based on the theory of “Organic Decentralisation” proposed by Saarinen in 1918. As shown in Figure (g), this paper uses Tallinn and Estonia as examples to illustrate changes in the city from the original model to a reconstructed model after decentralised planning. Such layout changes normally require a significant amount of time and investment, and they are novel integration directions for overall urban and rural planning (Ahern 1995). Therefore, studies on the ecological risk are of significant practical importance. In addition, irregular and decentralised patterns in cities formed naturally around resources, such as oils and minerals, are known as resource-based decentralised patterns (Jing 2006), and the theoretical model is shown in Figure (d). As shown in Figure (h), Richard Register’s plan for gradual decentralisation of Berkeley, California is used in this paper to illustrate the common layout pattern in resource-based cities, built-up areas in such cities have irregular layout patterns around resources.

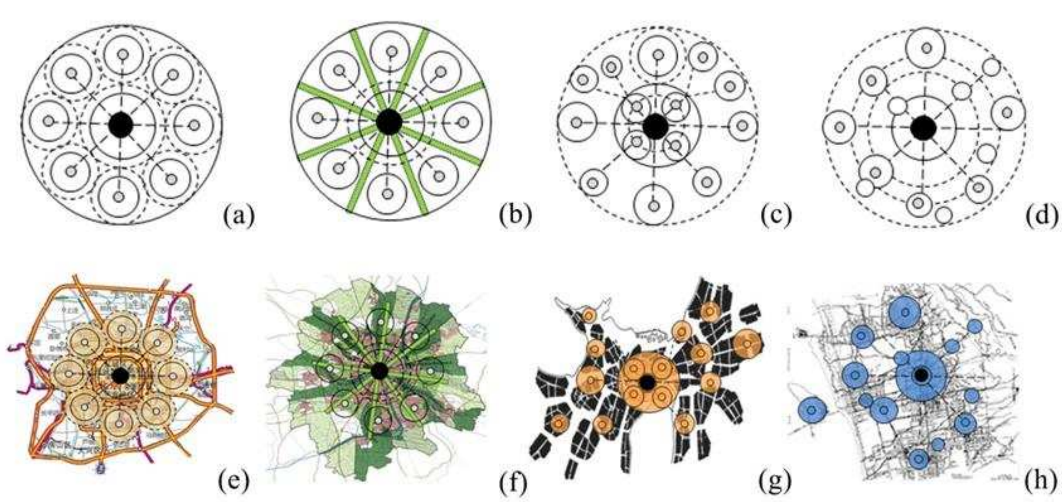

Figure 1. Four layout patterns of contemporary cities: Figure (a), centralised multiple nuclei model; Figure (b), green-corridor urban model; Figure (c), decentralised city model (satellite city model) and Figure(d), resource-based city model. Source of examples: Figure (e), City layout of Beijing, China; Figure (f), Ordinance for Green Spaces and Environmental Protection, Münster City Council; Figure (g), Eliel Saarinen's plan for the decentralisation of Greater Tallin, Estonia; Figure (h), Richard Register's plan for gradual decentralisation of Berkeley, California.

In summary, based on the above brief overview of the urban development patterns, it is suggested that current urban patterns primarily include four layout models: multiple nuclei centralised model, green-corridor urban model, decentralised urban model (satellite city model) and resource-based city model. A number of studies have investigated distribution planning to change layout models of various cities to reduce urban pollution and maintain ecologically sustainable development of urban landscapes. However, investigations performing a dynamic comparison of the four layout patterns for the same city have not been performed. As a result, there is a lack of quantitative verification regarding the layout model that has the lowest ecological risk and the model that is most suitable for sustainable urban development. It is noted that although the above review of the typical urban development patterns is not exhaustive, the extracted patterns would be useful for the comparison in terms of ecologically sustainable development.

In China, until 2015, the urbanisation rate has increased to 58% (Xu *et al*. 2016), and the corresponding urban spatial layouts become increasingly diversified and complicated. The expansion of "hybrid" urban complex spaces breakthrough the original frameworks, making multiple nuclei centralised model accounted for more than 80% of urban patterns, faced with the risk of ecological and environmental pollution (Cui and Wu 1990). Correspondingly, this urban spatial layout model is considered the most important one in this study. On the other hand, green-corridor urban model and decentralised urban model (satellite city model) take the minority proportion, and resource-based city model is also a typical spatial layout model. Beyond that, urban agglomeration development can also be regarded as a spatial form of urban development (Jing 2006), although it is noted that this study focused on individual cities.

A typical city in this study is with population over 100,000, with land-use including at least industrial land patches (ILP), urban land patches (ULP), waterpatches (WP), Abandoned Land Patches (ALP) and green-land patches (GLP), and with residents all working in the city area.

Urban ecological risk assessment method

Simulation modelling is the primary and most widely used method for performing ecological risk assessments (Suter 2006). In this study, developing an appropriate landscape ecological risk assessment method is particularly important. Ecological environmental index variations based on landscape patterns are comprehensive indicators of ecological environment systems in regions affected by both natural and anthropogenic factors (Tischendorf 2001), and they belong to multiple risk source ecological risk assessments (Suter 2006). This study is based on the Relative Risk Model, a regional ecological risk assessment method created by the American researchers Landis and Wegers in 1997 (Landis and Wiegers 1997). To determine correlations between anthropogenic activities and landscape ecological risks and assess urban ecological risks in a more comprehensive manner, this study considers two major landscape pattern parameters. Those two parameters, namely landscape characteristic indices and landscape distribution indices, incorporating ecological environmental indices, are used to obtain the overall ecological risk index by using the area ratio of patch components, which is calculated as follows:

$$ER_k = \sum_{i=1}^{N} \frac{S_{ki}(E_i + G_i)P_i}{2S_i} \qquad (1)$$

where ER_k is the ecological risk index, N is the quantity of patch component types, S_{ki} is the area of the i^{th} patch, and S_i is the total urban area. It is noted that k represents four urban pattern models ($k = 1, 2, 3, 4$), and i represents the land-use type in all the formulas of this paper ($i= 1, 2, 3, 4, 5$).

The six typical indices of landscape unit characteristics proposed by Riitters and O'Neil, which have been shown to have general significance (Riitters *et al.* 1995), were used to derive three landscape indices: Patches Number (N), Patches Aggregation (A) and Patches Fragmentation Degree (F). These indices are the most destructive with regard to environmental landscape characteristics and ecology, and the most representative indices have been selected to represent the impact of urban construction on landscape patterns. These indices are accrued to reflect the degree of interference by human development activities, with ecosystems represented by different landscapes. After N, A and F are normalised, the industrial characteristics index can be expressed as the follows:

$$E_i = aN_i + bA_i + cF_i \qquad (2)$$

where *Ei* represents the landscape pattern index affected by humans ($0<Ei<1$). According to the formulae by Liu et al (2005), on the landscape ecological risk assessment method, *a, b, c* are given weights of 0.5, 0.3 and 0.2, respectively. This method is also in line with other theoretical discussions (Hakanson 1980; Giles and Trani 1999). A sensitivity test, made for *Ei* by varying the weighting of *a, b, c* by 30%, shows that the variation in *Ei* is less than 1% in the period of 2005-2009. In turn, the changes in the overall results in the system dynamics model caused by possible variation of the above weightings would also be negligible.

Similarly, the ecosystem vulnerability index represents the vulnerability of various ecosystems, and it is related to the landscape evolution process stage (Chen and Pan 2003). The landscape distribution index (*G*) includes three landscape indices that are the most representative of the green area landscapes, including the adjacent exponential distribution (*J*), fractal index (*I*) and land scape area ratio (*R*). After the renormalisation of *E, I* and *R*, the landscape distribution index can be expressed as follows:

$$G_i = dJ_i + eI_i + fR_i \tag{3}$$

where *Gi* represents the landscape distribution index affected by humans ($0<Gi<1$). By using the same calculation method of Eq (2), *d, e, f* are given weights of 0.4, 0.3 and 0.3, respectively.

The relative air pollution index (API, *H*) is the most important environmental index of urban ecological risk (Jain and Khare 2008). Based on investigations of the effect of human activities on landscapes (Suter 2006), this study uses the relative air pollution index and patch pollution intensity index to reflect the degree of impact caused by urban construction on landscape evolution. The air pollution index proposed by Babcock (Babcock, 1970) is the sum of the normalised annual averages of SO_2 (sulphur dioxide), NO_2 (nitrogen dioxide) and PM10 (particulate matter 10). Based on five land-use types, air pollution intensity indices (*Oi*) have been derived, and they represent the ecological vulnerability of different patches and are defined as light, medium, high, intensive and extremely intensive (examples are green land, water bodies, saline-alkali soil, residential land and industrial land, which have corresponding values of 0.2, 0.4, 0.6, 0.8 and 1, respectively). Based on the above analysis, a process-based ecological environmental index can be expressed as follows:

$$P_i = (H + O_i) / 2 \tag{4}$$

where *Pi* is the relative air pollution index, which is the most important environmental index of urban ecological risk ($0<Pi<1$).

System dynamics model for urban development

This paper is based on the theory of artificial corridor effects on landscape ecology by

Forman (Forman and Deblinger 2000) and Dramstad (Dramstad 1996), the theory of regional industrial economies (Digiovanna 1996), correlations between industrial regions and population variations by Wrigley (Wrigley 2011) and investigations of industrial pollution environment in developing countries (Pargal and Wheeler 1995; Xu *et al.* 2016). In the case of typical cities, industrial development generates urban system energy flows as a form of artificial interference, and such flows are explained by the economic benefits of highly developed industry, which are important components of an urban economy. In addition, urban system energy attracts populations toward urban areas and is the primary driver factor of urban pollution and landscape ecology destruction. Moreover, the construction and relocation of enterprises constrain urban spatial layouts. Therefore, industrialised city systems are decomposed into population subsystem, industrial subsystem, economic investment subsystem, environment subsystem, landscape ecology subsystem and urban distribution subsystem in this study. A causal loop diagram for the six subsystems is shown in Figure 2.

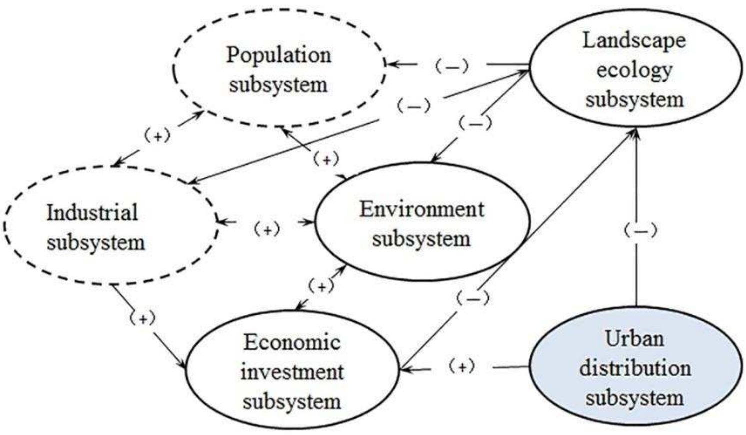

Figure 2 Causal loop diagram of subsystems

Modelling

Both decentralised and centralised urban layouts follow the same urban construction rule. Based on subsystem classifications and factor analysis methods for urban growth dynamics models, created using system dynamics (Xu *et al*. 2015; Han *et al*. 2009), this study further simplifies factors within a subsystem in the model. This is to improve the generality and accuracy of the model. The subsystems are described below.

Population subsystem belongs to a developing subsystem and is determined by the base population and population variation rate, which is controlled by the ratio of labour to industrial jobs (J) and liveability factors (LF). Usually, within certain environmental capacity, with the industrial development, the factories create more employment opportunities, and then, job requirements attract increase in urban population. Even if there are a few people moving out for some other reasons at the same time, in general, the overall relationship between industry and population will present a positive one, and this has been applied in a number of system dynamics model（Han *et al*. 2009; Xu *et al*. 2015; Sterman 1984; Ford and Sterman 1998). However, when the environmental pollution becomes so excessive that urban liveability is reduced, increases in the total population (TP) will cease, although this assertion may not be true in all places by considering those who do not have an option to move out. Nevertheless, this is not the case in the typical cities examined in this study. Population subsystems are linked to economic investment subsystems via environmental protection investment per capita (EPIPC), and they affect landscape patches through green-land construction and land management, which subsequently affects the development of landscape ecology subsystems.

Industrial subsystem belong to driver systems, and the total number of enterprises is affected by enterprise variation rates versus time, where the number of enterprises only includes large- and medium-sized enterprises listed in governmental annual reports. The activities of enterprise production and management create value in and increase the wealth of the entire society through the continuous growth of regional gross domestic product (GDP), growth of enterprise scale and increases in profit through re-investment. The most direct reflection of natural environment damage and excessive resource consumption during enterprise development is growth relative to environmental pollution and declining environmental capacity. Eventually, environmental pollution could be controlled by increasing the total amount of investments in environmental protection. The effect of industrial subsystems on landscape patches is reflected in patch pattern variations and landscape index variations.

Economic investment subsystem is control subsystems, and industrial investment (II) and total environmental protection investments can be regarded as two main factors that affect the regional GDP. Industrial investment directly affects the total number of enterprises and pattern of industrial land patches while total environmental protection investments are affected by regional GDP and determined by investment rate variations, which are linked to other systems by capital energy flow. Total environmental protection investments and total population would affect the relative environmental pollution through environmental protection investments per capita, and total environmental protection investments could fund green-land construction and saline-alkali soil management and promote artificial control over urban landscape patterns.

Environment subsystem belong to the constraining system, and at their core is relative environmental pollution (relative pollution is the sum of the COD (chemical oxygen demand) of polluted water, atmospheric SO_2 content and annually processed coal gangue after normalisation). In conjunction with landscape ecological risk indices, relative environmental pollution constrains the continuous expansion of populations and enterprises via liveability and environmental capacity, and it is controlled by economic investments and forms an indirect feedback loop with urban layout patterns.

Landscape ecology subsystem is an assessment subsystem used to measure ecological risk. Land can be classified as industrial land patches, urban land patches, water body patches, waste land patches and green-land patches. Previously proposed landscape pattern indices that are sensitive to interference are summarised, and an urban landscape ecological risk assessment system is created. The assessment and quantification method are described in Section 2.

Urban distribution subsystem belong to the assumed subsystem, and through assumed adjustments to large concentrations of urban patches, this subsystem affects the total urban area, total urban green-land and land-type spatial patterns. Thus, urban distribution subsystems affect landscape ecology subsystems in conjunction with other subsystems. This study simulates the system development and variation of four urban layout models: the centralised model, the urban green corridor model, the decentralised model and the randomly decentralised model.

To guarantee time continuity and relative stability during system operations, the system operation period is set to one "five year plan" (2005-2010), and values from this range are used to minimise the impact of policies on the model. Vensim DSS software (Ventana Systems, Inc., Harvard, MA, USA) is used to build the overall system dynamics model from the aforementioned subsystem factors and corresponding correlations (shown in Figure 3). It is noted that the model equations are listed in the appendix.

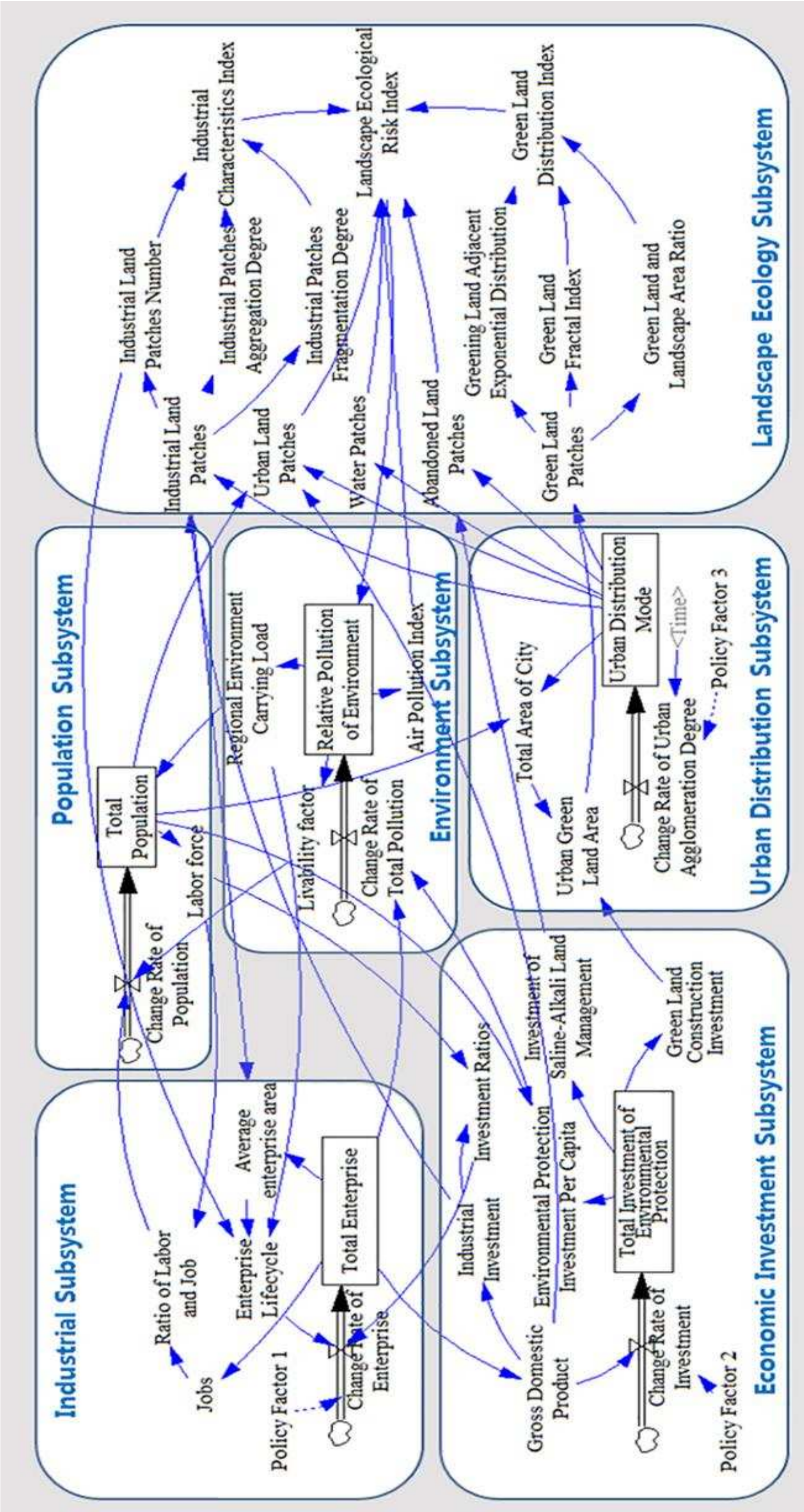

Figure 3. Overall system dynamics model of urban development.

Model verification

Because of limited equation editing functions in current software programs, inevitable errors are generated when the model is run. Based on validation methods of system dynamic modelling reported in various previous studies (Forrester and Senge 1978; Peterson and Eberlein 1994) and using Harbin as a test site (assuming that the urban aggregation index is 1), three types of validation were performed to fully validate and make up the possible defects of relatively shorter calibrated time (5 years). These include: historical data validation, which confirms the objectivity of simulation data in the modelling process; structural validation, which confirms the logic of model simulation, models defect detection and explains the time delay of a system; and simulation validation, which checks the errors between the predicted data and actual data of various system factors (Xu *et al*. 2015).

In particular, to verify that the formulae established and system regressions in the implementation of the model developed yield values that are sufficiently close to actual historical values, 41 groups of effective data in this model were validated. Over the five years, from 2005 to 2009, the error rate in the model operation process is 3.34%, which is less than the acceptable maximum of 5% (Sterman 1984). A structural test of the model was conducted by using a randomly selected route involving the six subsystems, to detect any possible defect in the model structure. Based on the results of the structural test, it can be concluded that the time variation and the system range of the model form a complete circuit with a time delay and multiple feedback effects with zero defect. With the landscape ecological subsystem as the output subsystem, taking the others as input subsystems, and using 2010 data, a prediction was made for the factors in the landscape ecological subsystem. By comparing with actual data, it can be observed that the prediction accuracy is very good, with an average error of 2.35%, much less than the commonly acceptable value of 5% (Ford and Sterman 1998).

Case Study

According to above analysis, an international, modernised, typical and centralised multi-nuclei city should be selected to verify the data and model analysis. Harbin is located in the central area of northeast Asia, and it is a critical historical industrial base in northeast China as well as an international city and the Eurasian continental bridge hub. The city has a history of approximately 100 years and is a booming urban economy. Moreover, its urban expansion is modernised, and it has diverse and comprehensive land-use types, with an urban area of 10,198 km^2 and a population of 5.537 million. A river runs through the centre of the city, and sub-region centres are clearly delineated. The urban size is moderate and quite typical, and complete remote sensing satellite images from 2005 to 2014 and complete urban system data resources are available, which ensures the feasibility of the study. In this study, 2011 is used as the year of the present state, and the dynamic evolution of the urban spatial is evaluated from different angles and multiple disciplines, such as from the population, economy, pollution and landscape ecology of the current society. Based on the development of the system dynamics model, quantitative modelling of various urban layout models is explored, and the urban landscape ecological vulnerability of Harbin is simulated and analysed. The simulation period runs through 2015 (because data from 2005-2015 are complete and can be used to correct and verify the accuracy of the model). This study addresses five previously proposed practical spatial layout patterns for urban development and assumes that index values of other decision variables, such as the economy, population and land classification, follow current growth trends (average growth rate of total enterprises (TE) is 4.98%, annual population growth rate is 1.96%, and economic growth rate is 6.83%). Variations of future landscape ecological risks and environmental pollution in relation to different population migration patterns, enterprise construction rates and environmental protection investments are simulated for the same city under the four layout models. This includes the centralised model, urban green corridor model, decentralised model and resource-based decentralised model. With a real city, Harbin, as a starting point, four models have been built, as explained below. In terms of urban morphology, Harbin is a centralised multi-nuclei city with seven districts, with a core in each district. In the model the urban layout was correspondingly divided into seven parts and numbered accordingly.

①Model 1: the centralised model, which is the original and conventional centralised urban development model.

②Model 2: the urban green corridor model, which guarantees a minimal width of 1.2 km for corridors between actual inner sites in the "green corridor," with seven evenly distributed regional patches constituting the urban green corridor model (Zhu *et al*. 2005).

③Model 3: the decentralised city (satellite city model), which ensures distinct decentralised characteristics and considers urban reachability, with seven regional patches distributed at an average spacing of 4 km (average distance of 16 km to urban centre) to form the decentralised city (satellite city model) (Ge *et al*. 2005).

④Model 4: the resource-based decentralised model, which is based on various aspects that include urban area and regional economy, with Daqing (165 km from Harbin) chosen as the blueprint for the resource-based city. The average site spacing is maintained at 0.8 km, and seven regional patches are arranged according to layout characteristics and patch spacing to form the resource-based decentralised model.

The primary transport systems of separated patches are connected (As shown in Figure (e), (h) and (k)), and residence and enterprise densities along both sides of roadways are distributed randomly according to the original density, with the remainder based on assumptions derived from the urban public green-land model. The layout patterns of each model are shown in Figure 4.

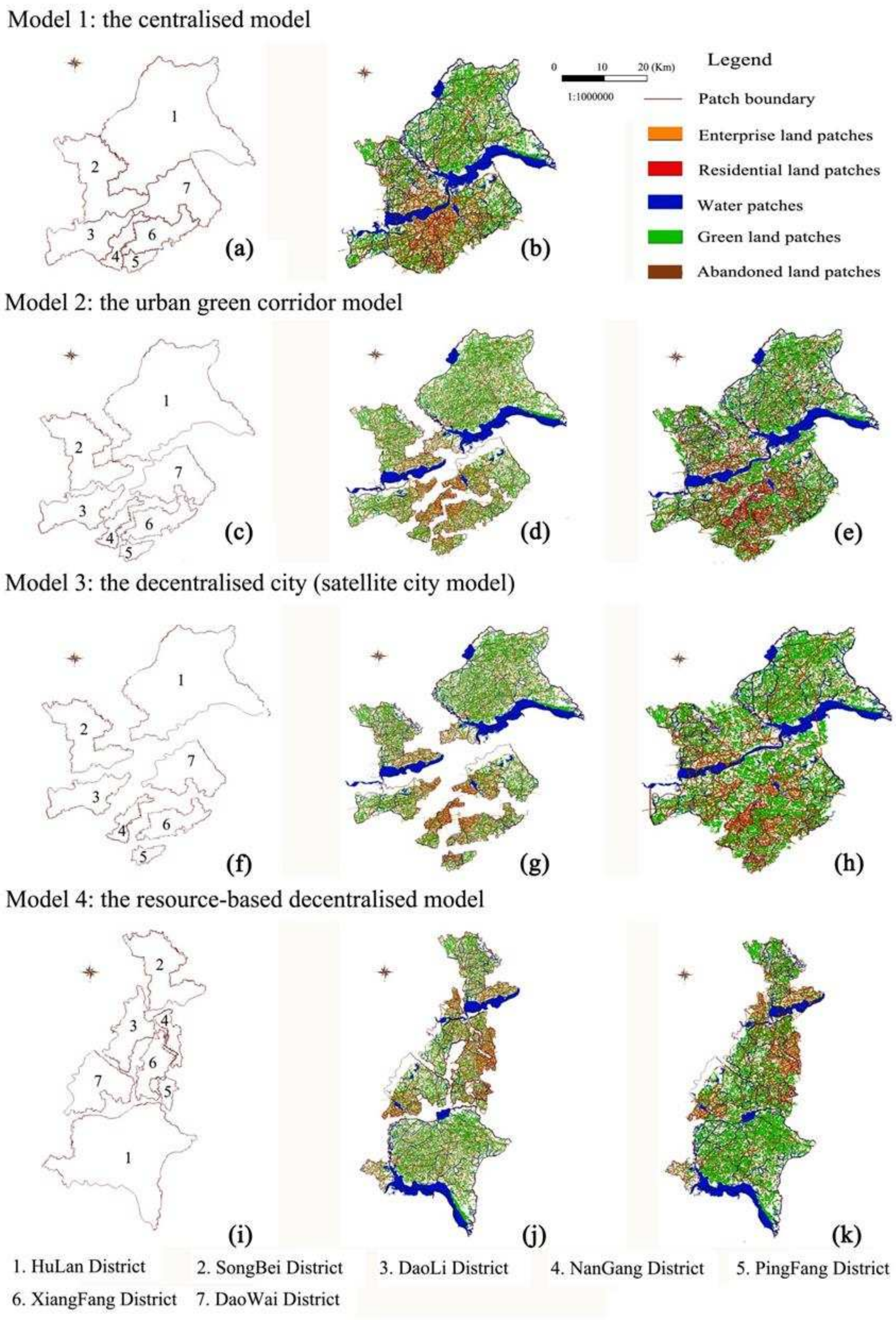

Figure 4. Diagram of four layout patterns urban model: Figure (a) and (b), centralised urban model; Figure (c), (d) and (e) green corridor urban model; Figure (f), (g) and (h), decentralised urban model (satellite city model) ; Figure (i), (j) and (k), resource-based city model.

Results analysis

The five-year (2005-2009) landscape indices of the centralised city and patches in the decentralised city are calculated by software Fragstats, and the actual historical data of other system factors are imported into system dynamics model of urban development. This is followed by modelling centralised city model, green corridor urban model, decentralised city model (satellite city model) and resource-based decentralised city with different landscape pattern indices. Although the data ranges of the input indices have been normalised in a scale between 0 and 1, in the system dynamics model the output indices are not necessarily within data range of 0 to 1. For the sake of convenience in reflecting and comparing the changes of prediction results, a normalization method has been adopted for those indices. The forecast results from 2010-2015 landscape indices are listed below, and the simulation and comparison of the industrial characteristics index, green-land distribution index, landscape ecological-risk index and environmental pollution index of the four models are shown in Figure 5.

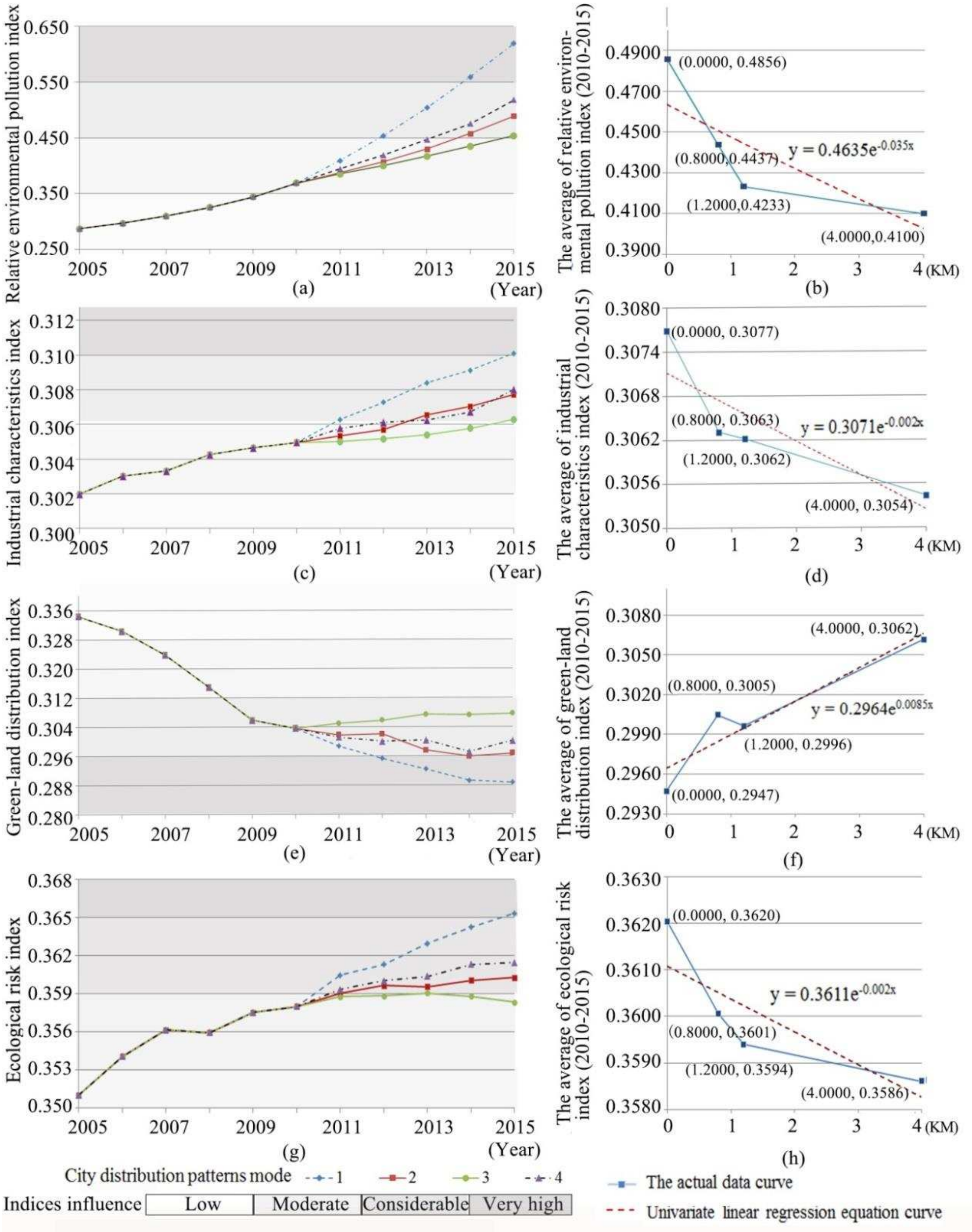

Figure 5. Comparison and simulation of city distribution pattern curves, including the relative environmental pollution index, industrial characteristics index, green-land distribution index and ecological risk index (as shown from (a), (c),(e) and (g)) as well as correlation simulations versus urban patch spacing (as shown from (b), (d),(f) and (h)) for 2010-2015 using the system dynamics model. (Model 1, centralised urban model; Model 2, green-corridor urban model; Model 3, decentralised city model (satellite city model); Model 4, resource-based city model).

As shown in Figure 5, the changes of the environmental pollution indices are relatively significant, whereas the changes of industrial characteristics indices, such as the green-land distribution index and ecological risk index, are relatively small. This is possibly because the calculations of landscape indices are derived from the land-use changes, which, at a city scale, are usually relative slow and weak even in a decade (Tischendorf 2001). As shown in Figure (a), the forecasts for 2011-2015 from the four models show that the centralised urban model has the highest relative environmental pollution index, while the decentralised urban layout model has the lowest relative pollution index. The relative pollution and patch spacing are negatively correlated, and the linear regression curve is shown in Figure (b), which clearly shows the exponential relationship between the relative environmental pollution index and urban patch spacing. When the urban patch spacing is within 1.2 km, the urban relative pollution is apparently reduced, whereas the effect diminishes with patch spacing increasing. Similarly, the centralised urban model has a higher industrial characteristics index than the other three models in the five simulation years, although it is noted that by 2015, there is only a small difference between the Maxima and Minima, as shown in Figure (c). This is because the changes of industrial characteristics index are derived from the relatively slow and weak industrial land-use changes. Among the models, the urban green-corridor model and resource-based urban layout model have alternating curves above that of the decentralised model, whereas both have alternating and climbing curves above that of the decentralised urban layout model. As shown in Figure (d), the industrial characteristics index decreases with increases in patch spacing. When urban patch spacing is within 0.8 km, the industrial characteristics index declines sharply; however, in the range of 0.8-4.0 km, the effect of spacing diminishes dramatically. A comparison of the green-land distribution indices for the four models is shown in Figure (e). The decentralised urban layout has the highest green-land distribution index, whereas the centralised urban model has the lowest. It is noted that, due to landscape index usually changes slowly, until 2015, the differences of green-land distribution index among the four models are rather small. Meanwhile, there are uneven and insignificant differences between the green corridor model and resource-based model, which have similar average green-land distribution by 2010-2015, 0.3004 and 0.2996, respectively. As shown in Figure (f), the green-land distribution index and urban patch spacing have a roughly positive correlation, whereas an absolute positive correlation is not observed when patch spacing is between 0.8 km and 1.2 km. This means that when green corridor spacing reaches 0.8 km, the effect on overall ecological protection has already been substantial. This result agree with Jokimaki's research of merging wildlife community ecology with animal behavioral ecology for a better urban landscape planning (Jokimäkia *et al.* 2011). As shown in Figure (g), the centrally distributed urban layout model presents the highest ecological risk index, and it is followed by the resource-based city and green corridor model, whereas the decentralised urban layout model has the lowest ecological risk index. It is noted that, due to the relatively small changes of landscape index and ecological environmental index, the differences among the models are rather small here. As shown in Figure (h), when the urban patch spacing is 0.8 km, the ecological vulnerability index reduces significantly, and the effect diminishes in the range of 0.8 km-1.2 km and is weakest in the range of 1.2-4.0 km.

It is noted that although the above comparative results are based on the case study city, Harbin, given that this is a typical developing city in China and also, it is of centralised multi-nuclei type, representing the most common urban pattern, the results can be generalised in a range of other similar cases.

Conclusions

This paper developed an urban ecological risk assessment method, and by integrating the method, established and validated an urban development system dynamics model. Using the model, four primary models of contemporary urban layouts were compared systematically, in order to identify those which are more suitable for urban ecological development.

Using the historical industrial city of Harbin in China as an example, a GIS landscape index estimation has been used to simulate the industrial characteristics index, green-land distribution index, landscape ecological risk index and environmental pollution index for four urban layouts. This includes the centralised urban model, urban green corridor model, decentralised urban model (satellite city model) and resource-based decentralised model. The simulation results are used to identify the layout model that is more suitable for urban ecological development.

The model simulation results show that the relative pollution index, average landscape characteristics index and ecological risk index are negatively correlated with patch spacing, whereas the green-land distribution index is positively correlated with patch spacing. This result indicates that the decentralised layout model promotes a reduction of urban ecological risk and increase of environmental pollution protection. When the same urban construction rate is maintained, the green corridor urban layout model with an average corridor width of 0.8 km (resource-based layout model) can reduce urban ecological risks, and green corridors with an average width of 1.2 km can ensure substantial urban environmental pollution reduction under the precondition of stable landscape ecology.

Acknowledgements

The authors are indebted to the Chinese Academy of Sciences and Harbin Normal University for providing useful data.

References

Ahern, J. (1995). “Greenways as a planning strategy.” *Landscape and Urban Planning*, 33 (1):131-155.

Al Rawashdeh, S., and Saleh, B. (2006). “Satellite monitoring of urban spatial growth in the Amman area, Jordan.” *Journal of urban planning and development,* 132 (4):211-216.

Anas, A., Arnott, R., and Small K. A. (1998). “Urban spatial structure.” *Journal of Economic Literature*, 1426-1464.

Babcock Jr, L. R. (1970). “A combined pollution index for measurement of total air pollution.” *Journal of the Air Pollution Control Association*, 20(10), 653-659.

Botequilha Leitão, A., and Ahern, J. (2002). "Applying landscape ecological concepts and metrics in sustainable landscape planning." *Landscape and Urban Planning*, 59(2), 65-93.

Chen, P., and Pan, X. (2003). "Ecological risk analysis of regional landscape in inland river watershed of arid area - a case study of Sangong River Basin in Fukang." *Chinese Journal of Ecology*, 22(4), 116-120.

Corbusier, L. (1967). *The Radiant City*, Orion Press.

Digiovanna, S. (1996). "Industrial districts and regional economic development: a regulation approach." *Regional Studies*, 30(4), 373-386.

Dramstad, W. E. (1996). *Landscape Ecology Principles in Landscape Architecture and Land-Use Planning*, Island Press.

Douglas, I. (2012). "Urban ecology and urban ecosystems: understanding the links to human health and well-being." *Current Opinion in Environmental Sustainability*, 4(4), 385-392.

Forrester, J. W., and Senge P. M. (1978). *Tests for Building Confidence in System Dynamics Models*. System Dynamics Group, Sloan School of Management, Massachusetts Institute of Technology.

Ford, D. N., and Sterman J. D. (1998). "Dynamic modelling of product development processes." *System Dynamics Review*, 14(1), 31-68.

Forman, R. T., and Deblinger, R. D. (2000). "The ecological road‐effect zone of a Massachusetts (USA) suburban highway." *Conservation Biology*, 14(1), 36-46.

Ge, S., Wang, L. X., Fang, B., and Wang Y. (2005). "A study of evaluation method of the satellite city land-use intensification - a case study of Acheng of Heilongjiang province." *Economic Geography*, **6**.

Giles, R. H., and Trani, M. K. (1999). "Key elements of landscape pattern measures." *Environmental Management,* 23(4), 477-481.

Han, J., Hayashi, Y., Cao, X., and Imura, H. (2009). "Application of an integrated system dynamics and cellular automata model for urban growth assessment: A case study of Shanghai, China." *Landscape and Urban Planning*, 91 (3), 133-141.

Hakanson, L. (1980). "An ecological risk index for aquatic pollution control: a sedimentological approach." *Water Research*, 14 (8), 975-1001.

He, C.Y., Zhao, Y. Y., Tian, J., and Shi, P. J. (2013) "Modeling the urban landscape dynamics in a megalopolitan cluster area by incorporating a gravitational field model with cellular automata." *Landscape and Urban Planning*, 113, 78-89.

Hoyt, H. (1941). "Forces of urban centralization and decentralization." *American Journal of Sociology*, 843-852.

Jain, S., and Khare, M. (2008). "Urban air quality in mega cities: a case study of Delhi City using vulnerability analysis." *Environmental Monitoring and Assessment*, 136(1-3), 257-265.

Jing, H. Z. (2006). "Overview of studies on urban development of resource-based cities in China." *Urban Studies*, 3, 20.

Jokimäkia, J., Jokimäkia, M. L. K., Suhonenc, J. Clergeaud, P., Pautassoe, M., and Juricicf, E. F.(2011). "Merging wildlife community ecology with animal behavioral ecology for a better urban landscape planning." *Landscape and Urban Planning*, 100(4), 383-385.

Landis, W. G., and Wiegers, J. A. (1997). "Design considerations and a suggested approach for regional and comparative ecological risk assessment." *Human and Ecological Risk Assessment*, **3**(3), 287-297.

Leao, S., Bishop, I., and Evans, D. (2004). "Simulating urban growth in a developing nation's region using a cellular automata-based model." *Journal of urban planning and development,* 130 (3):145-158.

Liu, S. L., Yang, Z. F. Chui, B. S., and Gan, S. (2005). "The landscape effect and ecological risk assessment of road— an example of Lancang river area." *Chinese Journal of Ecolog,* 24 (8):897-901.

Pargal, S., and Wheeler, D. (1995). *Informal Regulation of Industrial Pollution in Developing Countries: Evidence From Indonesia*, World Bank Publications.

Peterson, D. W., and Eberlein R. L. (1994). "Reality check: A bridge between systems thinking and system dynamics." *System Dynamics Review*, 10(2‐3), 159-174.

Riitters, K. H., O'Neill, R. V., Hunsaker, C. T., Wickham, J. D., Yankee, D. H., Timmins, S. P., Jones, K. B., and Jackson, B. L. (1995). "A factor analysis of landscape pattern and structure metrics." *Landscape Ecology*, 10(1), 23-39.

Saarinen, E. (1943). *City: Its Growth, Its Decay, Its Futur*, The MIT Press.

Suter II, G.W. (2006). *Ecological Risk Assessment*, CRC Press.

Sterman, J. D. (1984). "Appropriate summary statistics for evaluating the historical fit of system dynamics models." *Dynamica*, 10(2), 51-66.

Tischendorf, L. (2001). "Can landscape indices predict ecological processes consistently?"

Landscape Ecology, 16(3), 235-254.

Wright, P. M., and O'Sullivan, D. (2001). “Cellular automata and urban simulation: where do we go from here?” *Environment and Planning B: Planning and Design*, 28(2), 163-168.

Wright, F. L. (1935). *Broadacre City: A New Community Plan*, Architectural Record Publishing Company.

Wrigley, E. A. (2011). *Industrial Growth and Population Change,* Cambridge Books.

Xia, L., and Gar-On Y. A. (2002). “Neural-network-based Cellular Automata for Realistic and Idealized Urban Simulation.” *Acta Geographica Sinica*, 2, 005.

Xu, J., Kang, J., Shao, L., and Zhao T. Y. (2015). “System dynamic modelling of industrial growth and landscape ecology in China.” *Journal of Environmental Management*, 161, 92-105.

Xu, J., Kang, J., and Shao, L. (2016). “Subjective evaluation of the environmental quality in China’s industrial corridors.” *Journal of Environmental Engineering and Landscape Management*, 24(04), 21-36.

Zhu, Q., Yu, K. J., and Li, D. H. (2005). “The width of ecological corridor in landscape planning.” *Acta Ecologica Sinica*, 9, 036.

Appendix: List of model equations

Population subsystem:

TP (K: future)=TP (I: current)+DT*CRP(Change Rate of Population)

CRP=0.16-0.011*Ln (RLJ(Ratio of Labour and Job)*LIF)

RLJ=LF(Labour Force)/J

LF=-2379.139+6.04*TP

J=EXP(6.308-155.157/TE)

Industrial subsystem:

TE(K: future)=TE(I: current)+Dt*CRE(Change Rate of Enterprise)

CRE=PF1(Policy Factor 1)*EXP(-0.661-3050.505/(IR/EL))

AEA(Average Enterprise Area)=ILP/TE*10^6

EL(Enterprise Lifecycle)=-0.888+0.087*(AEA*ECC(Environment's Carrying Capacity)) +0.001*(AEA*ECC) ^2

Economic investment subsystem

TIEP(Total Investment of Environmental Protection)(K: future)=TIEP (I: current)+Dt*CRI(Change Rate of Investment)

CRI=PF2(Policy Factor 2)*(-5.226+0.317*Ln(GDP))

GDP=EXP(17.824-845.371/TE)

II=EXP(16.93-49458303/GDP)

GLCI=-49231.101+0.457*TIEP

IR(Investment Ratios) =II/LF

EPIPC=TIEP/TP

ISALM(Investment of Saline-Alkali Land Management)=EXP(12.156-240398.016/TIEP)

Environment subsystem

RPE(Relative Pollution of Environment)(K: future)=RPE (I: current)+Dt*CRTP(Change Rate of Total Pollution)

CRTP=2.126-0.314*Ln(EPIPC*API *LERI)

ECC=0.071*EXP(2.992*RPE*ICI)

API=0.877*EXP(1.345e-007*EPIPC*TE)

LIF=-6.545-7.719*Ln(RPE)

Urban distribution subsystem

UDM(Urban Distribution Mode)(K: future)=UDM (I: current)+Dt*CRUAD(Change Rate of Urban Agglomeration Degree)

TAC(Total Area of City)=EXP(9.072-42.629/(TP*UDM))

UGLA(Urban Green Land Area)=EXP(5.231-12.661/(GLCI/TAC))

Landscape ecology subsystem

ILP=1428.455-182.164*Ln(UDM*II)+6.195*(UDM*II)^2

ULP=EXP(7.224-10855.783/(UDM*GDP/TP))

WP=1745.374+2336.755*Ln(UDM) +3344.527*Ln(UDM)^2

ALP=95.837-0.01*ISALM/EXP(UDM)

GLP=EXP(8.636-23.629/(UDM*UGLA))

ILPN(Industrial Land Patches Number)=-43791.323+951.275*ILP-5.115*ILP^2

IPAD(Industrial Patches Aggregation Degree)=1942.163-41.885*ILP+0.228*ILP^2

IPFD(Industrial Patches Fragmentation Degree)=EXP(-3.472+189.79/ILP)

ICI=0.5*(IPFD/0.7231) +0.3*(IPAD/61.2996) +0.2*(ILPN/1178.4)

GLAED(Green Land Adjacent Exponential Distribution)=1.778-0.098*Ln(GLP)

GLFI(Green Land Fractal Index)=EXP(0.507-87.485/GLP)

GLLAR(Green Land and Landscape Area Ratio)=EXP(4.686-2846.164/GLP)

GLDI(Green Land Distribution Index)=GLFI/4.8663+GLAED/2.9225+GLLAR/152.612

LERI=-2.791+2.658*((Ln(ULP)+Ln(WP) +Ln(ALP))/3/(ICI+GLDI+API))+((Ln(ULP) +Ln(WP) +Ln(ALP))/3/(ICI+GLDI+API))^2