J. Geogr. Sci. 2020, 30(2): 333-352
DOI: https://doi.org/10.1007/s11442-020-1731-x

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Dynamic simulation of urbanization and eco-environment coupling:
Current knowledge and future prospects

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Abstract: Urbanization and eco-environment coupling is a research hotspot. Dynamic simulation of urbanization and eco-environment coupling needs to be improved because the processes of coupling are complex and statistical methods are limited. Systems science and cross-scale coupling allow us to define the coupled urbanization and eco-environment system as an open complex giant system with multiple feedback loops. We review the current state of dynamic simulation of urbanization and eco-environment coupling and find that: (1) The use of dynamic simulation is an increasing trend, the relevant theory is being developed, and modeling processes are being improved; (2) Dynamic simulation technology has become diversified, refined, intelligent and integrated; (3) Simulation is mainly performed for three aspects of the coupling, multiple regions and multiple elements, local coupling and telecoupling, and regional synergy. However, we also found some shortcomings: (1) Basic theories are inadequately developed and insufficiently integrated; (2) The methods of unifying systems and sharing data are behind the times; (3) Coupling relations and the dynamic characteristics of the main driving elements are not fully understood or completely identified. Additionally, simulation of telecoupling does not quantify parameters and is not systemically unified, and therefore cannot be used to represent spatial synergy. In the future, we must promote communication between research networks, technology integration and data sharing to identify the processes governing change in coupled relations and in the main driving elements in urban agglomerations. Finally, we must build decision support systems to plan and ensure regional sustainable urbanization.

Keywords: urbanization and eco-environment coupling; dynamic simulation; theory; methods; applications

1 Introduction

Urbanization drives environmental change on many scales, fundamentally changing regional landscapes and their ecology (Tratalos *et al*., 2007; Grimm *et al*., 2008). The International

Received: 2019-08-29 **Accepted:** 2019-10-18
Foundation: Major Program of National Natural Science Foundation of China, No.41590840, No.41590842
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Council for Science (ICSU) and the International Social Science Council (ISSC) launched the *Future Earth* initiative, which listed the *Urbanization and Global Environmental Change Project* (UGEC) as a core research project to study global environmental changes caused by urbanization (Li *et al*., 2008; Xie *et al*., 2010; Sanchez-Rodriguez *et al*., 2014). Research has shown that urban expansion determines landscape patterns, thus affecting land use and land cover change (LUCC), biodiversity, and hydrology. Waste and emissions during urbanization also affect the global climate and biogeochemical cycles (Chen *et al*., 2013; Schneider *et al*., 2015).

Urbanization in China ignores resource and environmental constraints (Fang, 2009). Urbanization in China has resulted in the loss of cultivated land, resource shortages, habitat fragmentation, and $PM_{2.5}$ pollution (Li *et al*., 2009; Zhou *et al*., 2014; Cui *et al*., 2016). Air and water pollution and other environmental problems are especially concentrated in urban agglomerations (Fang *et al*., 2010; Wang *et al*., 2014; Wang, 2017). Many researchers are interested in urbanization and eco-environment coupling because of their awareness of international developments in earth science and sustainability as well as their knowledge of the current state of urbanization in China (Kates *et al*., 2001; Reid *et al*., 2010; Fang *et al*., 2017). There is a multifaceted nonlinear interactive coupling relationship between urbanization and the eco-environment; therefore, the internal processes characterized by differences in stage and space, are complicated (Fang and Yang, 2006; Fang *et al*., 2016). Many scholars have used historical data from different regions to infer quantitative relationships that govern the coupling of urbanization and the eco-environment, and they have found that a second order polynomial or an inverted U-shaped curve is a good representation (Huang and Fang, 2003; Liu and Wang, 2015; Sun *et al*., 2017). The complexity of coupling relationships makes it difficult to study urbanization and eco-environment coupling within a single paradigm. A geographical study moves from knowledge description to process simulation and then to decision support (Fu, 2017). In the future, dynamic simulation of urbanization and eco-environment coupling would become an important activity.

Dynamic simulation reproduces historical geographical processes and predicts trends in their future development (Tang *et al*., 2010). Multi-scenario simulation of urbanization and eco-environment coupling can lead to the identification of coupling mechanisms and future trends. It also allows for optimal regulatory measures that coordinate urbanization and eco-environmental change to be selected. The successful dynamic simulation requires consistency between theory, method, and application; therefore, three key questions should be asked to ensure the consistency: (1) What are the theoretical foundations of the dynamic simulation, and what underlying regularities do these theories entail? (2) What simulation methods are available, and how accurate and applicable are they? (3) What specific applications are based on existing theories and methods, and how do these applications embody regional differences, identify the main control elements and reflect the cross-scale coupling? This paper will answer these questions by reviewing related theories, methods and applications.

2 Progress in theoretical research on dynamic simulation of urbanization and eco-environment coupling

Simulation is premised on the assumption that it can reveal the structure and underlying processes of a system. We draw on theories of systems science and cross-scale coupling to characterize the coupled urbanization and eco-environment system as an open complex system with multiple feedbacks to describe the system structure and evolution mechanism.

2.1 Human–environment interaction

Human–environment interaction is at the core of human geography. It originated as an object of study in the French school of geography represented by de la Blache and Brunhes (Wu, 1991). Many researchers have studied sustainable development from the perspective of human–environment interaction and the theory developed around it (Lu and Guo, 1998). The theory of human–environment interaction emphasizes the objective connection between human activity and the geographical environment; thus they together constitute a complex open system that has been called the geographic system of human–environment interaction (Wu, 2008).

Urbanization is a significant human activity; in a narrow sense, the eco-environment constitutes the geographical environment. A theory of human–environment interaction is foundational to the research for urbanization and eco-environment coupling; moreover, coordinated development between urbanization and the eco-environment is an embodiment of sustainable development. As human–environment interaction becomes more intricate than before, the boundary between urbanization and the eco-environment becomes fuzzier (Fan, 2014). Human–environment interaction determines the overall stability of the system. If the extent of human activity exceeds its carrying capacity, the geographic system of human–environment interaction would collapse. Thus the geographic system of human–environment interaction should take sustainable development as a long-term goal and control development to determine policy and to promote technological growth. To ensure the sustainable development of the geographic system of human-environment interaction, we must focus on the effects of human activity on natural resources and the eco-environment (Li *et al*., 2016).

2.2 Urban social-ecological system theory

The coupled urbanization and eco-environment system is a dynamic, multidimensional and collaborative complex system; it is constituted by a set of systems which include the social–economic–natural complex ecosystem (SENCE), the composite economy–resources–environment (ERE) system, and the urban ecological–economic (UEE) system (Ma and Wang, 1984; Liu *et al*., 2013; Fang *et al*., 2017).

The urban social–ecological system (USES) has been internationally recognized. Ostrom (2009) considered that a social-ecological system (SES) consists of four subsystems: the resource unit (RU), resource system (RS), governance system (GS), and user (U). The subsystems form a unity through complex interactions. USES is an adaptive system; however, its uncertainties, which significantly affect system resilience and sustainability, are caused by policies and behavior (Walker *et al*., 2002). USES provides a framework for the dynamic simulation of urbanization and eco-environment coupling. We can reduce the fuzziness of the relationships caused by uncertainty in the subsystems to reduce the difficulties of dynamic simulation. Because the relationships between urbanization, natural resources, and the eco-environment are direct, we can develop an urbanization–resources–environment (URE) system (Cui *et al*., 2019). Figure 1 shows that URE is an open, complex and dynamic system in a particular structure and with interactive functions (Zeng *et al*., 2000; Xie *et al*., 2016).

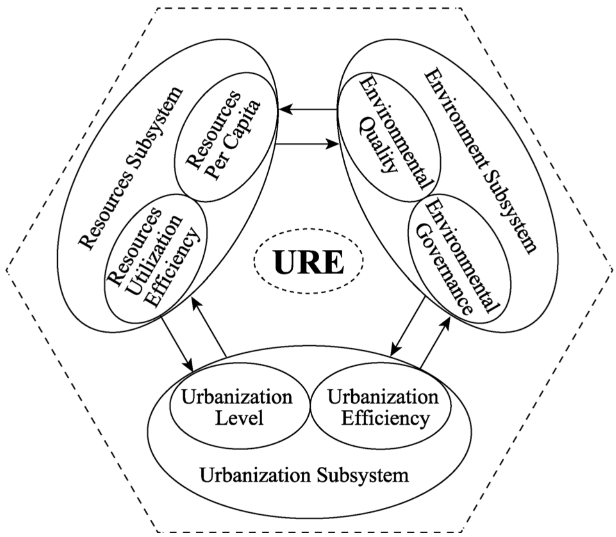

Figure 1 Interactions between urbanization, resources and environment in URE

2.3 Complex system theory

Complex system theory is derived from systems science and complexity science. The terms such as *self-adaptability*, *self-organization*, *uncertainty*, *emergence*, and *openness* are used to describe system characteristics and to explain the processes that lead to change in the uncertain system (Liu *et al*., 2008). Qian *et al*. (1990) proposed an open complex giant system; they presented that a comprehensive integration method combining qualitative and quantitative analysis was the feasible research method to simulate it.

A coupled urbanization and eco-environment system is a complex system with multiple feedback loops. The system is open and far from equilibrium (oscillating between an unsteady state and a steady state); it constantly exchanges matter, energy, and information with the outside world (Li *et al*., 2010). The system undergoes a process of repeated dynamic fluctuation (emergence→collaborative maintenance→critical phase change) and continuously moves towards a higher ordered state due to many self-organized changing processes such as mutual feedback of elements and energy transfer (Fang, 1989; Liu *et al*., 2016). A few slow-changing parameters (order parameters, which determine the order of the system) dominate the coevolution of the system (Liu *et al*., 2014). When change surpasses some critical point (threshold), the system produces a phase change (Dong, 2011). Urbanization, resources, and environmental factors can be regarded as order parameters, and urbanization is most important. The ultimate end of an evolving system is to change from chaos and disorder to coordination and order as it undergoes a complex series of multi-level spatio-temporal coupling processes. Though self-organization, self-adaptation, and self-learning lead to changes in system components and order parameters, the overall process of system change seems complex, dynamic, and random (Song *et al*., 2018).

2.4 Coupled human and natural system theory

At the start of the 21st century, humans were more concerned about global environmental changes than ever before. Increased anthropogenic emissions of greenhouse gases such as CO_2 had caused significant global warming; therefore, it damaged previously balanced ecosystems and endangered the safety of human social systems, leading to crises of water supply, food supply and health, and thereby posing significant challenges to sustainable development (IPCC, 2007). As a result of an essential incongruity between the cascading effects of human desires as well as goals and the balance of natural systems, humans realized that human activity is an important driver of global change (IGBP, 2001; Liu, 2002; Xu *et al*., 2013).

The processes that constitute interaction between humans and natural systems are not well understood (Liu *et al*., 2007). A coupled human and natural system (CHANS) was developed by Liu *et al*. (2007) to reveal and model multi-scale coupling mechanisms between humans and natural systems. CHANS represents complexities in organization, space, and time (Liu *et al*., 2007). (1) There is a nested hierarchy in the organization of the system, which is represented by direct or indirect influence and feedback loops (Allen and Starr, 1982; Gunderson *et al*., 2004). CHANS constitutes a complex network system that supersedes hierarchical levels through complex interactions between components (Sta *et al*., 2005). Characteristics of CHANS include vulnerability (Ii *et al*., 2003; Sven *et al*., 2017), critical threshold (MEA, 2005), and resilience (Holling, 1973; Jabareen, 2015). (2) There are many nested processes in CHANS, which intensify the interactions between global and local systems because of globalization, increasing population, material production, and information flow (Liu and Diamond, 2005; Lenschow *et al*., 2016). CHANS also shows spatial heterogeneity in urban and rural areas, where human activity damages natural systems in different ways (O'Meara, 1999; Liu *et al*., 2014). (3) The system drastically changes particularly in terms of population growth; therefore, it increases production and consumption which significantly increase the effects of humans on changes to the natural environment (Liu *et al*., 2003; Arrow *et al*., 2003; Entwisle and Stern, 2005). CHANS also incorporates change hysteresis (Rignot and Kanagaratnam, 2006; Bartlett, 2010). It couples human and natural systems on many scales, emphasizes the continuous change of the system in the space–time dimension, and explains the complex behavior and change processes in the coupled system.

2.5 Telecoupling framework

In previous studies, most attention has been paid to internal system interactions; but external influences were treated simply as external variables. However, in reality, remote interactions between systems have feedback effects. The telecoupling framework was developed to explain spatial coupling in open systems, especially remote interactions among economies, societies, and eco-environments (Liu *et al*., 2013; Fang and Ren, 2017).

A telecoupling framework is a multi-level framework composed of a series of CHANS. It contains five parts: system, flow, agent, cause, and effect (Liu *et al*., 2013). For example, Fang *et al*. (2016) used the telecoupling framework to analyze the impact of trade in photovoltaics between China and the European Union (EU) on energy sustainability. China forms a sending system and the EU a receiving system. China's photovoltaic exports accounted for 22.04% of the EU market share because of China's labor and environmental cost advantages and the EU's demand for photovoltaic products. As a result, China has benefited from job and tax growth, but suffered increased greenhouse gas and pollutant emissions, while the EU has mitigated climate change within its boundaries. Moreover, the coupling process between urbanization and the eco-environment exists across different spatial systems. For example, in Beijing, the high population density and a high concentration of industry result in the huge demand for water; therefore, the net volume of water imported to Beijing has increased from 3.6×10^8 m^3 in 2002 to 2.9×10^9 m^3 in 2012 (Sun *et al*., 2015).

2.6 Review of theoretical research

System science theory and cross-scale coupling theory provide underlying support for dynamic simulation. The former one includes human–environment interaction theory, urban social–ecological system theory, and complex system theory; the latter one includes coupled human and natural system theory and a telecoupling framework, forming the spatio-temporal coupling model.

The coupled urbanization and eco-environment system can be regarded as an open complex giant system with multiple feedback loops; therefore, we analyze it to find the processes that determine change. (1) There are complex nonlinear relations among various elements, including one–one, one–many and many–many relations. (2) The coupling includes the telecoupling framework and distance attenuation; it could be considered as strong within the system, and loose between systems. Therefore, strong coupling often determines the direction of system change, while loose coupling cannot be ignored. In this period of globalization, telecoupling is more intensive than it used to be. (3) We must be aware of the relationships between qualitative analysis and quantitative analysis to choose a suitable dynamic simulation method. The quantitative simulation could objectively explain some natural properties and coupling regularities. However, when policies develop, using a more subjective qualitative simulation could be more effective.

Because many systems theories are not fully developed, they are often standalone or incompatible with other theories. We must continue to develop complex system theory, cross-scale coupling theory, and other new theories. Moreover, the boundaries among disciplines should be blurred to encourage interdisciplinary studies; therefore, a network to research urbanization and eco-environment coupling should be formed to optimize efforts to solve the problem of uncertainty in dynamic simulation.

3 Progress in dynamic simulation methods of urbanization and eco-environment coupling

Breakthroughs in computer design, artificial intelligence, GIS, and other technologies have enabled the rapid development of dynamic simulation methods. Different methods have different disciplinary backgrounds, use different algorithms, as well as possess different advantages and disadvantages. Therefore, in terms of accuracy and applicability, the results have great differences. We now summarize the context of development, conditions of application and defects of different methods and analyze how to optimize them.

3.1 System dynamics

System dynamics (SD) is the oldest and most commonly used dynamic simulation method. SD blends systems science and computer simulation techniques to simulate geographic systems of human–environment interaction and urban complex systems, by combining qualitative and quantitative methods (Zhong *et al*., 2013). The procedure for using SD is: theoretical analysis→SD modeling→dynamic simulation→scenario regulation. SD has been widely used in the dynamic simulation of urban systems, urban sustainable development, and urbanization and eco-environment multi-factor coupling. Foundational work in SD is *The Limits to Growth* published by the Club of Rome in 1972. *The Limits to Growth* simulated the coupling of the global economy, natural resources, and the eco-environment by constructing a world model consisting of five modules (population, agricultural production, industrial production, natural resources, and pollution); therefore, *The Limits to Growth* pioneered the concept of sustainable development (Meadows *et al*., 1972). In subsequent research, SD was used to simulate urban systems growth and sustainable development, using concepts of systemacity, complexity, coordination, and sustainability; SD was also used to define the sustainable urbanization model of coordinated development of population, economy, natural resources, and the environment (Liu *et al*., 2013; Fang *et al*., 2017). The coupling process among urbanization and natural resources, energy, greenhouse gases and geological forms was simulated on global and regional scales (Zuo, 2007; Feng *et al*., 2013; Yan *et al*., 2016).

However, the flaw of SD is that the fixed structure of the model makes it difficult to simulate systems containing uncertainties, such as technological progress, government policy and human behavior; therefore, some variable relationships are limited to being defined by the use of regression. Additionally, simulated systems tend to be macroscopic, which puts SD at a disadvantage when dealing with microscopic systems.

3.2 Artificial intelligence

Artificial intelligence (AI), in the form of artificial neural networks (ANNs) and Bayesian networks (BNs), has developed rapidly; therefore, it can at least partially solve the problem to dynamic simulation for self-organizing, self-adapting, and self-learning systems. ANN and BN are similar in algorithmic complexity and network training methods; but they differ in topology, learning rules, and algorithmic principles. ANN includes the use of directed acyclic graphs and directed cyclic graphs, and uses an activation function to train the model and construct the learning rules. The directed acyclic graph is commonly used by the back-propagation neural network technique with a back-propagation algorithm to train a multi-layer neural network (Haykin, 2009). However, a directed acyclic graph is used by BN; the joint distribution is decomposed into multiple probability distributions for causal inference and diagnostic inference according to the conditional independence relations among variables (Zhang and Guo, 2006; Huang, 2013). On the one hand, ANN has the advantages of self-learning, associative storage, high-speed optimization and nonlinear mapping; but it is unsuitable for causal reasoning or dealing with uncertainty (Xu, 2010). On the other hand, BN is suitable for causal reasoning and dealing with uncertainty problems and incomplete datasets, while its algorithm is not particularly efficient and its structured learning capacity is limited (Li and Zhang, 2015). Currently, AI is mainly used to simulate urban expansion and its eco-environmental effects, to predict the demand for urban resources, and to identify sustainable management, urban ecological vulnerability as well as disaster risks (Cai *et al*., 2009; Froelich, 2015; Balbi *et al*., 2016).

There is a black box in the dynamic simulation of urbanization and eco-environment coupling, but AI could open it by deep learning. However, AI is still in the developmental stage; therefore, there is a disagreement that it is genuine intelligence rather than pseudo-intelligence. The prospect of using AI to simulate uncertain systems is appealing, and we could extend the scope of AI by embedding it in other techniques.

3.3 Land use and land cover change model

Land use and land cover change (LUCC) models refine the interpretation of spatial usage.

Spatial changes in urbanization and eco-environment coupling could be shown dynamically and could be analyzed to determine how urban boundaries would expand. LUCC models include conversion of land use and its effects at small region extent (CLUE-s), cellular automata (CA) and multi-agent systems (MAS) (Deng *et al*., 2009). The CLUE-s model is an empirical local equilibrium model that simulates multi-scale spatial distributions of land use (Tang *et al*., 2009). On the one hand, CA can simulate the complex discrete changes of the local land use system by presetting the transformation rules and using a bottom-up approach. However, CA is an idealized model based on the assumption of spatial homogeneity, which makes it difficult to take account of spatial heterogeneity (Zhao *et al*., 2016). On the other hand, MAS includes many agents and incorporates behavior, decision-making and other factors into the processes that affect land use change; therefore, MAS can simulate changes that occur in an adaptive system better (Chen *et al*., 2008). However, the application of MAS is at a preliminary stage; therefore, the model is limited by the assumption of spatial homogeneity.

CLUE-s, CA and MAS simulate land urbanization and eco-environment coupling based respectively on empirical data, spatial information rules, and complex system theory; however, they are limited to the spatial perspective and must be coupled with other models to increase their applicability.

3.4 Integrated method

SD+, a recently-developed combinatory method, is a bottom-up method that uses combinations of various other methods, and it has widely used (Gu *et al*., 2016). (1) The combination of SD with GIS is an important enhancement to the dynamic simulation of spatial change (Wan *et al*., 2016). (2) The combination of SD with CA is at the forefront of systems technology; therefore, it improves the interpretation of the environmental effects of urban land change (Wang *et al*., 2013). (3) The combination of SD with agent-based modeling (ABM) has been explored as a solution to the problems surrounding randomness, discreteness, spatial heterogeneity, and adaptability (Guerrero *et al*., 2013). (4) The combination of SD with CLUE-s is expected to facilitate the simulation of land use change for different urban, economic, and social development scenarios (Tian *et al*., 2016). In addition, Hu and Sun (2017) combined fuzzy integration, a genetic algorithm, and an artificial neural network to detect the exogenous sources that sound an alarm for regional energy security.

SD incorporates qualitative and quantitative characteristics, and it becomes an important interface for the combined systems. However, it is challenging to integrate technology and to verify the authenticity and effectiveness of existing achievements. In the future, we must combine system engineering, artificial intelligence, LUCC simulation and prediction, 3S, and other technical disciplines to build a linked dynamic simulation technology chain.

3.5 Interactive decision support system

To support decision-making for regional sustainable planning, researchers have developed many systems based on different objectives; researchers are longing to develop an interactive decision support system; however, the decision support systems are empirical. For example, Chen *et al*. (2016) designed an ecological security decision support system, which included key modules for ecological restoration and reconstruction, risk prediction and early warning, to link and coordinate regional ecological security in the Beijing–Tianjin–Hebei urban agglomeration. Fang *et al*. (2017) designed an interactive decision support system for urbanization and eco-environment coupling based on multi-level, multi-scale, multi-perspective and multi-scenario optimization.

The development of an interactive interface between dynamic simulation and decision support is promoted by technology. Interactive decision support currently lacks developed products and relies on experience and judgment. In future, we must build an intelligent interactive decision support system.

3.6 Review of dynamic simulation methods

Dynamic simulation methods are diversified, refined, intelligent and integrated because of the use of computers, 3S and artificial intelligence. Different strengths and weaknesses of common techniques, such as SD, AI (ANN and BN) and LUCC modeling (CLUE/CLUE-s, CA and MAS), are shown in Table 1.

Table 1 Comparison of techniques for dynamic simulation of urbanization and eco-environment coupling.

Name	Discipline	Advantages	Disadvantages	Application
System dynamics	Systems science and computer simulation	Modeling process is simple and can be combined with an index system to identify system boundary and related variables	Difficult to reflect the characteristics of adaptive and spatial change in the system, and the feedbacks are in part regression relationships	Urban system change, urban sustainable development and urbanization and eco-environment element coupling
Artificial neural network	Artificial intelligence	A typical human brain model with three advantages: self-learning, associative storage and high-speed optimization	Defective in learning, causal explanation and other aspects, especially in dealing with system uncertainty	Urban land expansion, environmental change, and resources demand
Bayesian networks	Artificial intelligence, probability theory, statistics and graph theory	Good at causal and diagnostic reasoning, as empirical data can be incomplete	Difficult to deal with the large number of nodes and the learning ability is less than for ANN	Identification of urban ecological vulnerability and demand for resources
CLUE-s	LUCC, systems science and computer simulation	Good at dealing with different spatial scales based on empirical data	Focus on local equilibrium analysis	Land use allocation on multiple spatial scales
Cellular automata	LUCC, systems science and computer simulation	Simplifies complex problems by bottom-up modeling and can simulate complex discrete systems	Difficult to solve the problem of spatial heterogeneity and lacks explanation of the mechanism	Urban sprawl and land use change
Multi-agent system	Artificial intelligence and complexity science	Compensates for the neglect of policy factors and explains land use change processes	Research space is abstracted as homogeneous and model validation is difficult	Policy-driven urban sprawl and land use change

Dynamic simulation methods have many shortcomings: (1) Combining or integrating methodologies is difficult and it is hard to simulate the multi-scenario, multi-scale, multi-factor and multi-agent. (2) Many research results are limited to qualitative analysis because of a lack of systematic quantitative analysis and simulation methods for cross-scale coupling. (3) Because the development of interactive decision support systems is in the feasibility stage, there is a lack of developed products and few technical services in planning departments. (4) It is difficult to obtain urbanization and eco-environment coupling data, especially primary data.

We must unify simulation technology and encourage data sharing, develop linked dynamic simulation technology and interactive decision support systems, and build databases that support big data. These activities will accelerate the transition from theoretical research to practical dynamic simulation and thus provide decision support for regional sustainable urbanization.

4 Progress in applications of dynamic simulation of urbanization and eco-environment coupling

The case studying areas of different types, multiple elements, telecoupling and cross-scaling are involved in the applications; therefore, they determine how to represent regional differences, identify the main control elements, and emphasize cross-scale coupling.

4.1 Different types of areas

There have been many studies at national and provincial scales. For example, Roberts (1994) argued that the expansion of urban populations led to the environmental crisis, low rural productivity, wealth concentration, and disruption of urban zoning in developing countries. Liu *et al*. (2005) studied the processes of urbanization and eco-environment coupling in China and found that the stress of urbanization on the eco-environment and the constraints of the eco-environment on urbanization are coterminous. Zhang and Jiao (2015) considered that urbanization and eco-environment coupling in China is at a running-in stage; that coordination in the eastern region is better than in the central and western regions. Tan *et al*. (2015) quantified the changing spatio-temporal processes of urbanization and eco-environment coupling in Jilin province from 2000 to 2012 and found urbanization and eco-environmental changes were highly coordinated because of the implementation of the *Northeast Area Revitalization Plan*. Spatial differences exist among areas of urbanization and areas of the eco-environment because of different geographical features suggest that different types of area should be analyzed separately.

(1) Urban area. Two methods are commonly used in studying urban areas. The first method is to study individual cities. Hayashi *et al*. (1994) compared London, Tokyo, Nagoya and Bangkok and showed that an urban transport system leads to increased energy consumption and environmental degradation. Wilby and Perry (2006) used London as an example to show that urban green space planning can reduce the effects of urbanization on reducing biodiversity and environmental quality. Zhang *et al*. (2015) used the ARDL model to investigate the relationship between urbanization and carbon emissions in Beijing from 1980 to 2013 and found that urbanization had a significant impact on carbon emissions in both the short and long term. He *et al*. (2017) simulated urbanization and eco-environment coupling processes in Shanghai from 1980 to 2013 and found that it could be represented in an S-shaped curve.

The second method is to study urban agglomerations. An urban agglomeration is an important region which competes internationally in terms of trade and industry, while it faces severe resource and environmental constraints (Fang *et al*., 2017). Wang *et al*. (2014) used an interactive coercing model (ICM) followed by a dynamic coupling coordination degree model (DCCDM) to represent the relationship between urbanization and eco-environment in the Beijing–Tianjin–Hebei urban agglomeration; they found that it could be represented in an inverted U-shaped curve. Zhao *et al*. (2016) found that urbanization and eco-environment coupling in the Yangtze River Delta urban agglomeration from the improved environmental Kuznets curve model (EKC) with the dynamic coordination coupling degree model (CCD) could be represented in an S-shaped curve.

(2) River basin. In the area of a river basin, water resources, the hydrologic environment and water ecology all bear importantly on the economic and social system; therefore, the interaction between the hydrological system and the urbanization pattern is significant (Yuan *et al*., 2012). Fang and Bao (2004) simulated the development of the water–ecology–economy complex system in the Heihe River Basin and suggested the WEE scheme to manage coordinated development of the basin. Zhang *et al*. (2010) simulated the collaborative development of the human–land system in the Weihe River basin from 1996 to 2006 and found that it conformed to the S-shaped curve. Yang and Tong (2013) simulated the spatio-temporal coupling processes of the economy–water environment system in the Songhua River Basin from 1991 to 2010 and found that they showed a nonlinear increasing trend. Guo and Xu (2013) simulated the interactive coupling processes of urbanization and eco-environment in the Huaihe River basin using fuzzy matter–element analysis and found that they had a good synergistic effect. Du (2014) simulated the spatio-temporal coupling of water resources and the economy in Dongting Lake basin from 2002 to 2012 using the gray relational degree model and inferred that they were in the coordination stage.

(3) Arid area. An arid area is ecologically fragile; therefore, urbanization is strongly constrained by resources and the eco-environment. Qiao *et al*. (2006) investigated the function, trajectory, type and stage of urbanization and eco-environment coupling in an arid area, and found that it was a dynamic process with interactive stress between the parameters. Abdirahman *et al*. (2010) investigated the sustainability of the water–economic–social system in the Qiemo Oasis. Dong *et al*. (2013) used a VAR model to simulate the spatio-temporal processes of urbanization and water–land resources coupling in an oasis on the northern slope of Tianshan Mountains and found that urbanization leads to increased water consumption. Tang *et al*. (2014) analyzed the response relationship between urbanization and water resources in Zhangye and found that the processes move towards synergy.

(4) Mountainous area. Mountains are usually categorized as restricted or forbidden development zones in the major function-oriented zoning categories, exemplifying the dilemma between development and protection. Wang *et al*. (2014) simulated the spatio-temporal development of vegetation cover over hilly terrain in southern China from 2000 to 2010 and found that human activities and climate jointly influenced the change of NDVI. Wang *et al*. (2016) quantified the ecological risk index for Jinlinwan in Qujing and found that the layered gradient mode of development would increase the ecological risk. Wen *et al*. (2016) quantified the vulnerability of a social–ecological system (SES) in Qinling Mountains from 1997 to 2013 and created a plan to control development for many adaptation targets.

4.2 Multi-element coupling and control

The urbanization and eco-environment coupling are considered as a complex unity of many elements by us via systems science and complexity science. Zhang and Jiao (2015) divided the urbanization system into population, space, economy and society; the ecosystem was divided into environmental pollution and environmental treatment. Zhang *et al*. (2016) divided the urbanization system into urbanization level and urbanization efficiency; the eco-environment system was divided into eco-environment level, eco-environment pressure and eco-environment protection using an efficiency-level theory. The process of urbanization and eco-environment coupling can be regulated by identifying the key controlling factors from the analysis of multi-element coupling and control.

(1) Water resources are important influence factors on urbanization. The demand for water resources from urbanization is direct and necessary; however, the population size and the scale of production should be maintained within the carrying capacity of available water resources. The hydrological system also affects urbanization patterns and processes (Bao and Chen, 2015). Varis and Somlyody (1997) quantified the contribution of water resources to urbanization to investigate the driving forces of urbanization in the Third World; therefore, identified water is a key variable in the process. Srinivasan *et al*. (2013) examined the vulnerability of the urban human–water system in a developing country; they took Chennai as an example, and found that the system dynamics, variability and spatial dependence were the most influenced vulnerability. Mcdonald *et al*. (2014) found that 78±3% of the total global surface water went to big cities; however, the demand for water resources was still significant. In arid areas, the influence of water resources on urbanization is more decisive (Zhang *et al*., 2012).

(2) Land resources also constrain urbanization. Current studies tend to regard urbanization as requisitioning the landscape; it is mainly manifested in the transformation from natural, rural and other regional landscapes to urban landscapes, accompanied by dynamic changes in land use types and landscape fragmentation (Antrop, 2004; Weng, 2007). Land resources provide space and resource support for urbanization; therefore, a lag in land development will lead to low land use efficiency and adversely affect urbanization. In China, coordination between population urbanization and land urbanization has become a hotly-debated topic. Li (2013) explained that the reason why China's population urbanization lags behind its land urbanization is that, there is the joint effect of the rapid expansion of land use, increasingly available land finance and control of household registration. Lv *et al*. (2016) quantified coordination between population urbanization and land urbanization in Nanchang from 2002 to 2011 and found that population lag has replaced land lag.

(3) Some researchers have investigated landform as a stressor of urbanization. Over 50% of Chinese cities and towns are situated in mountainous areas; therefore, mountain urbanization is a major concern (Li, 1998). Topography, geomorphology and related geological events or disasters are important stressors of mountain urbanization when compared with plains, basins and coastal zones. The Three Gorges Project provides an example. Zhang *et al*. (2011) analyzed the spatio-temporal changes in urbanization patterns over the Three Gorges Reservoir area before and after the project; they concluded that the Three Gorges Project destroyed the integrity of existing urban space, but created a balanced urbanization pattern in the region. Cao and Xiao (2013) argued that urban functions and forms and the organization and structure of road networks need to follow the mountain landform. Han and Zhang (2017) used the Entropy–TOPSIS model to identify the coupling relationship between ur-

banization and geological disasters in China and found that they tended gradually to coordinate.

(4) Some researchers have created comprehensive bearing capacity quantification models that incorporate the main drivers. Zhang *et al*. (2016) quantified the coupling relationship between urbanization and eco-environment carrying capacity in Chongqing from 2000 to 2012 and concluded that urbanization led to increased pressure on the regional eco-environment. Liu *et al*. (2016) quantified the response relationship among natural resources and environment carrying capacity and urbanization in Shandong Province from 1991 to 2014; they found that it transitioned from positive to negative. Chi *et al*. (2017) studied the natural resources and environment carrying capacity for urbanization in the Miaodao islands and concluded that a critical state had been reached.

4.3 Local coupling and telecoupling

The introduction of a telecoupling framework extends the coupling scale into many dimensions such as time, space and organization. Eakin *et al*. (2014) examined the external effects of telecoupling between society and ecology on a land system. Using the teleconnection framework, Deines *et al*. (2016) analyzed the sustainability of the teleconnection of an overseas water source to the urban water supply in Beijing and found that it reduced risk to the water supply. Lenschow *et al*. (2016) argued that teleconnection between social ecosystems brings risks to globalization and that global governance should be strengthened. Quan *et al*. (2016) quantified that the ecological risks of inter-basin water diversion using the IBWTPS model and concluded that the best way to strengthen ecological security is to share information. Hulina *et al*. (2017) studied the effects of global population migration on biodiversity and found that they cascaded into other systems such as tourism, land use, and climate change. Fang and Ren (2017) simulated dynamic changes in locally coupled and telecoupled elements in the Beijing–Tianjin–Hebei urban agglomeration from 1980 to 2015, using the framework of urban energy metabolism, to provide a scientific basis for coordinated development.

Recently, cross-regional economic cooperation, cultural exchanges, trade, commuting and pollution have become increasingly prominent concerns; therefore, they lead the government, business and public sectors to pay more attention to regional collaborative development. Li and Liu (2014) analyzed the coordinated development processes of the regional economy in China from 1992 to 2011, using the Haken model, and found that regional economic relations and industrial categories replaced regional comparative advantages as economic drivers. Bo and Chen (2015) argued that there were three obstacles to the coordinated development of the Beijing–Tianjin–Hebei region: the reduction in industrial diversity, a huge development gap, and lack of governance processes. Fang (2017) investigated the regularity of coordinated development in the Beijing–Tianjin–Hebei urban agglomeration and found that it was a nonlinear increasing spiral process.

4.4 Applications review

The application of the results of simulation is mainly focused on three components: multiple-case regions; multiple elements, local coupling, and telecoupling; and regional synergy. (1) The types of areas used in cases are diversified, and much attention is given to urban agglomerations. The areas used as cases include urbanization areas, river basins, arid regions and mountainous areas. Research covers theoretical research, empirical demonstration and observation, process analysis, and decision support for urban agglomerations provided by urbanization and eco-environment coupling. (2) The trend for unifying multiple elements is significant; therefore, the main driving elements have been comprehensively identified. As systems science and complexity science continue to develop and their use grows, increasing numbers of studies have shown that urbanization and eco-environment coupling is a complex unification of many factors. (3) Local coupling and telecoupling are both of interest. International research has shifted to spatial scales, while domestic Chinese research has paid more attention to regional collaborative development.

We also found some drawbacks. (1) The identification of the main driving elements ignores system dynamics. Many studies only consider spatial differences, but it is necessary to understand regularity, trends, and dynamics. (2) The complete chain of relationships and processes in urbanization and eco-environment coupling has not been identified. Fragmented applications (those that consider some, not all) do not fully reveal the complete chain of relationships. (3) Telecoupling simulation focuses on micro cases such as cross-border tourism, energy trading, urban security, ecological risk, and species invasion; however, telecoupling simulation is not quantified, lacks systematic unity and is disconnected from regional application.

In the future, we must take national strategy and responses to global change as goals, and show the local coupling and telecoupling relationships identified by the simulations in key areas such as urban agglomeration. On the other hand, we must also emphasize the dynamic nature of the driving elements, as well as the scientific basis of the coordination strategy, and thus promote the application of research into aspects of systems behavior such as inflection point identification, threshold definition, dynamic simulation and monitoring, and risk warning and response.

5 Review and prospects

There is a complex nonlinear interactive coupling between urbanization and the eco-environment. Science is the key to accurately simulating this complex dynamic relation. Systems science and cross-scale coupling theory allow us to define the coupled urbanization and eco-environment system as an open complex giant system with multiple feedback loops.

We reviewed the current literature for dynamic simulation of urbanization and eco-environment coupling. (1) As dynamic simulation becomes more popular, theory and analysis have been improved. Studies of urbanization and eco-environment coupling refer to and improve the environmental Kuznets curve (EKC), showing relationships that can be represented by inverted U-shaped or S-shaped curves. (2) Dynamic simulation technologies have become more diversified, refined, intelligent, and integrated. Improved simulation technologies based on SD, artificial intelligence and land use and land cover change models are being rapidly developed, leading to increased use and development of simulation technology for unified systems. (3) Current simulations are used mainly for three aspects: multiple regions and multiple elements, local coupling and telecoupling, and regional synergy. However, we also found some shortcomings: (1) The development and unification of basic theories are inadequate; (2) The methods of unifying separate systems and transferring data among them are not as advanced as they might be; and (3) The coupling relations and the dynamic characteristics of the main driving elements have not been fully identified. Moreover, telecoupling simulation does not quantify and is not systemically unified; therefore, it cannot be used to model spatial synergy transference.

In the future, we should promote the development of complex systems theory, cross-scale coupling theory and other new theories; therefore, the benefits of cross-disciplinary research into the unified human–nature system should be realized; thus we should form a multi-disciplinary research network for urbanization and eco-environment coupling. We must also promote the unification of simulation technology and data transfer, develop unified dynamic simulation technology and interactive decision support systems, and build database support for big data. Eventually, we should identify the local coupling and telecoupling relationships; thus we promote the application of research into topics such as inflection point identification, threshold definition, dynamic simulation and monitoring, and risk identification and response.

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