Article:

Xu, J., Kang, J., Shao, L. et al. (1 more author) (2015) System dynamic modelling of industrial growth and landscape ecology in China. Journal of Environmental Management, 161. 92 - 105. ISSN 1095-8630

https://doi.org/10.1016/j.jenvman.2015.06.026

System dynamic modelling of industrial growth and landscape ecology in China

Jian Xu[a,b], Jian Kang[b,a,*], Long Shao[a], Tianyu Zhao[a]

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

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

*Contact details of the corresponding author:

Abstract: With the rapid development of large industrial corridors in China, the landscape ecology of the country is currently being affected. Therefore, in this study, a system dynamic model with multi-dimensional nonlinear dynamic prediction function that considers industrial growth and landscape ecology is developed and verified to allow for more sustainable development. Firstly, relationships between industrial development and landscape ecology in China are examined, and five subsystems are then established: industry, population, urban economy, environment and landscape ecology. The main influencing factors are then examined for each subsystem to establish flow charts connecting those factors. Consequently, by connecting the subsystems, an overall industry growth and landscape ecology model is established. Using actual data and landscape index calculated based on GIS of the Ha-Da-Qi industrial corridor, a typical industrial corridor in China, over the period 2005-2009, the model is validated in terms of historical behaviour, logical structure and future prediction, where for 84.8% of the factors, the error rate of the model is less than 5%, the mean error rate of all factors is 2.96% and the error of the simulation test for the landscape ecology subsystem is less than 2%. Moreover, a model application has been made to consider the changes in landscape indices under four industrial development modes, and the optimal industrial growth plan has been examined for landscape ecological protection through the simulation prediction results over 2015-2020.

Keywords: System dynamics, modelling, landscape ecology, industrial development, landscape index, China

1. Introduction

China is currently still in the process of industrialisation [1], but the ecological and environmental degradation has restricted the rapid development of economy [2]. Recently, a pattern of industrial corridors has been developing rapidly in China, where several cities are connected by roads or railways, making up a banded industrial area with shared economic development goals [3]. This industrial development model could have serious effects on the sustainability of the landscape ecology of the area [4]. Recent research in system science indicates that the nature-society-economy system of an area is an open complex system [5-7], and thus, decision makers need a quantitative model to control industrial growth and protect the sustainable development of landscape ecology in industrial areas.

Research on the relationships between industrial development and environment began in the early 20th century. Weber [8] proposed the theory of industrial location. Based on the theory of industry life-cycle stages and the theory of shifts in international trade and international investment by Losch [9] and Vernon [10,11], Krugman's spatial economic model [12] is one of a series of general equilibrium problems. However, studies on the quantitative relationships between large-scale industrial development and landscape ecology have been rather limited.

System dynamics, based on the establishment of the urban dynamics model and the world model by Forrester [13] and “The Limits to Growth” theory by Meadows [14], has been used to solve the problem of large-scale systems, which are high-order, multi-variable, multi-feedback, counterintuitive and insensitive to changes in internal parameters. Focusing on the optimisation of the overall system rather than subsystems [15], this model is better at reflecting the nonlinear and dynamic changes of a system than traditional models, such as linear programming, econometrics and the input-output model. This model can help to coordinate the relationships among industry, population, urban economy, environment and landscape ecology. The nine system dynamics models developed by Senge [16], especially “The Limits to Growth” model, are the keys to understanding enterprise growth systems. A number of studies have used system dynamics to examine various environmental factors, including river change [17], environmental pollution [18, 19], land use [20] and public awareness and policy [21]. However, the relationships between industrial development and landscape ecology have not been quantitatively explored.

Therefore, this study aims to develop a system dynamics model of the relationships between industrial development and landscape ecology, and explore an optimal industrial growth mode for landscape ecological protection through model simulation prediction, in particular for the industrial corridors in China. This paper first defines the industry-economy system framework, considering five subsystems. Consequently, the main factors in the systems are analysed, and a flow chart connecting the subsystems is established to model the industry-ecology system. Finally, the model is validated in terms of historical behaviour, logical structure and future prediction. Moreover, four modes of enterprise development (original growth, “S” growth, uniform increase and uniform decrease) have been considered from 2015 to 2020, by comparing landscape pattern indices, to determine an optimal enterprise development mode.

2. Scope and purpose of system dynamics model

Given the complexity of the research objective, this section first examines the destruction caused by industrial development to landscape ecology; analyses the tendencies, causes and consequences of the industry-economy-landscape ecology system; and summarises the effect of an industrial corridor on the system considered and the principles of the feedback loop. Then, the framework of the research and system behaviour are defined. Dynamic assumptions are made according to the practical problems of each subsystem, providing background and boundaries for the overall dynamic model.

2.1 Defining the problem

As the “world’s factory”, China’s GDP growth rate was 9.87% over the past decade [22]. Figure 1 shows the distribution and development of the large industrial corridors in China, together with the results of an ecological vulnerability assessment. Due to the rapid development of the industrial corridors, China's environmental pollution has become world famous. It can be observed that most of the fast-developing industrial corridors are in eastern China, and the ecological conditions of eastern China are generally better than those in the rest areas of China, This means the contradiction between economic growth and ecological protection in eastern China is the most serious. Since the 1960s, industrial expansion has significantly taken over farmland and grassland in China, in addition to negatively affecting urban planning. Such developments, which have been dominantly oriented by economic considerations, have damaged the landscape ecology and produced serious air pollution and CO_2 emissions [23, 24] in eastern China, which has already attracted great international attention. Therefore, a quantitative model system that combines industrial development, population growth, economy and environment is needed to evaluate the landscape ecology and solve the environment problems in industrial areas of China.

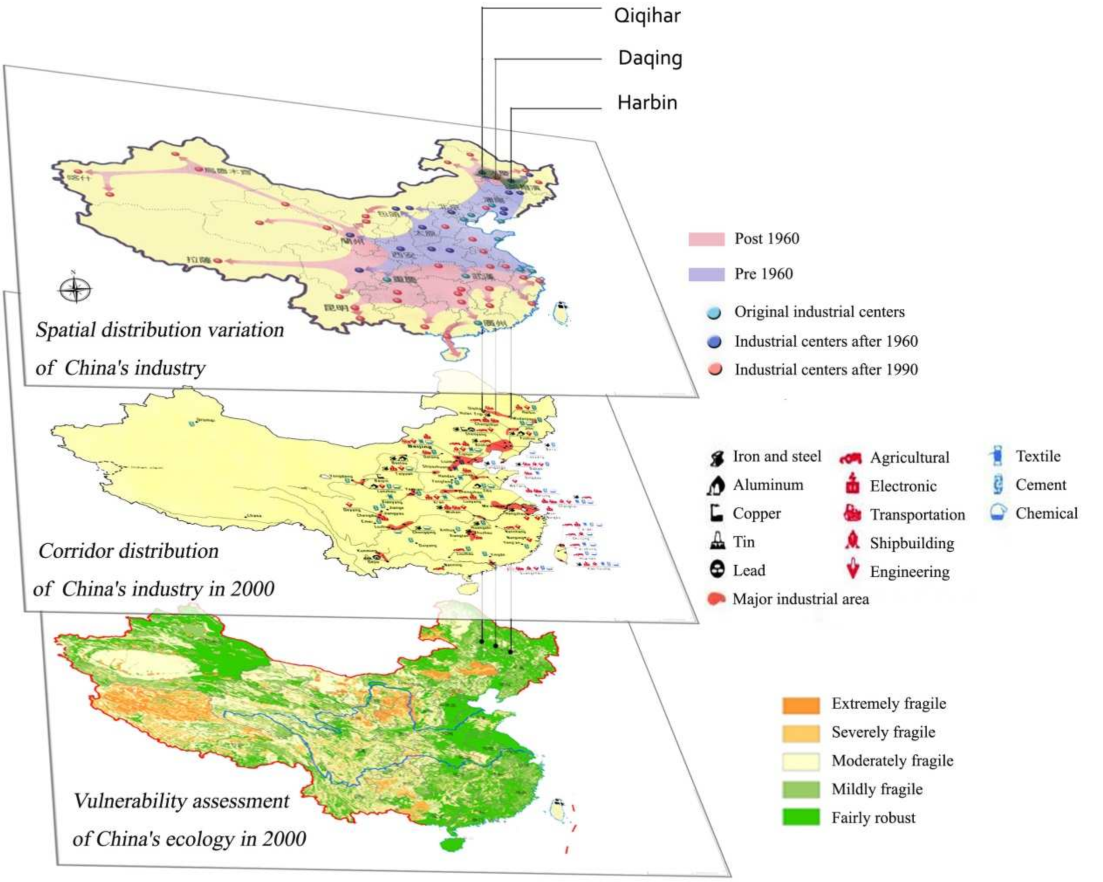

Fig. 1 Spatial distribution variation [adopted from www.tlsh.tp.edu.tw/~t127/industrychina/industry06.htm] and corridor distribution [adopted from www.china9.de/landkarten/landkarten-china.php] of China's industry and the ecological vulnerability assessment [assessment www.dljs.net/dltp/29967.html]. Web sites accessed on 18 February 2014.

2.2 System structure

Since the 1990s, the foci of industrial development in China have gone from being scattered throughout the country to being concentrated in industrial corridors [25]. Forman [26, 27], Reed [28] and Dramstad [29] studied the effect of such corridors on the environment and landscape ecology. Based on those studies, as well as the industrial district model [30], the research of Wrigley [31] on the relationships between industrial regions and population changes and the work by Pargal [32] on industrial pollution in developing countries, a system is proposed in this study to capture the effects of industrial corridors on the population, urban economy, environment and landscape ecology, as shown in Fig. 2.

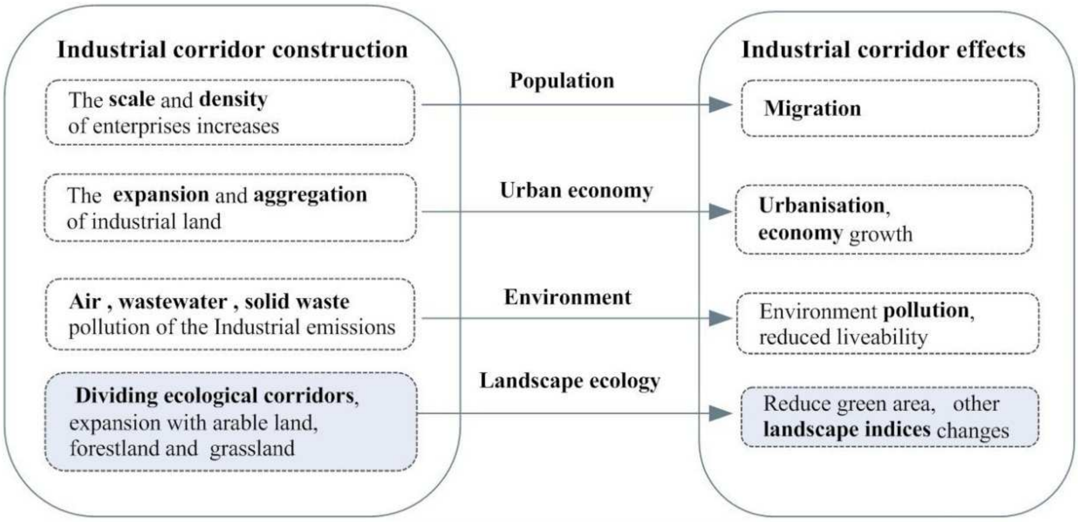

Fig. 2 Effects of industrial corridors.

Correspondingly, five subsystems are proposed, including the industrial subsystem, urban economic subsystem, population subsystem, environment subsystem and landscape ecology subsystem, as shown in Fig. 3, where industry development, along with population growth, economic development and environment, are responsible for the negative effects of human intervention on ecology [33], and landscape ecology is the quantitative evaluation criterion of natural ecology [34, 35].

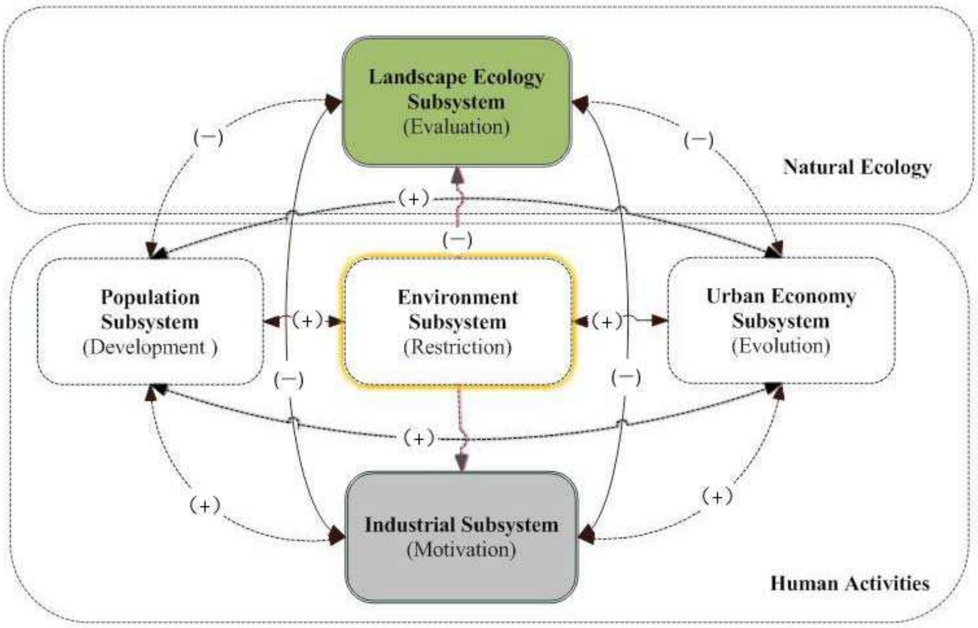

Fig. 3 Interactive relationships among different subsystems.

2.3 Dynamic assumptions

To avoid the infinite expansion of the above industry-ecology system, optimise the system function, improve system accuracy and make the system manageable using the system dynamics software VENSIM, the following assumptions are made:

1) Industry subsystem. According to the fractal growth theory of the size, shape and dimension of urban settlements [36] and the enterprise life-cycle theory [37, 38], complex industry types, the products demand of small weighting factors and financial factors of high uncertainty, such as the international economy environment, are neglected, whereas the effects of the enterprise number, life cycle and scale of enterprises on economy, cities, environment and resources, which are of greater weight, are emphasised.

2) Environment subsystem. Pollution is considered without classifying industry types. The air pollution, wastewater pollution and solid waste pollution of the enterprises considered are combined to calculate the gross regional pollution. According to the general statistical data, the relationship between industry pollution and the gross regional pollution can be derived.

3) Urban economic subsystem. Population growth is taken as the key reason for urban land expansion, and other factors related to urban area change are neglected. According to statistics for the period from 1990 to 2000, the correlation between the city area expansion rate in China and the rate of population urbanisation is greater than 90% [39].

2.4 System data acquisition

As a case study site, the Ha-Da-Qi industrial corridor in northeast China is chosen to establish the industrial growth-landscape ecology model. This corridor, built on an old industrial base, has been rapidly developed since 2005 with strong government support [40]. Given the limitation in continuous historical remote sensing satellite image resources of industrial corridors (essential for landscape index calculation) and the demand of temporal continuity and the stability of the system, the running period of the system is 2005-2010 in this study, corresponding to the duration of the “five-year plan” [41] of Chinese government, which is important for minimising the influence of policy changes on the model.

3. Factor selection

In this section, relationships among factors included in each subsystem are analysed, and important factors are selected according to their weighting based on statistical analysis. The connections among those important factors are shown in Fig. 4, where factors in solid circles are generic factors that are applicable for all industrial corridors and factors in dashed circles are regional factors that need to be statistically analysed and selected for each region. When the model is applied in other areas, the factor selection will be different according to the regional differences.

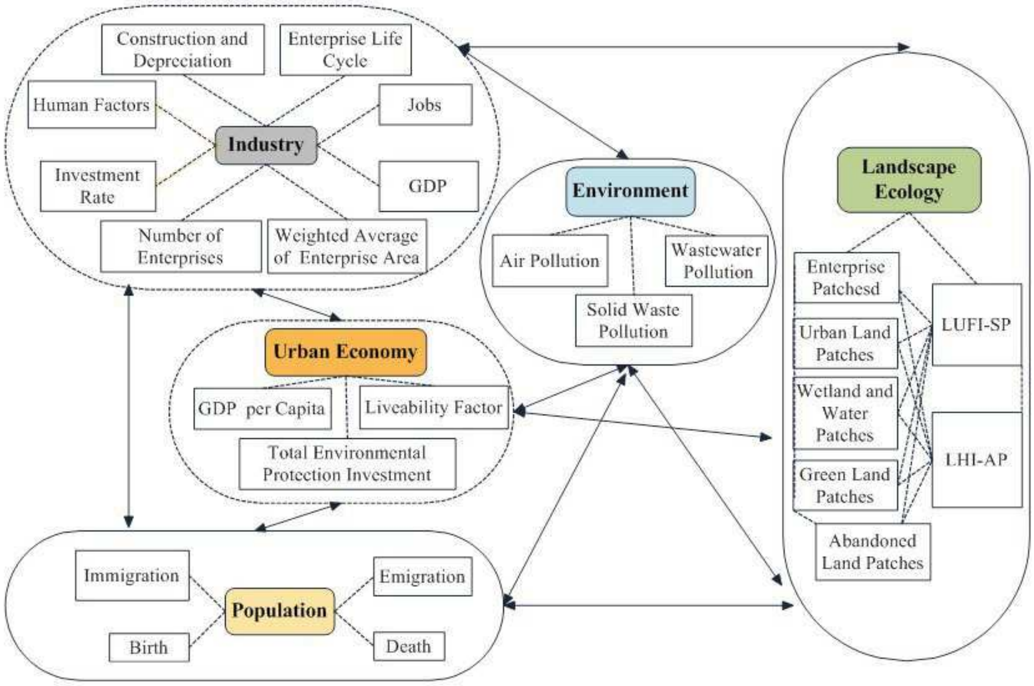

Fig. 4 Main factors of the five subsystems.

3.1 Industrial factors and urban economic factors

After reviewing previous studies [42-45], 18 indices for evaluating the developmental level of innovative cites in China were obtained. These factors can be divided into two categories: enterprise economic development factors and urban economic development factors. The former includes the total number of enterprises, number of industrial zones, enterprise life cycle, average enterprise area, investment ratios, jobs, industrial investment, total imports and exports and the average number of enterprises employees. The latter includes the urbanisation rate, regional GDP, per capita GDP, urban area, total investment of environmental protection, average wage of workers, total imports and exports, total tax and the ratio of the industrial production to the regional GDP. Because the industrial subsystem and the urban economic subsystem are motivation subsystems and are closely related to each other, they include many key factors in the whole system. A combination of principal component analysis (PCA) and factor analysis (FA), using SAS software, was used to reduce the number of variables, eliminate variable collinearity and reveal maximum impact factors.

Based on the data collected from three cities in the Ha-Da-Qi industrial corridor in 2008 for the 18 factors [46], the total contribution rate of 6 factors, i.e., the total number of enterprises, regional GDP, investment ratios, industrial investment, enterprise life cycle and jobs, is greater than 75%, which is sufficient to reflect the level of industrial development. On the other hand, the variance contribution rate of 5 factors, i.e., the regional GDP, per capita GDP, urban area, urbanisation rate and the labour force-job ratio, is greater than 72%, which is sufficient to reflect the level of urban economic development in the Ha-Da-Qi industrial corridor.

3.2 Population factors

The population subsystem has the fewest relevance factors and the most intuitive variables. The established population statistical method [47] is commonly applied to various system dynamic models. The state variable of the population subsystem is the regional total population, where relevant factors include the birth rate, death rate, immigration and emigration. Those factors are also affected by the total population, the liveability factor, job attractiveness factors and the degree of environment pollution. This method is not restricted by regional differences.

The population data of the Ha-Da-Qi industrial corridor are derived from the government yearbook [46]. Of particular consideration is the impact of region-specific Family Planning Policy.

3.3 Environment factors

In the environment subsystem, environmental quality is reflected by wastewater pollution, air pollution and solid waste disposal [48, 49]. Relevant evaluation methods/factors include chemical oxygen demand (COD) for wastewater pollution [18, 21, 50]; the maximum values, including background values, for air pollution and the consumption of the main form of energy under various conditions; and the production of garbage of the industrial area, in terms of solid waste disposal.

For the Ha-Da-Qi industrial corridor [46], COD is used as an index of wastewater pollution and SO_2 as an index for air pollution, where the maximum values recorded in one hour plus the background values under conditions of wind, light wind and calm wind are 0.47867, 0.50829 and 0.45874 mg/m^3, respectively, which are all very high. For solid waste disposal, the evaluation factor is coal gangue because in this region, the main form of energy consumed is coal, which generates over 85% of total solid waste.

3.4 Landscape ecology factors

The explanation of ecologic landscape modes is one of the main objectives in landscape ecology. The use of statistics regarding landscape patterns and ecological processes is the only method that can explain ecologic landscape modes. Landscape indices, which provide quantitative information for landscape patterns [51], are used in this model. Generally, there are two types of landscape indices, namely landscape unit feature indices and landscape heterogeneity indices. The former describe the comprehensive features of one patch, and the latter describe the distribution of all patches in a landscape pattern and maintain the stability of landscape functions [52]. In 1995, Riitters and O'Neill analysed the irrelevance of 55 landscape indices using 85 maps and found that 5 landscape indices play dominant roles [53, 54]. Therefore, this study uses the average patch perimeter-to-area ratio, relative patch area, fractal dimension and patch connectivity as the evaluation factors of the landscape pattern. When the model is applied in other areas, it is necessary to choose different landscape heterogeneity index according to the sensitivity differences of local landscape indices.

For the Ha-Da-Qi industrial corridor [46], the following eight landscape indices, which have the strongest sensitivity and the best performance for reflecting changes in landscape patterns, are selected: the number of patches, patch density, edge density, landscape shape index, Euclidean nearest neighbour distance distribution, Shannon's diversity index, Simpson evenness index and Aggregation index.

4. Model development

Based on the factors selected above, after analysing the complex relationships among subsystems, flow diagram of the five subsystems was obtained using the Vensim software program, which is a simulation software package for improving the performance of real systems, used for developing, analysing, and packaging systems dynamic feedback models. The diagrams and the model equations describing both the internal behaviours of each subsystem and the relationships among the factors and other subsystems are shown as Supplementary Materials.

4.1 Industrial subsystem

The industrial subsystem, as the motivating subsystem of the overall system, is continuously growing and generates contradictions and pressure for other subsystems [55]. This subsystem is an "enterprise ecosystem", whose development follows the law of general self-similar fractals [37, 38]. The total number of enterprises(NE) is the state variable, which is influenced by the enterprise construction ratio(ECR) and the enterprise depreciation ratio (EDR)[56]. The ECR is influenced by the investment rate, technology development factor, human factors, as well as the urban economic subsystem and landscape ecology subsystem. The EDR is influenced by the enterprise life cycle, as well as the environment subsystem and landscape ecology subsystem [57]. The total number of enterprises determines jobs, which forms a feedback loop with the population subsystem, and also directly affects the enterprise total urban economy subsystem, environment subsystem and landscape ecological subsystem.

4.2 Population subsystem

In term of population subsystem, total population is the state variable, which is influenced by the four rate variables, namely the immigration rate, emigration rate, birth rate and death rate. The birth rate and death rate are related to the total population in a specific way [31]. The development of industry, through jobs and job attractiveness factors, leads to an increase in immigration and the aggregation of the labour force. In addition, the aggregation of the labour force can also provide feedback to promote the development of enterprises. The environment subsystem affects the liveability factor, which in turn, affects the rate of immigration, whereas the green space-to-population ratio (GSPR) between the urban economic subsystem and the total population can also provide feedback to influence the liveability factor. The migration rate has the closest relationship with the urban economic subsystem, while the total population also directly impacts on the environment subsystem and unban economic subsystem.

In order to prevent the system expands unlimitedly outwards, reasonable constraint boundary has to be set up to omit some secondary contradictions and highlight the main contradiction. In term of the population, “household registration system” and “temporary residence permits” were used to calculate the population migration, and it was also noted that almost all the people who are working in the industrial corridors also live in the industrial corridor areas.

4.3 Environment subsystem

The environment subsystem is represented by two variables: the environmental capacity and the relative level of environmental pollution, which are closely related with the other four subsystems. Thus, the core of the environment subsystem is the resource system, which involves wastewater treatment, air pollution treatment and solid waste disposal. Through the total environmental protection investment of the urban economic subsystem, the industrial subsystem manages three pollution types. This relationship affects the rate of green space development and saline land treatment, which in turn, affects land-use types and landscape patterns.

It is noted that the research scope of this study is industrial corridor, and industrial zones are generally established around the edges of highways and railways. As shown in Fig.1, there are green buffer zones around the industrial corridors which can weaken the environment pollution and thus, the environmental pollution around the industrial corridors is lower than that inside the industrial corridors. Therefore, the model of this paper does not consider the environmental impact outside of the industrial corridors. If the pollution spreads to other areas outside the industrial corridors, more variables should be added to expand the model boundary.

4.4 Urban economic subsystem

The urban economic subsystem is an evolutionary system [58]. Because factors in the urban subsystem and the economic subsystem are closely related and the number of these factors is relatively small, factors associated with the two subsystems were analysed together. In this study, the research scope is defined as the economic changes of the towns and cities within the industrial corridors, ignoring the influence of remote cities around the industrial corridors. The key problem related to this subsystem is urbanisation, which indicates the process through which the population in concentrated in urban areas and rural areas are transformed into urban areas [59], China has been experiencing rapid urbanisation since the economic reform starting in 1978, and up to now， urbanisation has been rising and will continue in almost all the cities in the future [60]. Urbanisation mainly involves population migration, economic development, spatial expansion and the improvement of quality of life, which are also interrelated [42]. Using these four factors, urbanisation is linked to the economic, population, landscape ecology and environment subsystems, forming a full loop through which regional industrial production and regional GDP generate economic flow; moreover, total environmental protection investment affects the liveability factor, which in turn, affects urban areas and urban green areas.

4.5 Landscape ecology subsystem

The landscape ecology subsystem is the evaluation subsystem. The evaluation of land sustainability should be based on the amount of land and the factors related to productivity development. Maintaining the productivity of lands is closely related to the structures and functions of landscapes. The indices associated with landscape structures, functions and varieties are important factors that determine whether the use of lands is sustainable [61]. The landscape pattern indices are categorised into two groups: four landscape indices constitute landscape unit index to describe the landscape pattern change of industrial patches, and another eight landscape indices constitute landscape heterogeneity indices to describe landscape pattern change of all landscape patches. The two groups of indices influence the industrial subsystem and the environment subsystem, and the other four subsystems influence the types of land use, which in turn, affect the landscape pattern indices.

4.6 Integrated model

Based on the analysis of the five subsystems, the factors connecting the subsystems were examined; the results are shown in Fig. 5. Consequently, an overall system dynamic model of industrial growth and landscape ecology was established by integrating the five subsystems, as shown in Fig. 6.

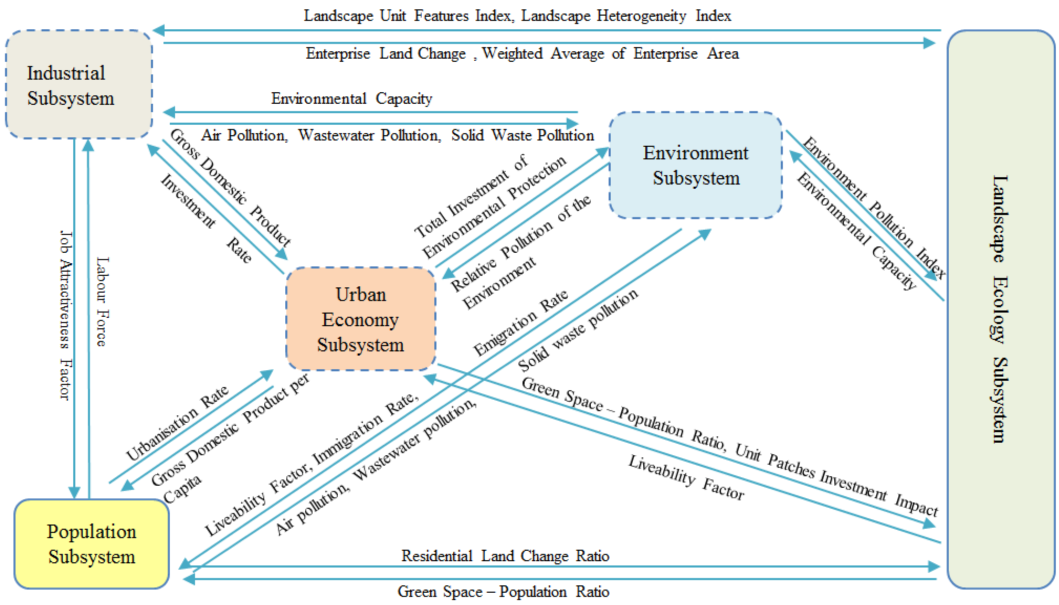

Fig. 5 Relationships among the five subsystems.

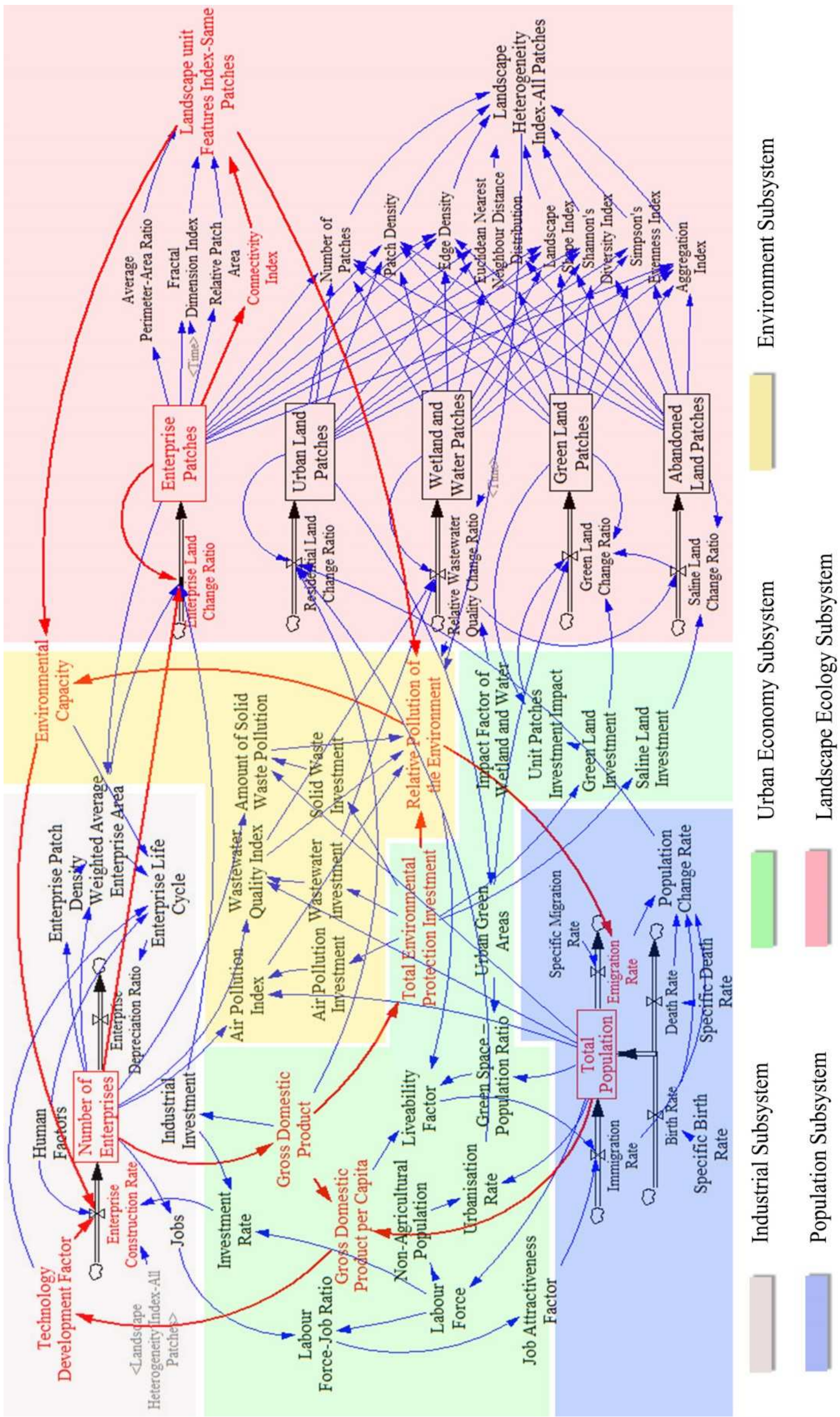

Fig. 6 System dynamics model of industrial growth and landscape ecology, where the variables with boxes are state variables (level variables), the variables under double solid horizontal lines are rate variables, and the

variables without boxes are auxiliary variables. A randomly selected route (indicated by thick lines) involving the five subsystems for structural validation of the model.

5. Model validation

In this study, based on validations of system dynamic modelling reported in various previous studies [62-66] and using the Ha-Da-Qi industrial corridor as a test site, three types of validation were performed to fully validate and make up the possible defects of relatively shorter calibrated time (five years)[18]: historical data validation, which confirms the objectivity of simulation data in the modelling process [67]; structural validation, which confirms the logic of model simulation, models defect detection and explains the time delay of a system [68]; and simulation validation, which checks the errors between the predicted data and actual data of various system factors [69].

5.1 Historical data validation

To verify that the formulas established and system regressions in the implementation of the model developed yield values that are sufficiently close to actual historical values, 50 groups of effective data in this model were validated; as in the process of system dynamic modelling, the generation of errors is inevitable even with rather mature models [67]. As shown in Table 1, over the five years from 2005 to 2009, factors whose historical validation error rate is less than 1% account for 42.4%, those whose error rate is between 1% and 5% account for 42.4%, those whose error rate is between 5% and 10% account for 10.4%, those whose error rate is between 10% and 20% account for 4.8% and those whose error rate is greater than 20% account for only 0.08%. For 84.8% of the factors, the error rate in the model operation process is less than 5%, and the mean error rate of all factors is 2.96%, which is less than the acceptable maximum of 5% [70].

Table 1. Difference (%) between historical and simulated data.

Abbreviation	Unit	Difference (%) (by year)				
		2005	2006	2007	2008	2009
TP	Million	0.22	0.21	0.66	0.62	0.63
LF	Ten Thousand	1.31	2.11	0.30	0.54	0.28
NAP	Million	0.83	0.51	0.46	0.32	0.16
IR	——	0.84	0.96	1.35	0.92	1.28
ER	——	1.28	1.26	1.45	1.53	1.32
UR	——	1.04	0.30	0.20	0.31	0.47
GSPR	——	0.89	0.1	3.4	3.1	3.54

			2	9	8	
J	Ten Thousand	2.05	2.93	0.42	2.49	2.17
NE	——	2.02	1.29	7.75	0.01	2.86
ECR	——	1.35	1.27	1.64	1.51	1.39
EDR	——	0.87	1.58	1.33	0.95	1.46
GDP	Billion CNY	7.76	6.50	2.00	11.89	2.31
GDPC	CNY	7.74	6.57	1.70	12.45	2.88
II	billion CNY	7.76	1.61	5.88	13.57	4.81
IVR	CNY/People	2.99	3.64	5.56	12.96	5.07
TEPI	Billion CNY	5.87	1.15	20.69	3.11	24.09
GLI	Billion CNY	1.13	1.21	1.55	0.91	1.48
APVI	Billion CNY	1.83	1.15	1.07	1.86	1.65
WI	Billion CNY	1.16	1.28	1.33	1.26	1.53
SWI	Billion CNY	0.48	0.36	0.67	0.93	0.84
SLI	Billion CNY	1.28	2.19	2.76	3.47	2.85
API	——	0.87	2.04	2.58	0.70	
WQI	——	17.07	8.85	7.66	11.20	4.82
ASWP	——	15.74	12.56	3.36	4.60	11.54
RPE	——	11.55	8.38	1.94	3.91	6.02
EC	——	8.47	12.96	7.88	19.64	6.96
UGA	Million Square Metres	1.11	0.08	2.81	2.55	4.15
WAEA	Square Metres	0.22	2.94	9.47	1.79	3.08
EPD	——	0.94	0.24	1.09	0.41	1.17
EP	Square Kilometres	1.31	1.47	1.68	2.32	1.48
ELCR	——	5.89	3.99	6.07	6.71	
ULP	Square Kilometres	2.96	2.83	1.79	2.46	2.75
WWP	Square Kilometres	1.56	1.37	2.43	2.18	1.85
GLP	Square Kilometres	8.35	8.17	6.72	7.39	7.75
ALP	Square Kilometres	4.21	3.83	3.92	3.76	2.95
APAR	——	0.95	0.76	0.78	1.64	2.67
FDI	——	0.48	0.03	1.84	0.19	0.41
RPA	——	10.88	0.98	0.89	4.26	4.60
CI	——	1.55	0.4	0.0	0.5	0.16

			1	1	7	
NP	——	0.37	0.13	0.52	0.67	0.22
PD	——	5.91	8.82	5.99	7.40	2.74
ED	——	0.19	0.03	0.30	0.05	0.15
ENN_MN	——	0.59	0.17	1.44	0.25	0.26
LSI	——	0.38	0.27	0.55	0.63	0.23
SHDI	——	0.66	0.81	0.55	0.33	0.94
SIEI	——	1.85	1.65	1.85	2.27	1.80
AI	——	0.01	0.02	0.02	0.02	0.01
LUFI-SP	——	0.94	0.45	1.78	1.07	2.53
LHI-AP	——	0.73	0.68	0.55	0.92	0.58

5.2 Structural validation

In this study, a structural test of the model was conducted by using a randomly selected route involving the five subsystems, as shown in Fig. 6, to detect any possible defect in the model structure [64].

A comparison between the historical data and simulated data of the 12 variables on the selected route is shown in Fig. 7. It can be observed that with the continuous influence of the science and technology development factor, the total number of enterprises grew quickly each year between 2005 and 2007. Annual growth was relatively between 2007 and 2008, whereas after 2008, the growth rate became even lower. During this period, the patch area of production land continued to rise, and the connectivity of enterprise patches also increased annually. Between 2005 and 2006, the regional GDP did not display a sharp increase at the onset of enterprise construction. With the increase in enterprise number and the expansion of the enterprise scale, after 2006, enterprises began to play a powerful role in promoting the regional economy and, in general, the law of development of enterprise and regional economy. As the enterprises developed, immigration also led to an increase in population. In contrast, per capita GDP continued to rise, promoting the science and technology development factors to drive the enterprise construction ratio, thus forming a complete feedback circuit with a time delay. Of the three types of pollution for enterprise management, even after the system balance, the environmental bearing capacity increased before 2006 but decreased annually after 2006. The improvement of regional GDP increased the total investment of environmental protection, and at the same time, relative environmental pollution also increased annually. The landscape unit characteristic index continuously increased, which indicates that the comprehensive landscape index is increasing and the landscape ecology is deteriorating. Overall, 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 defects.

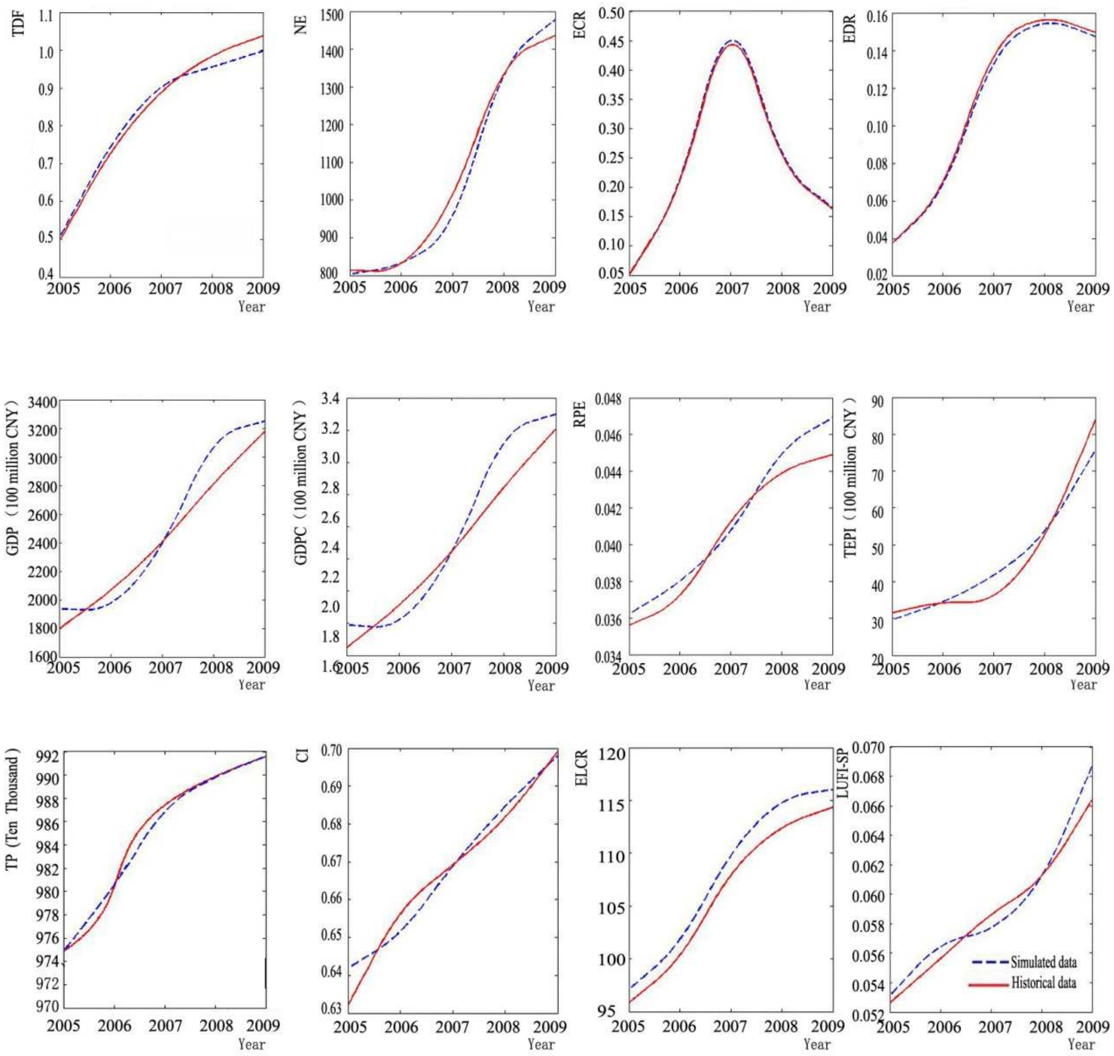

Fig. 7 Comparison between historical data and simulated data of the 12 variables on the selected route.

5.3 Simulation test

The simulation test results are the most important indicator for model effectiveness [63]. Taking the industrial, urban economy, population and environment subsystems as the input subsystems, the landscape ecological subsystem as the output subsystem and using 2010 data, a prediction was made for the factors in the landscape ecological subsystem and compared with actual data, as shown in Fig. 8. It can be observed that the prediction accuracy is very good, with an average error of 1.29%, much less the commonly acceptable value of 5% [66].

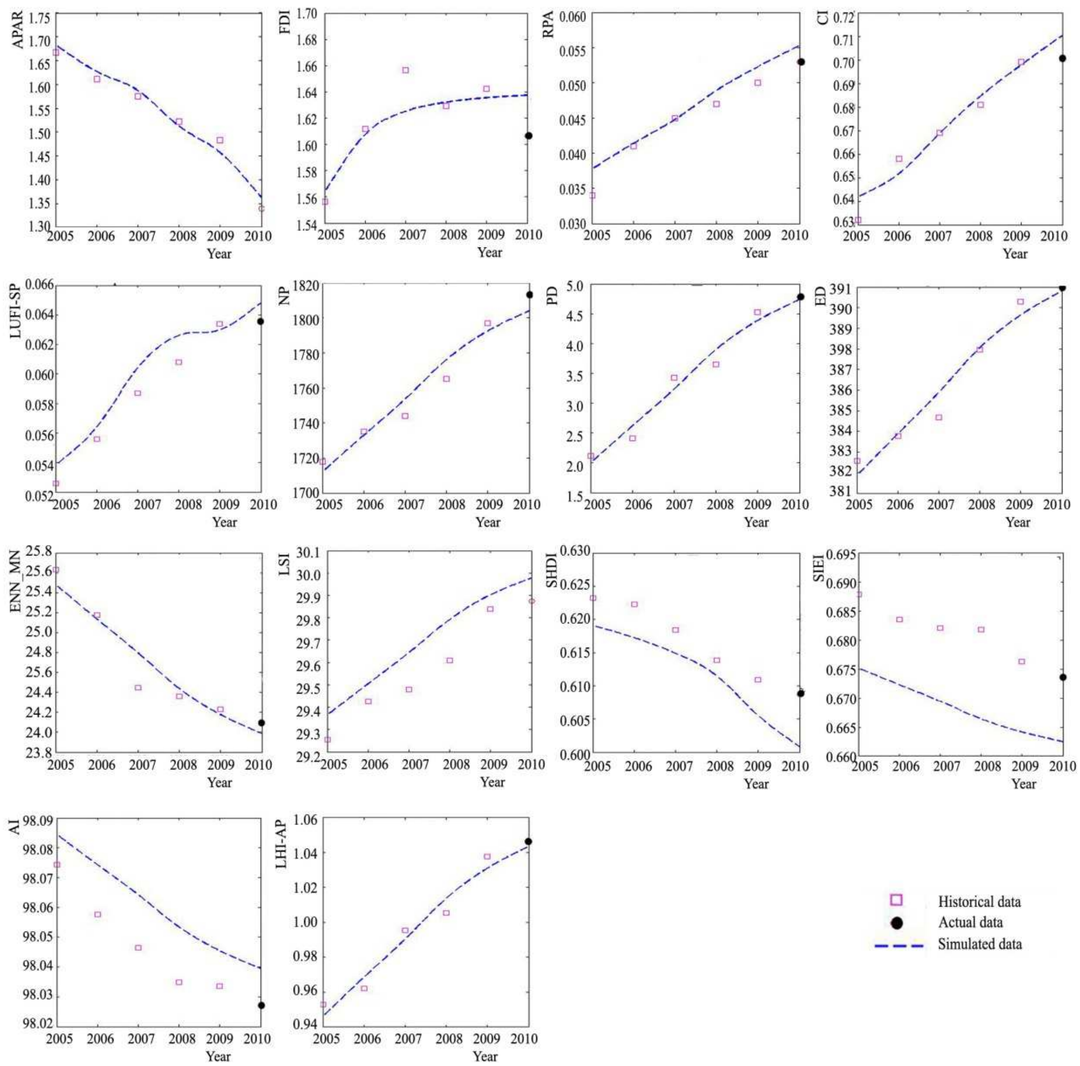

Fig. 8 Comparison between simulated data and actual data for the factors in the landscape ecological subsystem.

6. Model application

With the established model as described above, the following four modes of enterprise development have been simulated for the period of 2015-2020: (1) original growth mode, (2) “S” growth mode [37]; (3) uniform decrease mode (for comparing with the uniform increase mode, and the decrease rate is 6%); (4) uniform increase mode, with an increase rate of 6%, which is the average increase rate of Ha-Da-Qi industrial corridor in the last decade, and with this increase rate the value will be the same as that of the “S” growth mode in 2020. Correspondingly, the changes in unit landscape characteristics and landscape heterogeneity index, which can represent the total landscape pattern changes, are shown in Fig. 9 and Fig. 10, respectively. The enterprise patch connectivity index and the enterprise relative patch area are shown in Fig.11, and the landscape diversity index and the landscape patch aggregation index, which are the most sensitive landscape indices in landscape characteristics level, are shown in Fig.12.

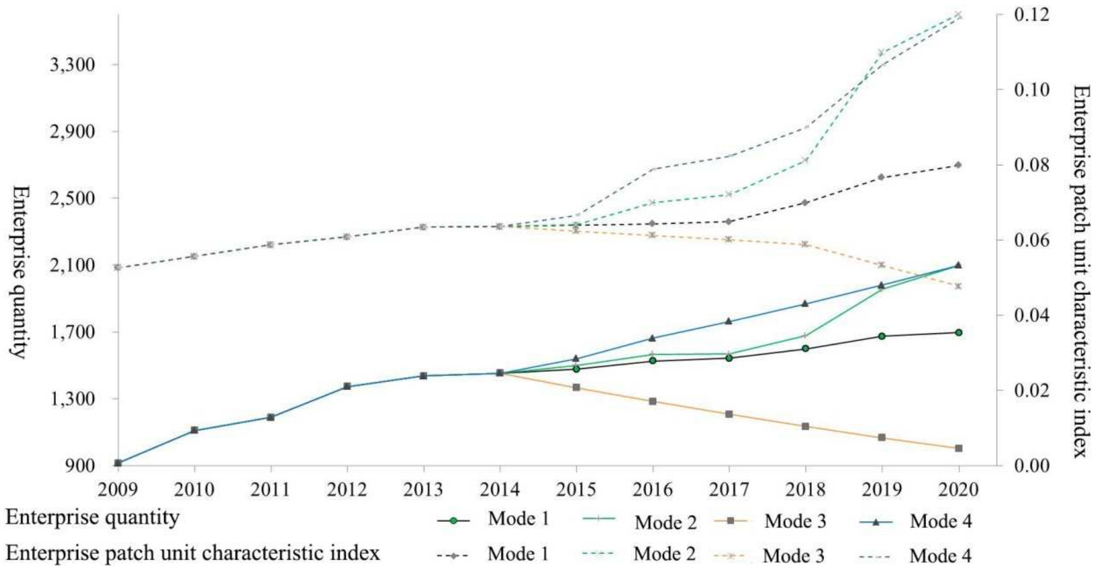

Fig. 9 The simulation of unit characteristic index under four enterprise development modes.

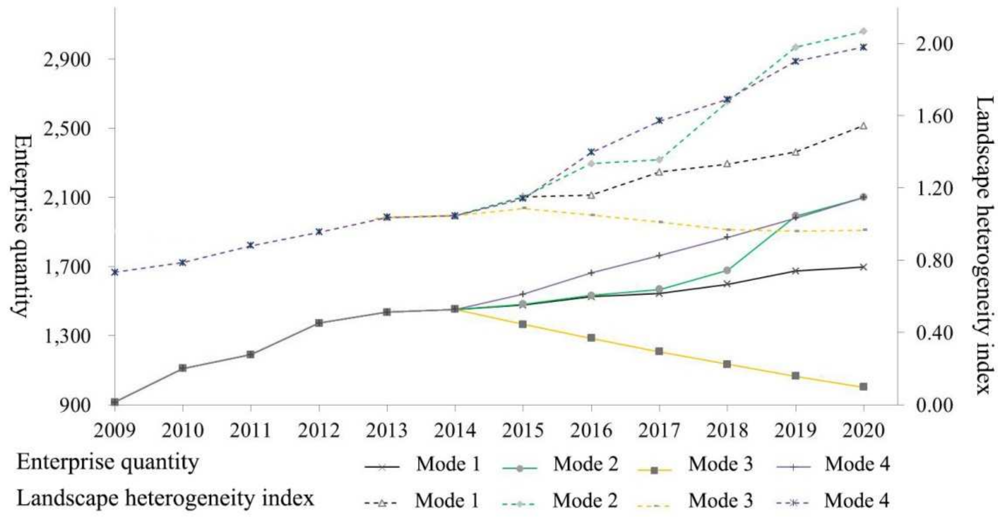

Fig. 10 The simulation of landscape heterogeneity index under four enterprise development modes.

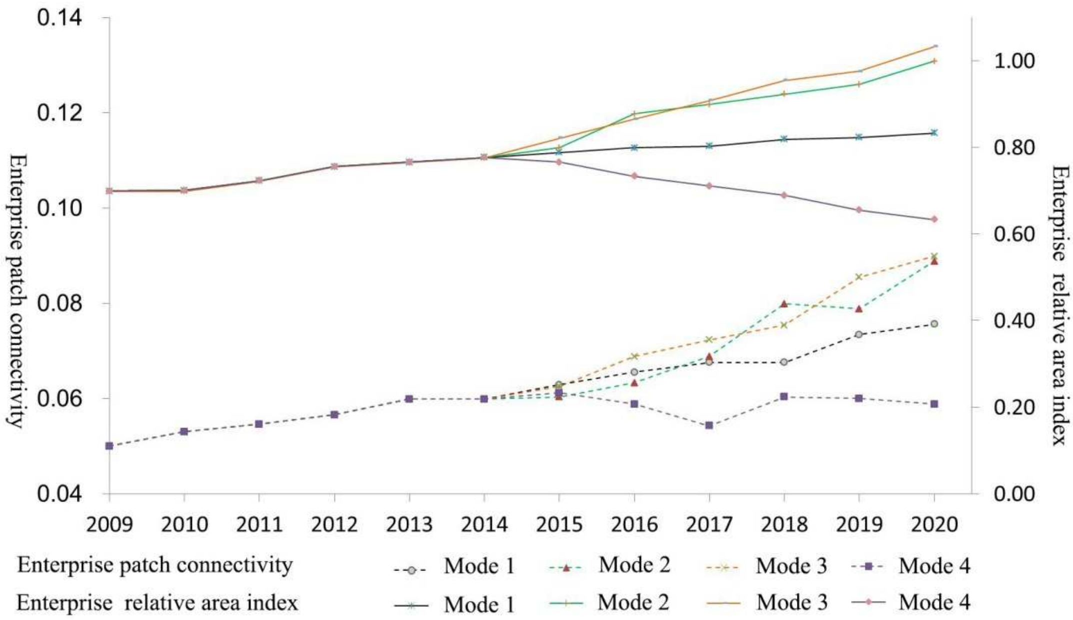

Fig. 11 The simulation of enterprise patch connectivity and relative area index under four enterprise development modes.

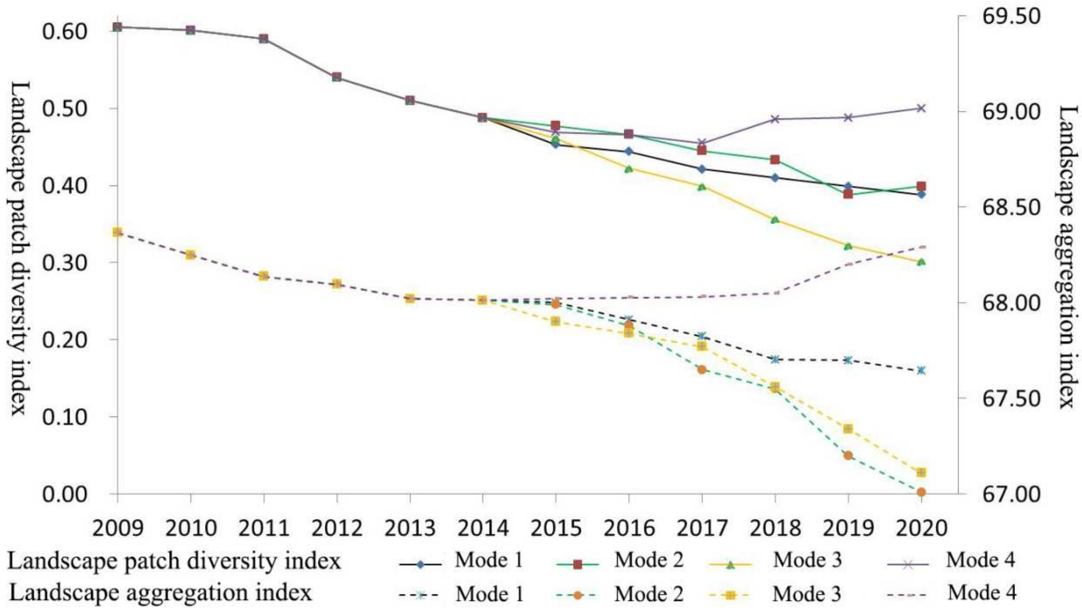

Fig. 12 The simulation of landscape patch diversity index and landscape aggregation index under four enterprise development modes.

It can be seen that the landscape indices are considerably affected by the enterprise quantity. As shown in Fig. 9, the enterprise unit characteristic index is directly proportional to the enterprise quantity. In general, the average change rate of enterprise unit characteristic index is greater than the average change rate of enterprise quantity. As shown in Fig.10, the landscape heterogeneity index is also affected by the enterprise quantity, and the curve trend corresponds to that of the enterprise quantity, but its curve volatility changes significantly by the influence of other system factors. As shown in Fig. 11, the changes of patch connectivity and enterprise quantity almost show changes in the same direction, which suggests that the enterprise quantity has promotion on the formation of the artificial corridor, causing negative effects on the ecological system, but the enterprise relative area index is proportional to the enterprise quantity, and the rate of change and the curve trend direction have no strong relationships with the enterprise quantity. As shown in Fig. 12, the changes curve of the landscape patch diversity index and landscape aggregation index show changes in the same direction, and they have roughly inverse proportional relationships with the enterprise quantity.

Further analysis shows that in the Ha-Da-Qi industrial corridor: (1) The industrial development is inversely proportional to the landscape ecological protection, and the changes of enterprise quantity have a 1-2 year delay on the landscape index; (2) By integrating all the evaluation factors of the landscape indices, and through the comparison of the three growth stages of the “S” mode and the uniform increase mode, it is found that when the enterprise quantity growth rate is below 10% in 2014-2017, and 10%-14% in 2017-2018, the "S" type mode is the optimal, whereas when the enterprise growth rate is more than 14% in 2018-2019, the uniform increase mode is the optimal; (3) Through a comparison between “uniform increase” and “uniform decrease”, it is seen that the landscape ecological destruction is much faster than that to be repaired, and in this case, the ecological restoration time is about twice of the destruction time, so that the landscape ecological planning is especially important under the fast industrial development.

7. Conclusions

China is confronted with the problem of ecological planning and management caused by bustling industrial corridor development. This study has systematically analysed factors that could possibly affect both industrial development and the landscape ecology. Five subsystems, namely industry, urban and economic, population, environment and landscape ecology subsystems, were established and correlated among one another. A system dynamic model for industry growth and landscape ecology was established, and using actual data for the Ha-Da-Qi industrial corridor over the period 2005-2009, the model was validated in terms of historical behaviour, logical structure and future prediction, where for 84.8% of the factors, the error rate in the implementation of the model is less than 5%, the mean error rate of all factors is 2.96% and the error of the simulation test for the landscape ecological subsystem is less than 2%.

The simulation of what-if scenarios, considering four modes of enterprise development, has been made for 2015-2020, through the analysis of the changes in landscape indices, and it has been found that: (1) The construction of large-scale enterprises has caused damages in landscape ecology; (2) When the enterprise growth rate is less than 10%, “S” style mode is optimal in terms of landscape ecological protection; (3) The landscape ecological destruction is much faster than the ecological restoration.

Acknowledgements

The authors acknowledge the financial support of the National Natural Science Foundation of China “Heritage corridor conservation of industrial cultural landscape of the Chinese eastern railway” (No. 51278141). The authors are also indebted to the Chinese Academy of Sciences and the Harbin Normal University for providing useful data.

References:

[1] Ren, B. P., 2005. Industry-financed agriculture: The strategy′ s transition and policy preference of the mid-term stage of the industrialization in China. Journal of Northwest University (Philosophy and Social Sciences Edition), No. 4: p.35-44 (in Chinese).

[2] Ouyang, Z.Y., 2004. On a kind of saving economical system——A theoretical review of the performance of "China's Agenda 21". Journal of Renmin University of China , No. 3: p. 106-113(in Chinese).

[3] Jin, B., Lu, T., Deng, Z., 2011. Transformation and upgrading of China's industrial structure: process, issues and trends . China Industrial Economics, No. 2: p.5-15 (in Chinese).

[4] Zhang, K.M., Wen, Z.G., 2008. Review and challenges of policies of environmental protection and sustainable development in China. Journal of Environmental Management, 88(4): p. 1249-1261.

[5] Qian,X., Yu, J., Dai, R., 1990. A new scientific field–open complex giant systems and the methodology. Chinese Journal of Nature, 13(1): p. 3-10 (in Chinese).

[6] Fang,Y., Cote R.P., Qin, R., 2007. Industrial sustainability in China: Practice and prospects for eco-industrial development. Journal of Environmental Management, 83(3): p. 315-328.

[7] Meng, X., Sun, M., Jones M., 2013. Practitioners' pperspectives on supply chain collaboration in UK construction projects. International Journal of Information Technology Project Management, 4(1): p. 27-40.

[8] Weber, A., 1909. Theory of the Location of Industries. The University of Chicago Press.

[9] Lösch, A., Woglom, W.H., Stolper, W.F., 1954. The Economics of Location. Vol. 1940. Yale University Press New Haven.

[10] Vernon, R., 1966. International investment and international trade in the product cycle. The Quarterly Journal of Economics.

[11] Hoover, E.M., Vernon, R., 1962. Anatomy of a Metropolis. New York: Doubleday Anchor Books.

[12] Fujita, M., Krugman, P.R., Venables, A.J., 1999. The Spatial Economy: Cities, Regions and Iinternational Trade. Vol. 213. Wiley Online Library.

[13] Forrester, J.W., Mass, N.J., Ryan, C.J., 1976. The system dynamics national model: understanding socio-economic behavior and policy alternatives. Technological Forecasting and Social Change, 9(1): p. 51-68.

[14] Meadows, D.H., Meadows, D.L., Randers,D.J., Behrens III, W.W., 1972. The Limits to Growth: A Report to The Club of Rome. Universe Books, New York. New American Library.

[15] Wang, Q., 1995. Advanced System Dynamics. Beijing: Tsinghua University Press.

[16] Senge, P.M., 1997. The fifth discipline. Measuring Business Excellence, 1(3): p. 46-51.

[17] Guo, H.C., Liu, G.H., Huang, G.A., Fuller, Zou, R., Yin,Y.Y., 2001. A system dynamics approach for regional environmental planning and management: a study for the Lake Erhai Basin. Journal of Environmental Management, 61(1): p. 93-111.

[18] Anand, S., Vrat, P., Dahiya, R., 2006. Application of a system dynamics approach for assessment and mitigation of CO_2 emissions from the cement industry. Journal of Environmental Management, 79(4): p. 383-398.

[19] Sha, J., Liu, M.,Wang, D., Swaney, D.P., Wang, Y.Q., 2013. Application of the ReNuMa model in the Sha He river watershed: Tools for watershed environmental management. Journal of Environmental Management, 124: p. 40-50.
[20] Weng, Q.H., 2002. Land use change analysis in the Zhujiang Delta of China using satellite remote sensing, GIS and stochastic modelling. Journal of Environmental Management, 64(3): p. 273-284.
[21] Stave, K.A., 2003. A system dynamics model to facilitate public understanding of water management options in Las Vegas, Nevada. Journal of Environmental Management, 67(4): p. 303-313.
[22] Kan, H., 2009. Environment and health in China: challenges and opportunities. Environmental Health Perspectives, 117(12): p. A530.
[23] Cao, J.S., Li, W.H., Tan, J.G., Song, W.M., Xu, X.H., Jiang, C., Chen, G.H.,Chen, R.J., Ma, W.J.,Chen, B.H., Kan, H.D., 2009. Association of ambient air pollution with hospital outpatient and emergency room visits in Shanghai, China. Science of The Total Environment, 407(21): p. 5531-5536.
[24] Qi, Y., Yang, X.Z., 2002. Concept and application of ecological industry chain system. Chinese Journal of Environmental Science, 23(6): p. 114-118.
[25] Wen, M., 2004. Relocation and agglomeration of Chinese industry. Journal of Development Economics, 73: p.329-347
[26] Forman, R.T., 2000. Estimate of the area affected ecologically by the road system in the United States. Conservation Biology, 14(1): p. 31-35.
[27] Forman, R.T., Deblinger, R.D., 2000. The ecological road‐effect zone of a Massachusetts (USA) suburban highway. Conservation Biology, 14(1): p. 36-46.
[28] Reed, R.A., Johnson‐Barnard, J. and Baker, W.L., 1996. Contribution of roads to forest fragmentation in the Rocky Mountains. Conservation Biology, 10(4): p. 1098-1106.
[29] Dramstad, W.E., 1996. Landscape Ecology Principles in Landscape Architecture and Land-use Planning. Island Press.
[30] Digiovanna, S., 1996. Industrial districts and regional economic development: A regulation approach. Regional Studies, 30(4): p. 373-386.
[31] Wrigley, E.A., 2011. Industrial Growth and Population Change. Cambridge University Press.
[32] Pargal, S., Wheeler, D., 1995. Informal regulation of industrial pollution in developing countries: Evidence from Indonesia. Vol. 1416. World Bank Publications.
[33] Bei, J., 2005. China's industrial development under the binding of resource and environment. China Industrial Economy, No. 4: p. 5-14 (in Chinese).
[34] Turner, M.G., Gardner, R.H., 1991. Quantitative Methods in Landscape Ecology. Springer-Verlag New York.
[35] Jongman, R.H., Ter Brank, C.J., Van Tongeren,O.F., 1995. Data Analysis in Community and Landscape Ecology. Cambridge University Press.
[36] Longley, P.A., Batty, M., Shepherd, J., 1991. The size, shape and dimension of urban settlements. Transactions of the Institute of British Geographers, Vol. 16, No. 1: p. 75-94.
[37] Liu, Z.F., Li, Y.J., 2009. On enterprise niche based on life cycle theory. Commercial Research, No.1: p. 22-29 (in Chinese).

[38] Hu, B., Zhang, D.B., Ma, C.X., Jiang, Y., Hu, X.Y., Zhang, J.L., 2007. Modeling and simulation of corporate lifecycle using system dynamics. Simulation Modelling Practice and Theory, 15: p.1259-1267.
[39] Liu, J.Y., Tian, H.Q. Liu, M.L., Zhuang, D.F., Melillo, J.M., Zhang, Z.X., 2005. China's changing landscape during the 1990s: Large - scale land transformations estimated with satellite data. Geophysical Research Letters, 32(2): p.43-47.
[40] Chen, Y.J., 2003. The basic situation of the old Northeast Industrial Base. Economic Research Review, No. 77: p.149-177 (in Chinese).
[41] Liu, G.G., Zhang, Z.Y., Dong, Z.K., Wu, L., 2006. Research Report on the 10 Five-Year Plans in China. The Chinese People's Publishing House (in Chinese).
[42] Li, Y.B., Chen, F., Li, R.D., 2007. Simulation of regional urbanization and eco-environment coupling and regulation policies: taking Jiangsu Province as a case. Geographical Research, No. 26: p.187-196 (in Chinese).
[43] Charnes, A., Cooper, W.W., Li, S., 1989. Using data envelopment analysis to evaluate efficiency in the economic performance of Chinese cities. Socio-Economic Planning Sciences, 23(6): p. 325-344.
[44] Li, F., Liu, X.S., Hu,D., Wang, R.S.,Yang, W.R., Li, D., Zhao, D., 2009. Measurement indicators and an evaluation approach for assessing urban sustainable development: A case study for China's Jining City. Landscape and Urban Planning, 90(3): p. 134-142.
[45] Fan, C.C., Scott, A.J., 2003. Industrial agglomeration and development: a survey of spatial economic issues in East Asia and a statistical analysis of Chinese regions. Economic Geography, 79(3): p. 295-319.
[46] Heilongjiang Statistical Yearbook , Harbin Statistical Yearbook, Daqing Statistical Yearbook, Qiqihaer Statistical Yearbook, 2000-2010. China Statistical Publishing House.
[47] Wolfenden, H.H., 1925. Population Statistics and Their Compilation. The Actuarial Society of America.
[48] Chen, B., Sodagar, B., King, B., Chisholm, P., 2012. Using virtual reality techniques to support the participatory design process for sustainable architecture. Architect, 159(5): p.18-22.
[49] Holling, C.S., 1978. Adaptive environmental assessment and management. Adaptive Environmental Assessment and Management.
[50] Norris, R., Georges, A., 1986. Design and analysis for assessment of water quality, in Limnology in Australia. Springer. Vol.61: p. 555-572.
[51] Tischendorf, L., 2001. Can landscape indices predict ecological processes consistently? Landscape Ecology, 16(3): p. 235-254.
[52] Chen, W., Xiao, D., Li, X., 2002. Classification, application, and creation of landscape indice. The Journal of Applied Ecology, 13(1): p. 121-125.
[53] Riitters, K.H., O'Neill, R. V., Hunsaker, C.T., Wickham, J.D., Yankee, D.H., Timmins, S. P., Jones, K.B., Jackson, B. L., 1995. A factor analysis of landscape pattern and structure metrics. Landscape Ecology, 10(1): p. 23-39.
[54] Pan, J., Wang, Y.L., Zhang C.Y., Ye, M.T., Wu, J.S., 2006. Research on the influence of land use Classification on Landscape Metrics. Acta Geographica Sinica, 61(2): p.157-168.
[55] Forrester, J.W., 1961. Industrial Dynamics. Vol. 2. MIT Press, Cambridge, MA.

[56] Nah, F.F.-H., Lau, J.L.-S., Kuang, J., 2001. Critical factors for successful implementation of enterprise systems. Business Process Management Journal, 7(3): p. 285-296.

[57] vAyres, R.U., 2001. Industrial ecology: wealth, depreciation and waste. Frontiers of Environmental Economics, University of California Press.

[58] Forrester, J.W., Karnopp, D., 1971. Urban Dynamics. American Society of Mechanical Engineers.

[59] Gilbert, A., Gugler, J., 1982. Cities Poverty and Development: Urbanization in the Third World. Oxford University Press.

[60] Song, S., Zhang, K. H., 2002. Urbanisation and city size distribution in China. Urban Studies, 39(12): p. 2317-2327.

[61] Jaeger, J.A., 2000. Landscape division, splitting index, and effective mesh size: new measures of landscape fragmentation. Landscape Ecology, 15(2): p. 115-130.

[62] Barlas, Y., 1996. Formal aspects of model validity and validation in system dynamics. System Dynamics Review, 12(3): p. 183-210.

[63] Forrester, J.W., Senge, P.M., 1978. Tests for Building Confidence in System Dynamics Models. System Dynamics Group, Massachusetts Institute of Technology.

[64] Bell, J.A., Senge, P.M., 1980. Methods for enhancing refutability in system dynamics modeling. System Dynamics. TIMS Studies in the Management Sciences, 14: p. 61-73.

[65] Richardson, G.P., Pugh III, A.I., 1981. Introduction to System Dynamics Modeling with Dynamo. Productivity Press Inc.

[66] Ford, D.N., Sterman, J.D., 1998. Dynamic modeling of product development processes. System Dynamics Review, 14(1): p. 31-68.

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

[68] Barlas, Y., 1989. Tests of model behavior that can detect structural flaws: demonstration with simulation experiments. In Computer-Based Management of Complex Systems. Springer. p. 246-254.

[69] Barlas, Y., 1994. Model validation in system dynamics. in Proceedings of the 1994 International System Dynamics Conference. Sterling, Scotland.

[70] Sterman, J.D., 1984. Appropriate summary statistics for evaluating the historical fit of system dynamics models. Dynamica, 10(2): p. 51-66

List of abbreviation

Industrial Subsystem

Number	Abbreviation	Description	Type*	Unit
1	NE	Number of Enterprises	L	——
2	ELC	Enterprise Life Cycle	A	Year
3	WAEA	Weighted Average of Enterprise Area	A	Square Metres
4	ECR	Enterprise Construction Ratio	R	——
5	EDR	Enterprise Depreciation Ratio	R	——
6	J	Jobs	A	——
7	TDF	Technology Development Factor	A	——
8	HF	Human Factors	C	——
9	LFJR	Labour Force-Job Ratio	A	——
10	JAF	Job Attractiveness Factor	A	——

Population Subsystem

11	TP	Total Population	L	10000 Persons
12	IR	Immigration Rate	R	10000 Persons/Year
13	ER	Emigration Rate	R	10000 Persons/Year
14	BR	Birth Rate	R	10000 Persons/Year
15	DR	Death Rate	R	10000 Persons/Year
16	PCR	Population Change Rate	A	10000 Persons/Year
17	SBR	Specific Birth Rate	C	10000 Persons/Year
18	SDR	Specific Death Rate	C	10000 Persons/Year
19	SMR	Specific Migration Rate	C	10000 Persons/Year
20	LF	Labour Force	A	10000 person
21	NAP	Non-Agricultural Population	A	10000 Persons

Environment Subsystem

22	EC	Environmental Capacity	A	——
23	RPE	Relative Pollution of the Environment	A	——
24	API	Air Pollution Index	A	——
25	WQI	Wastewater Quality Index	A	——
26	ASWP	Amount of Solid Waste Pollution	A	——

Urban Economic Subsystem

27	APIV	Air Pollution Investment	A	CNY
28	WI	Wastewater Investment	A	CNY
29	SWI	Solid Waste Investment	A	CNY
30	TEPI	Total Environmental Protection Investment	A	10000 CNY
31	GLI	Green Land Investment	A	CNY
32	SLI	Saline Land Investment	A	CNY
33	UR	Urbanisation Rate	A	——
34	GSPR	Green Space – Population Ratio	A	100 Square Metre/Person
35	UGA	Urban Green Areas	A	Square Kilometres
36	LIF	Liveability Factor	A	——
37	UPII	Unit Patches Investment Impact	C	——
38	GDP	Gross Domestic Product	A	10000 CNY
39	GDPC	Gross Domestic Product per Capita	A	CNY
40	IVR	Investment Rate	A	CNY/Person
41	II	Industrial Investment	A	10000 CNY
42	IFWW	Impact Factor of Wetland and Water	C	——

Landscape Ecology Subsystem

43	EP	Enterprise Patches	L	Square Kilometres
44	ULP	Urban Land Patches	L	Square Kilometres
45	WWP	Wetland and Water Patches	L	Square Kilometres
46	GLP	Green Land Patches	L	Square Kilometres
47	ALP	Abandoned Land Patches	L	Square Kilometres
48	ELCR	Enterprise Land Change Ratio	R	Square Kilometres/Year
49	RLCR	Residential Land Change Ratio	R	Square Kilometres/Year
50	RWQCR	Relative Wastewater Quality Change Ratio	R	Square Kilometres/Year
51	GLCR	Green Land Change Ratio	R	Square Kilometres/Year
52	SLCR	Saline Land Change Ratio	R	Square Kilometres/Year
53	EPD	Enterprise Patch Density	A	——

54	APAR	Average Perimeter-Area Ratio	A	——
55	FDI	Fractal Dimension Index	A	——
56	RPA	Relative Patch Area	A	——
57	CI	Connectivity Index	A	——
58	NP	Number of Patches	A	——
59	PD	Patch Density	A	——
60	ED	Edge Density	A	——
61	ENN_MN	Euclidean Nearest Neighbour Distance Distribution	A	——
62	LSI	Landscape Shape Index	A	——
63	SHDI	Shannon's Diversity Index	A	——
64	SIEI	Simpson's Evenness Index	A	——
65	AI	Aggregation Index	A	——
66	LUFI-SP	Landscape Unit Features Index -Same Patches	A	——
67	LHI-AP	Landscape Heterogeneity Index-All Patches	A	——

* C means constant variable.
A means auxiliary variable.
L means level variable.
R means rate variable.

Appendix 1: List of dynamic flow diagram of five subsystems.

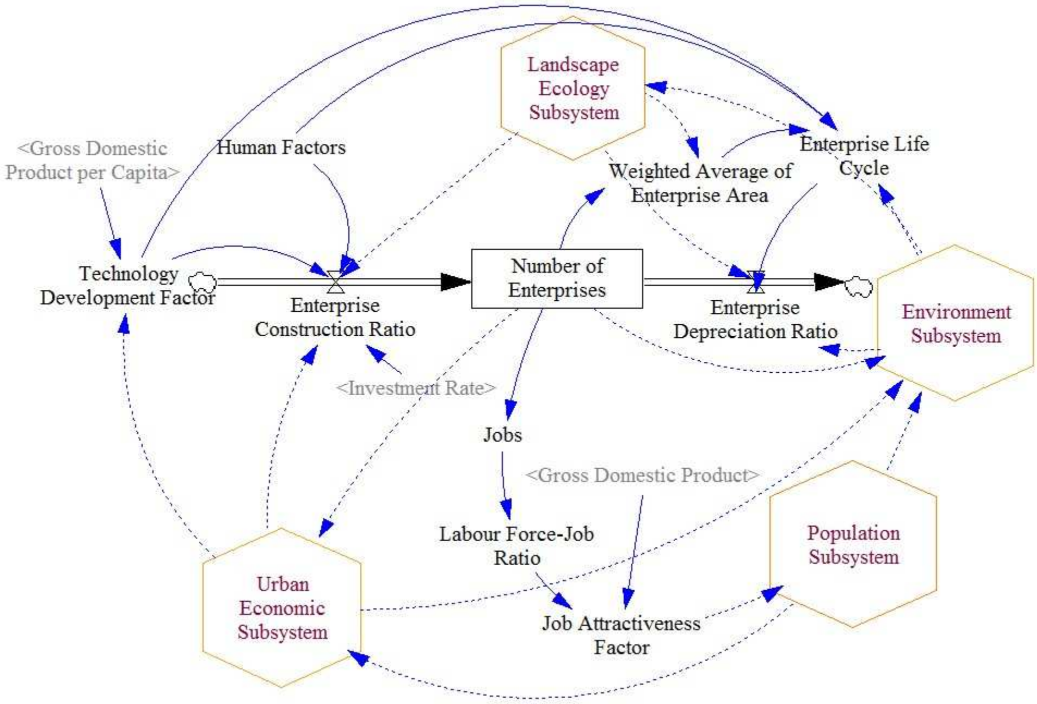

Fig. A1. Dynamic flow diagram of the industrial subsystem.

(Annotation to Fig. 5-9: The variables with boxes are state variables (level variables); the variables under double solid horizontal lines are rate variables; and the variables without boxes are auxiliary variables; the solid lines denote that the relationship between model variables of subsystems is material flow (relations have calculation formula), whereas the dashed lines denote information flow that the causal relationships between subsystems).

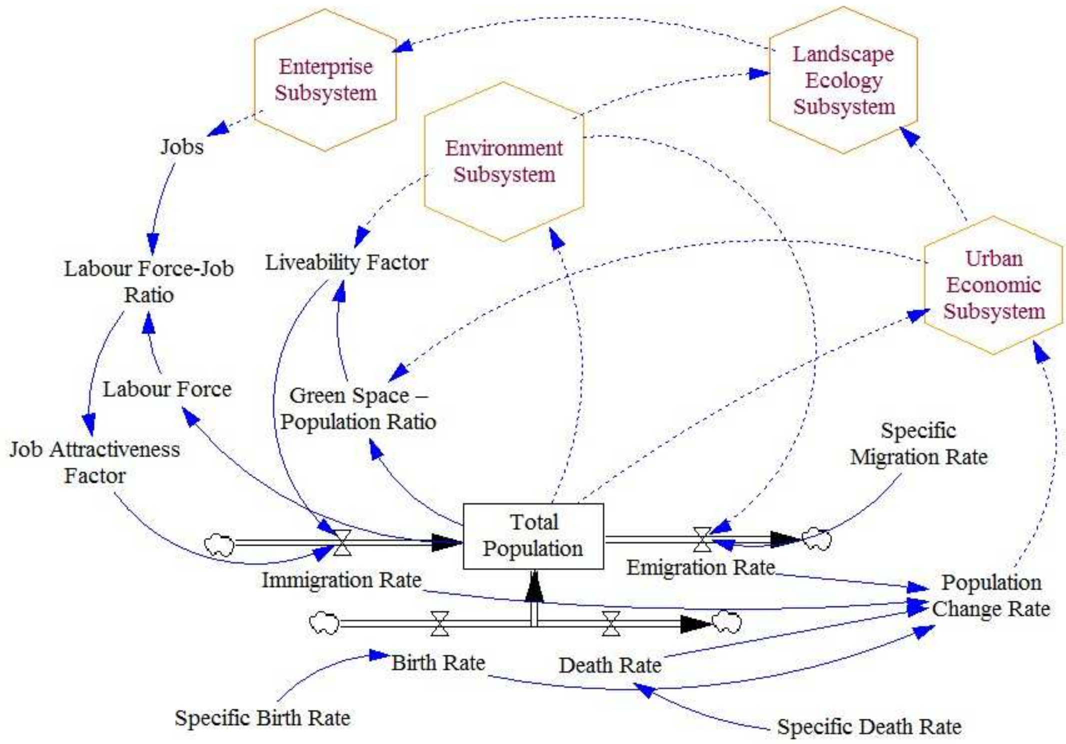

Fig. A2. Dynamic flow diagram of the population subsystem.

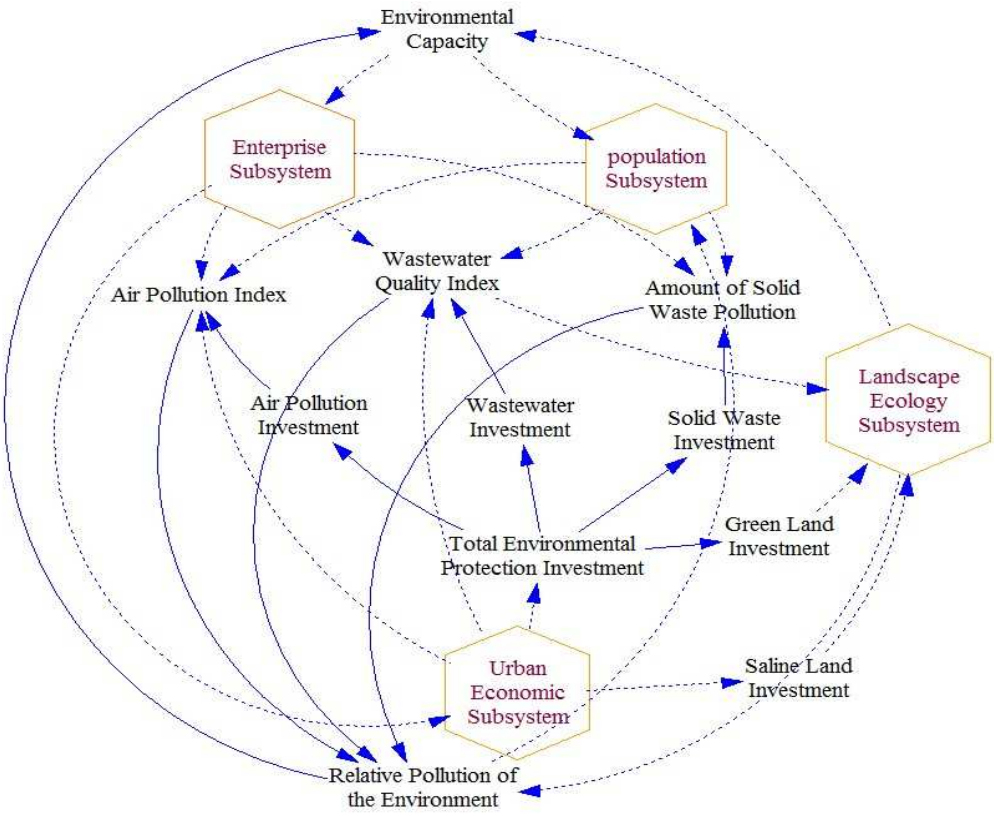

Fig. A3. Dynamic flow diagram of the environment subsystem.

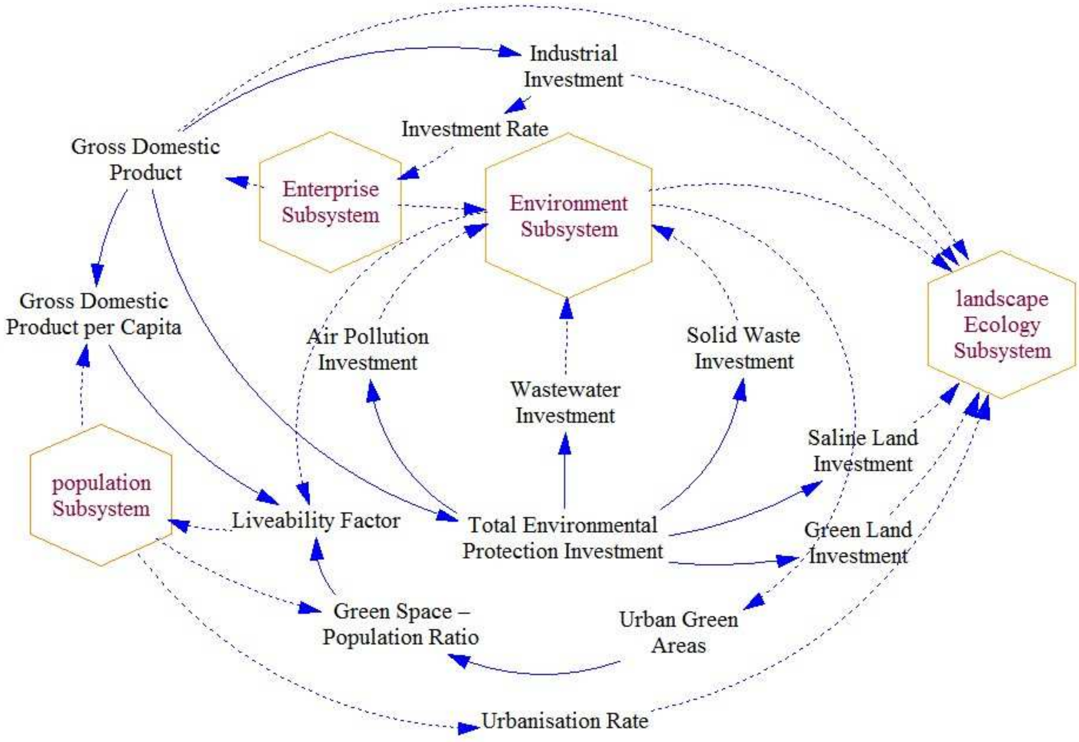

Fig. A4. Dynamic flow diagram of the urban economic subsystem.

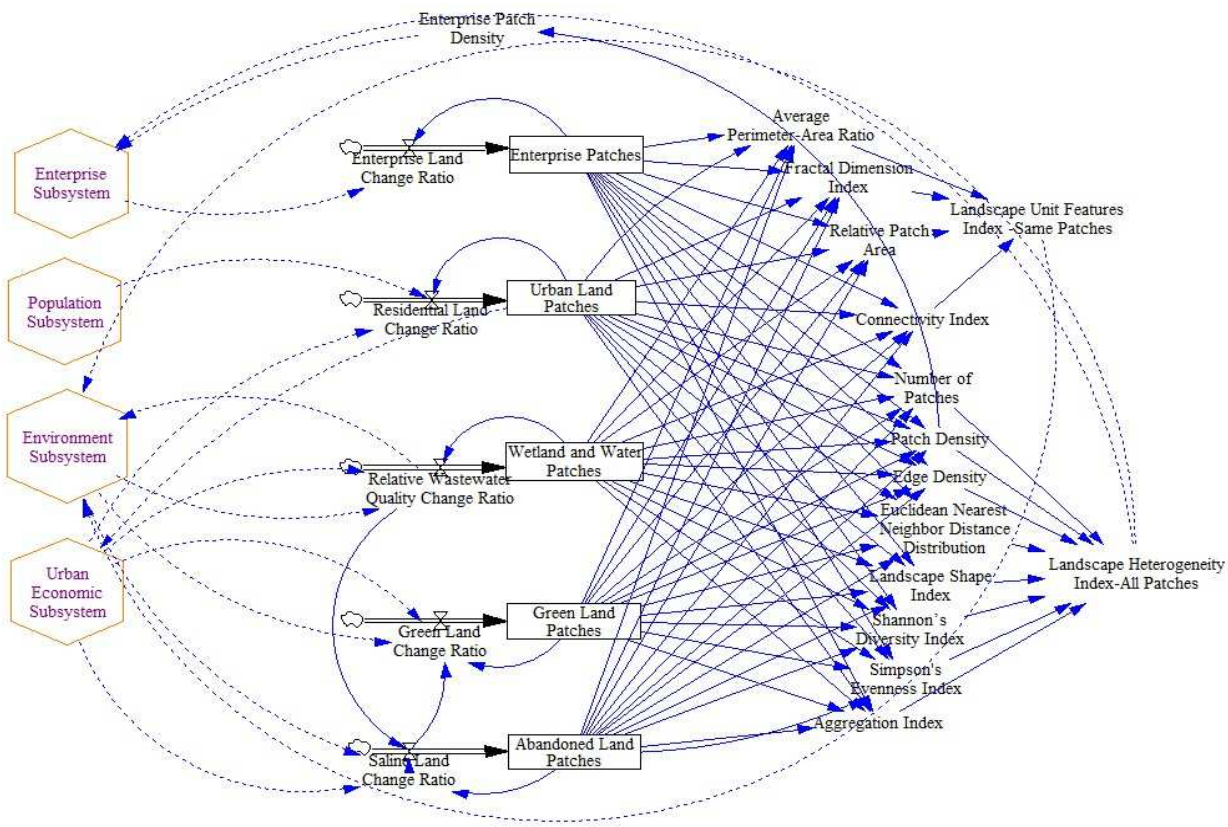

Fig. A5. Dynamic flow diagram of the landscape ecology subsystem.

Appendix 2: List of model equations

Industrial subsystem:

NE(K: future) = NE(I: current) +Dt*(ECR - EDR)

ELC = TDF*HF *Exp(1.369+2.109/(WAEA /EC))

WAEA = Enterprise Patch Density * Number of Enterprises / Enterprise Patches

ECR = Exp(0.052-2.61/(TDF*HF(LHI-AP *Ln(IVR*EC))))

EDR = If then else (ELC<4.5, 2.988-1.306*ELC+0.143*Power(ELC, 2), 37.573-15.334*ELC+1.563*Power(ELC, 2))

J = Exp(6.27-118.973/NE)

TDF = Exp(0.1-(Delay1I(0.0013*Ln(GDPC), 2, 0.8)))

HF is constant variable, 1.0

LFJR = J/LF

JAF = 1- Delay1I(0.8* LFJR, 2, 0.8)

Population subsystem

TP（K: future）= TP（I: current）+DT*(IR-ER)

IR = Exp(-5.174+0.549/(JAF *LIF))

ER = SMR (Time)+0.056-0.359* RPE +0.664*Power(RPE, 2)

BR = SBR

DR = SDR

PCR = IR +BR -ER –DR

SBR is constant variable, 1.05

SDR is constant variable, 1.04

SMR is constant variable, 1.01

LF = -1537.65+2.047*TP

NAP = 0.174*LF+390.748

Environment subsystem

EC = LUFI-SP *Exp(5.882-1.297/ RPE)

RPE = LUFI-SP*(API+WQI+ASWP)/ LHI-AP+0.2557

API = Exp(-1.258+6877.54/(NE*(APIV/TP)))

WQI = 9.331*Power(NE*(WI/TP),-0.334)

ASWP = 0.9-0.056*Ln(NE*(SWI/TP))

Urban economic subsystem

APIV = 0.212*TEPI

WI = 0.186*TEPI

SWI = 0.2*TEPI

TEPI = 109857*Power(2.718,5.532e-008*GDP)

GLI = 0.32*TEPI

SLI = 0.082*TEPI

UR = NAP/TP

GSPR = UGA/TP

UGA = 1.48*UP-844.389

LIF = GSPR *Ln(GDPC)/RPE

UPII = -0.888+0.087*GLI+0.001* GLI ^2

GDP= Exp(17.974-973.054/NE)

GDPC = GDP/TP

IVR = II /LF

II = Power(GDP,2.225) * 1.057e-010

IFWW is constant variable, 0.98

TEPI = 109857*Power(2.718,5.532e-008*GDP)

Landscape ecology subsystem

EP = ELCR*EP

ULP = RLCR*ULP

WWP = - RWQCR *WWP

GLP = GLCR* GLP

ALP = SLCR*ALP

ELCR = If then else((II/3.01992e+006+NE/1080.2)<2,0.135*Delay1I(Step(1.05, 15), 15, 0.68)*(II/3.01992e+006+NE/1080.2)* WAEA /EP, 0.046*Power(Smooth3I(Step (2.043,2),4,0.4264)* (II/3.01992e+006+NE/1080.2)* WAEA /EP,0.006))

RLCR = 0.003*(PCR+ UR) * GDP / (10000 * ULP)+0.005

RWQCR = If then else(Time<2007, Trend(WI/WWP, 1, 0.0786)-0.44* WQI, 0.01* IFWW (WI/WWP *100))

GLCR = 0.01* IIUP (0.04* Trend(UGA/GLP, 2, 0.8) *GLI+ SLCR)

SLCR = Delay1I(RWQCR, 2, SIN(SLI /ALP))

APAR = -1.252*Ln(EP)+7.395

FDI = Exp(0.369-0.073/Time)+ 1/Ln(EP)

RPA = 0.076* Ln(EP)-0.309

CI = 0.087* Exp(0.438*Ln(EP))

NP = 637.905*(Ln(EP)+ Ln(ULP) + Ln(WWP) + Ln(GLP) + Ln(ALP))-17930.1

PD = 18.843*(Ln(EP)+ Ln(ULP) + Ln(WWP) + Ln(GLP) + Ln(ALP))-578.201

ED = -1511.46+61.489*(Ln(EP)+ Ln(ULP) + Ln(WWP) + Ln(GLP) + Ln(ALP))

ENN_MN = Exp(-9.61+395.694/ (Ln(EP)+ Ln(ULP) + Ln(WWP) + Ln(GLP) + Ln(ALP)))

LSI = 85.858*4*(Sqrt(EP)+ Sqrt(ULP)+ Sqrt(WWP)+ Sqrt(GLP)+ Sqrt(ALP))/(2*Sqrt(3.14*7086)) -136.49

SHDI = -0.121*(Ln(EP/7086)+ Ln(ULP/7086) + Ln(WWP/7086) + Ln(GLP/7086) + Ln(ALP/7086))-1.019

SIEI = 3.354-0.087*(Ln(EP)+ Ln(ULP) + Ln(WWP) + Ln(GLP) + Ln(ALP))

AI = -0.308*(Ln(EP/7086)+ Ln(ULP/7086) + Ln(WWP/7086) + Ln(GLP/7086)+ Ln(ALP/7086))+93.894

LUFI-SP = EP/7086* (0.2* APAR /1.5718+0.3* FDI /1.6193+0.3* RPA /0.0434+0.2* CI /0.6678)

LHI-AP = 1 / 8 * (NP/ 1751.8 + PD/ 3.23 +ED / 385.85 +LSI / 29.52 + ENN_MN / 24.77 + SHDI / 0.61 + SIEI / 0.68 + AI / 98.05)