

# A proposal for the theoretical analysis of the interactive coupled effects between urbanization and the eco-environment in mega-urban agglomerations

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**Abstract:** Mega-urban agglomerations are strategic core areas for national economic development and the main regions of new urbanization. They also have important roles in shifting the global economic center of gravity to China. However, the development of mega-urban agglomerations has triggered the interactive coercion between resources and the eco-environment. The interactive coupled effects between urbanization and the eco-environment in mega-urban agglomerations represent frontier and high-priority research topics in the field of Earth system science over the next decade. In this paper, we carried out systematic theoretical analysis of the interactive coupling mechanisms and coercing effects between urbanization and the eco-environment in mega-urban agglomerations. In detail, we analyzed the nonlinear-coupled relationships and the coupling characteristics between natural and human elements in mega-urban agglomerations. We also investigated the interactive coercion intensities between internal and external elements, and the mechanisms and patterns of local couplings and telecouplings in mega-urban agglomeration systems, which are affected by key internal and external control elements. In addition, we proposed the interactive coupling theory on urbanization and the eco-environment in mega-urban agglomerations. Furthermore, we established a spatiotemporal dynamic coupling model with multi-element, multi-scale, multi-scenario, multi-module and multi-agent integrations, which can be used to develop an intelligent decision support system for sustainable development of mega-urban agglomerations. In general, our research may provide theoretical guidance and method support to solve problems related to mega-urban agglomerations and maintain their sustainable development.

**Keywords:** mega-urban agglomeration; urbanization; eco-environment; interactive coupled effects; coupling theory; process of theoretical analysis

A mega-urban agglomeration usually refers to a cluster of cities, including a core megacity and at least three large cities, as the basic components in a specified area. The cit-

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ies comprising a mega-urban agglomeration are compact in geography and closely connected in economy, which relies heavily on well-developed infrastructure networks such as transportation and communication. Ultimately, high levels of integration are achieved among cities in mega-urban agglomerations (Fang *et al.*, 2010; Fang and Yu, 2017). Currently, integration in mega-urban agglomerations focuses on six regions that include regional industrial development, infrastructure construction, establishment of regional market, overall planning and construction of urban and rural areas, environmental protection and ecological construction, and social development and basic public services. In regard to urban integration, a mega-urban agglomeration is not bound by administrative divisions, and it will develop into an economic community as well as a community with shared interests in administrative regulation, industrial network, rural and urban planning, transportation network, information sharing, finance, market, technology development, environmental protection and ecological construction (Fang *et al.*, 2011a; Fang and Mao, 2015). As such, mega-urban agglomerations have reached the advanced stage of industrialization and urbanization. When an urban agglomeration has an area greater than 50,000 km<sup>2</sup>, a population exceeding 50 million and a national economic proportion of more than 10%, it can be defined as a mega-urban agglomeration. China is currently forming the “5+9+6” urban agglomeration spatial pattern. The 5 mega-urban agglomerations include Yangtze River Delta agglomeration, Pearl River Delta agglomeration, Beijing-Tianjin-Hebei agglomeration, middle reaches of Yangtze River agglomeration and Chengdu-Chongqing agglomeration. These agglomerations occupy 9.06% of the total area in China. Their urban population accounts for 45% of the total population in China. Their combined gross domestic product (GDP) was half of China’s GDP in 2013. The fixed assets investment in these regions is 60% of the total domestic fixed assets investment and 65% of the total foreign investment in China.

## **1 Theoretical value of the study on the coupled effects of urbanization and the eco-environment in mega-urban agglomerations**

Mega-urban agglomerations are strategic core regions for national economic development and the main regions of new urbanization, which play important roles in shifting the global economic center of gravity to China (Fang, 2014a). However, these regions have been facing increased coercion between resources and the eco-environment in their development. In order to reduce coercion and improve the quality of urban development, China has proposed to take a green, low-carbon, efficient and intensive urban development path that can match the carrying capacity of resources and the environment (Wang, 2016; Tan, 2017). Therefore, the study of coupling mechanisms and interactive coercing effects between urbanization and the eco-environment in mega-urban agglomerations not only represents frontier and high-priority research topics in Earth system science over the next decade, but will also meet the urgent need to provide an important scientific basis for systematically formulating national strategies related to sustainable development of mega-urban agglomerations.

### **1.1 Interactive coupled effects between urbanization and the eco-environment in mega-urban agglomerations represent frontier research in Earth system science over the next decade**

Based on the analysis of international frontier research, the study of the coupled effects between urbanization and eco-environment represents key research topics in Earth system sci-

ence and sustainability science over the next decade (Kates *et al.*, 2001; Clark, 2007; Reid *et al.*, 2010). This is because global acceleration of urbanization is posing actual or potential threats to surrounding eco-environments. As early as 1991, the World Health Organization (WHO) identified two major problems facing the world today, which included the deterioration of the natural environment and the rapid decline in the quality of life in urban environments, and the critical impact of urbanization on global environmental changes and its potential to threaten human survival. In 1995, Wally Ndow, the Assistant Secretary-General of the United Nations, issued a warning in “An Urbanizing World” that “Urbanization may provide an unexampled bright prospect for the future, but also may be a knell for an unprecedented calamity, and our future is decided by what we do nowadays.” (Fang *et al.*, 2008; Habitat U, 1996).

In 2005, the International Human Dimensions Programme on Global Environmental Change (IHDP) developed an “Urbanization and Global Environmental Change” research plan. It was the core project of global change research, which focused on studies to strengthen the coupled relationship between urbanization and global environmental change through spatiotemporal scale crossing, spatiotemporal scale comparison and communication between policy makers and the public. The Future Earth (FE) program released in 2012 is a 10-year international research initiative designed to help society respond to the challenges of global change, and to gain key knowledge and explore opportunities for global sustainable transformations. In this project, urbanization is regarded as the most intense human activity on Earth’s surface, and the threshold, risk and critical point of urbanization are the frontier research topics. In April 2014, the committee on New Research Opportunities in the Earth Sciences (NROEC) at the National Research Council (NRC) of the U.S. National Academies highlighted 7 high priority Earth sciences research fields in the next decade in their publication (“New Research Opportunities in the Earth Sciences”). The 6th research topic is “coupled hydrogeomorphic-ecosystem response to natural and anthropogenic change”. The committee believes that humans are altering terrestrial ecosystems through agricultural activities and urbanization (CNROES, 2014) at the National Science Foundation, 2014). In November 2014, the Science and Technology Alliance for Global Sustainability released “Future Earth 2025 Vision”. The building of healthy, resilient and productive cities was one of the 8 key focal challenges proposed in the “Future Earth” research plan.

## **1.2 Mega-urban agglomerations are the new regional units for our nation to participate in global competition and international division of labor, which play important roles in shifting the global economic center of gravity to China**

In the accelerated processes of global urbanization and economic globalization, the rapid expansion of urban agglomerations has become an irresistible trend. With adequate industrial aggregation and economic size, urban agglomerations participate in the global re-division of labor, competition, communication and cooperation, and thus form a strong economic community as well as a community of shared future. According to the United Nations prediction, the proportion of global urban population will exceed 75% of the total population by 2050. Meanwhile, the 40 largest metropolitan areas in the world, which occupy a very small area of the Earth’s surface, are projected to contain 18% of the world’s population. These areas will also participate in 66% of the global economic activities and

account for approximately 85% of technological innovations. Additionally, it was stated in the latest *World City Report* that the world's metropolitan areas are gradually growing even larger into mega-metropolitan areas and mega-urban agglomerations. It is therefore clear that in the era of globalization and informatization, mega-urban agglomerations, the hub for China's entry into the world and the portal for the world's entry into China, heavily influence China's international competitiveness, and will affect the new pattern of global politics and economics in the 21st century. Compared to the most developed mega-urban agglomerations in the world, such as the Atlantic coast region in the northeastern United States, the Great Lakes area of the United States, northwestern Europe, along the Pacific coast of Japan and the London agglomeration in the United Kingdom, the level of development, and the degree of resources and environmental protection in China's mega-urban agglomerations are relatively low. China's mega-urban agglomerations are also regions with the most severe haze pollution and other environmental pollutants. This is due to comparatively lower regional economic gross than the most developed mega-urban agglomerations, and heavy environmental pollution and serious ecological problems. As such, it is necessary to reveal the interactive promotional and coercing relationships between urbanization and the eco-environment in China's mega-urban agglomerations from an international perspective. Subsequently, this will provide scientific support for resources and eco-environmental protection in the development of healthy and productive agglomerations.

### **1.3 Mega-urban agglomerations are the “main areas” of China's new urbanization and the “core regions” of domestic economic development**

In regard to national strategic needs, the first Central Urbanization Work Conference held in December 2013 and the “National New-type Urbanization Plan (2014–2020)” released in March 2014 both stated that urban agglomerations are the main regions for promoting new types of urbanization. Both the plans, “11th Five-Year Plan” (2006–2010) and “12th Five-Year Plan” (2011–2015), also emphasized that urban agglomerations are the main regions for advancing new urbanization. Moreover, the 17th and 18th National Congress of the Communist Party of China has considered urban agglomerations as the new economic growth core for over a decade, and clearly reinforced that the size and layout of an urban agglomeration should be determined on the basis of appropriate scientific planning and match its resources and environmental carrying capacity. In the “National New-type Urbanization Plan (2014–2020)”, urban agglomeration was mentioned 50 times. According to available statistics, the total area currently comprising China's urban agglomerations accounts for only 20% of the total area in China. However, 60% population, 80% economic gross, 70% fixed asset investments and 98% foreign capitals of the entire country are concentrated in these regions. The five national mega-urban agglomerations in the Yangtze River Delta, Pearl River Delta, Beijing-Tianjin-Hebei, middle reaches of Yangtze River and Chengdu-Chongqing regions only comprise 9.05% of the total area, while they collectively account for 45% urban population, 50% economic gross and 60% foreign capitals of the entire country. Thus, mega-urban agglomerations are the main regions of China's new urbanization and core regions of domestic economic development, and as such, these regions will determine the future of new urbanizations and lead economic development in China (Fang, 2014b).

#### **1.4 With high-density aggregation, high-speed expansion, high-intensity pollution and high risk characteristics, mega-urban agglomerations represent areas “most severely affected” by critical urban and eco-environmental issues, and their development has significantly threatened resources and the environment**

Regarding practical problems and in the context of long-term extensive economic development patterns, mega-urban agglomerations are and also will be the most active and the highest potential areas of current and future economic developments in China. On the contrary, they are also areas that are extremely sensitive and severely affected by highly concentrated and intensified eco-environmental problems. According to the available statistics, industrial wastewater discharges, industrial waste gas emissions and industrial solid waste productions in China's agglomerations are all greater than 67% of the domestic totals. From the facts stated above, it is clear that although urban agglomerations account for over 75% of total domestic economic outputs, they also produce over 75% of the total pollution outputs, which consequently overload the environments of the agglomerations. Large areas of haze pollution have frequently covered all the urban agglomerations in the eastern coastal and northeastern China, which reflect the emerging issue of environmental pollution in urban agglomerations (Liu *et al.*, 2017). In particular, mega-urban agglomerations are exhibiting the “four-high and four-low” problems and have become sensitive and problematic regions with pronounced urban and eco-environmental problems. “Four-high” refers to unsustainable high-density aggregation, high-speed expansion, high-intensity pollution and high-risk threats (Wu *et al.*, 2015; Chauvin *et al.*, 2017). “Four-low” refers to the low level of resources and environmental protection, low level of development, low compact level and low input-output efficiencies (Fang *et al.*, 2008; Fang and Guan, 2011; Fang and Liu, 2011). In the process of selection and incubation of urban agglomerations, a disregard for resources and eco-environmental carrying capacity has been a persistent issue. Meanwhile, some urban issues need to be urgently addressed such as the unscientific planning and expansion, inclusion of cities that do not meet the inclusion standard and simply grouping cities together to form an agglomeration (Fang, 2015).

#### **1.5 Studies on the interactive coupled effects between urbanization and the eco-environment in mega-urban agglomerations are at an early stage, and much is still required to urgently meet the national need**

From the overview of the current domestic and foreign research on the interactive coupling mechanisms of urbanization and the eco-environment, and the effect of urbanization on resources and environmental protection in urban agglomerations, it is apparent that current research focus is on the resources and ecological issues induced by agglomerations aggregated at a high density (Fang *et al.*, 2016). In addition, theoretical studies to investigate the interaction between high-density agglomerations and resources and environment have gradually garnered attention from researchers. Meanwhile, field studies on the impact of high-density agglomerations on the eco-environment and its systemic regulations have been carried out in some areas (Hummel *et al.*, 2013; Cao *et al.*, 2017). Moreover, quantitative studies aimed at quantifying the resources and environmental carrying capacity in urban agglomerations aggregated at high density have just started. Lastly, research on the coordinated

development of industrial aggregates and the eco-environment in urban agglomerations has gradually drawn interest from researchers. However, in the overview of the current studies on urban agglomerations, the research has primarily focused on its spatial expansion, economic development, spatial structure and morphology. Not much has been done to investigate the coupling mechanisms of urbanization and the eco-environment in urban agglomerations, and the systemic regulations to protect resource and environmental dynamics. Moreover, the depth of these studies was not sufficient (Liu *et al.*, 2007).

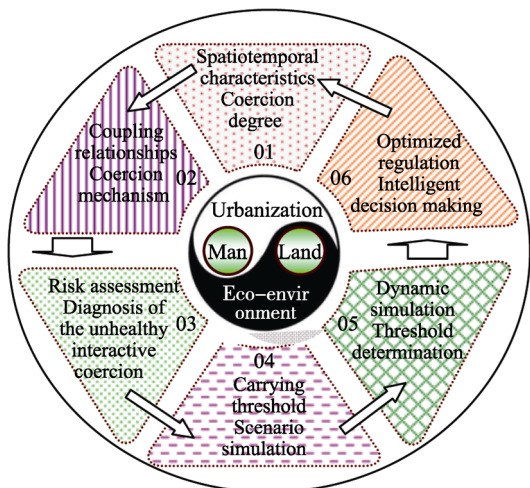
### **1.6 It is impossible to study the development of mega-urban agglomerations within a single discipline due to its extreme complexity, and therefore, interdisciplinary research is urgently needed to advance the study of human geography to the next level**

In regard to discipline development, mega-cities and mega-urban agglomerations have been the focus of urban geography following the initiation of globalization. With the accelerated process of urbanization, traditional urban geography is not sufficient to reveal the cross-city, cross-boundary, cross-field, cross-disciplinary and even cross-country characteristics of mega-urban agglomerations. The basic functions of cities have exceeded the traditional social and economic functions, and have started to interact with eco-environments more frequently. A series of complete urban planning cases have taken practical strategies to prioritize the resources and eco-environment carrying capacity based on the principle of “negative planning”. Overall, a new theoretical framework for human geography is urgently needed to promote its development as a discipline, which in return will guide and satisfy the emerging need for urban development.

## **2 Theoretical analysis of the interactive coupled effects between urbanization and the eco-environment in mega-urban agglomerations**

In regard to theoretical analysis, how do we identify the key control factors in the interactive coercion between urbanization and eco-environment in mega-urban agglomerations by means of advanced methods such as remote sensing, geographic information system (GIS) and sensor networks (Kramer *et al.*, 2017)? How do we quantitatively describe the interactive coerced nonlinear coupled relationships and the status of these couplings between all the natural and human elements in general? How can we identify internal and external elements, and further quantitatively reveal the local coupling and telecoupling mechanisms among the interactive coerced internal and external elements in mega-urban agglomerations? Is it possible to quantify the patterns of these interactive couplings between internal and external elements in mega-urban agglomerations? How do we identify the bottom line of coercion on eco-environments from cities of different sizes and different types of industries in mega-urban agglomerations? How can we identify the limit of urban expansion and industrial development that can be tolerated by the eco-environment? How do we scientifically evaluate the unhealthy status and uncertainty risk of the interactive coercion between urbanization and eco-environment in mega-urban agglomerations, and further decide the urbanization thresholds and reverse compute the protective level of resources and environment using GIS, integrated modeling and big data analysis? In order to answer these questions, we need a scientific proposal. As such, we constructed a logic framework for the theoretical

analysis of interactive coupling between urbanization and the eco-environment in mega-urban agglomerations (Figure 1).

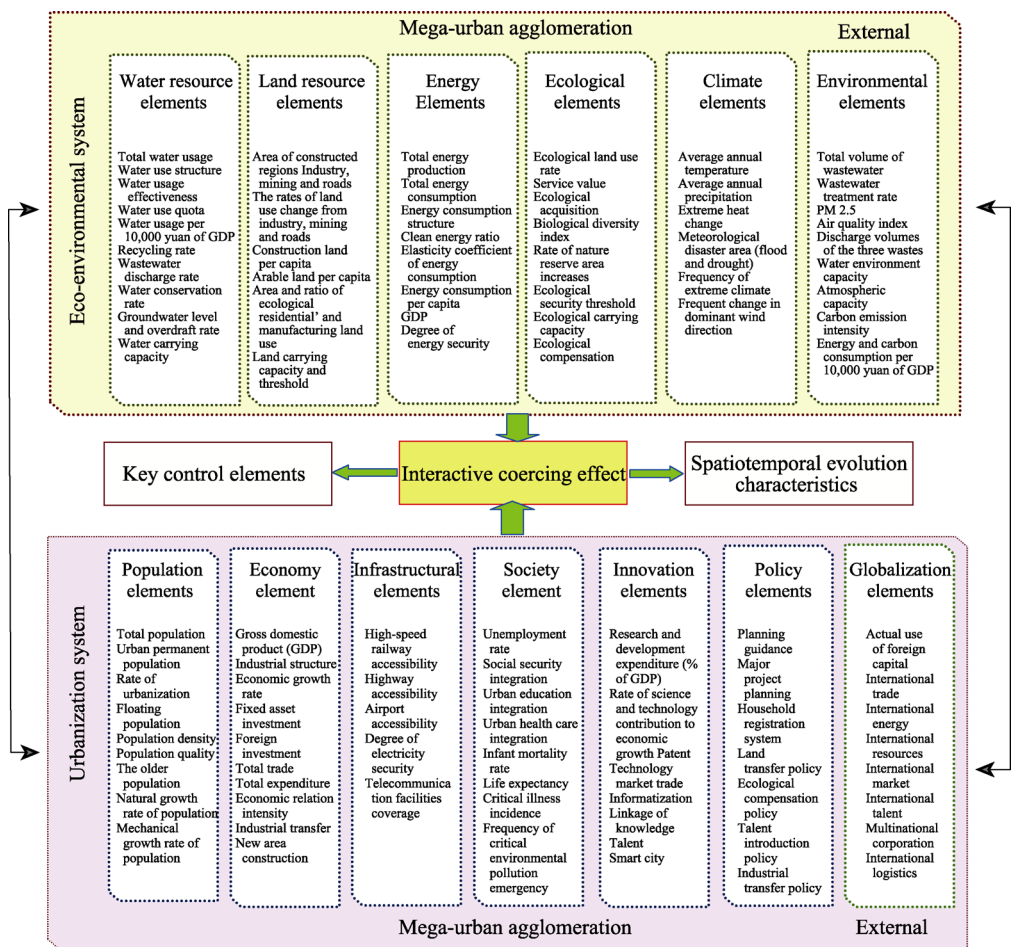


**Figure 1** Schematic diagram of the logic framework of coupled effects

### 2.1 The key control elements and the spatiotemporal evolution characteristics associated with the interactive coercion between urbanization and the eco-environment

Our overall aim is to reveal the key control elements and spatiotemporal evolution characteristics of the interactive coercion between urbanization and the eco-environment in mega-urban agglomerations. Using advanced techniques such as remote sensing, GIS and sensor networks, we will perform systems analysis and spatial statistics to investigate the general dynamic characteristics of natural elements (water, soil, energy, ecology, climate and environment) and human elements (population, economy, society, infrastructure, policy, innovation and globalization). In detail, our objective is to reveal the coercion relationships between resources and the eco-environment, and the characteristic index of urbanization. Moreover, we also want to identify the supportive and restrictive effects of regional resources and eco-environmental elements on urbanization. Furthermore, through screening for key control elements, we will unveil their spatiotemporal evolution characteristics and interactive coercing effects on the eco-environment.

(1) To reveal the dynamic evolution characteristics of the coupled system between urbanization and the eco-environment, and of the responding indices in mega-urban agglomerations. At the county scale, we will identify spatiotemporal evolution characteristics of natural and human elements, and of the responding indices (Figure 2). Natural elements include land resource, water resource, energy, ecology and environment. Human elements refer to population, economy, infrastructure, society, innovation and policy. Meanwhile, in order to further reveal the various natural and human coercing effects, we will analyze the natural and human characteristics of agglomerations. Natural characteristics of agglomerations will include severe water and land shortages, severe pollution, high ecological sensitivity and risks, and high PM<sub>2.5</sub> concentrations, while human characteristics of agglomerations will include high-speed economic growth, high-intensity economy, high population density, major regions of urbanization, concentrated domestic and foreign capital invest-



**Figure 2** Schematic diagram of urbanization and eco-environmental elements, and the responding indices in mega-urban agglomeration (U and C are parameters respectively.)

ments, concentrated import and export trades and highly accelerated urbanization.

(2) To analyze the spatiotemporal coupling characteristics between urbanization and the eco-environment in mega-urban agglomerations. First, based on the socioeconomic statistics over the years and spatial comparison analytic methods, we will analyze the dynamic change curve of the interactive promotional and coercing relationships of man-water, man-land, man-carbon, man-climate, man-energy, man-housing, man-biology and man-pollution in mega-urban agglomerations. In general, we want to further reveal the spatiotemporal evolution characteristics of the interactive coercion between human-centered urbanization and water-land-biology-centered eco-environments in mega-urban agglomerations. Second, we can elucidate the temporal characteristics in different periods and the spatial heterogeneity patterns of the interactive coercion relationships between urbanization and the eco-environment, which are driven by different factors in mega-urban agglomerations. Third, by applying structural equation modeling, we can quantify the supportive effects of resources and environmental elements on urbanization, and identify the advantageous aspects of resources and the environment, which promote urbanization. Lastly, we can quantitatively recognize the various restrictive effects of spatially different resources and environments on



urbanization.

(3) To screen for key control elements in the interactive coercion between urbanization and the eco-environment, and their coercing effects. Based on the long-term socioeconomic data series, and resources and environmental survey data, we will use grey relational analysis, cluster analysis and principal component analysis to identify key internal and external control elements and their thresholds, which will have the most significant impact on the interactive coercion between urbanization and the eco-environment.

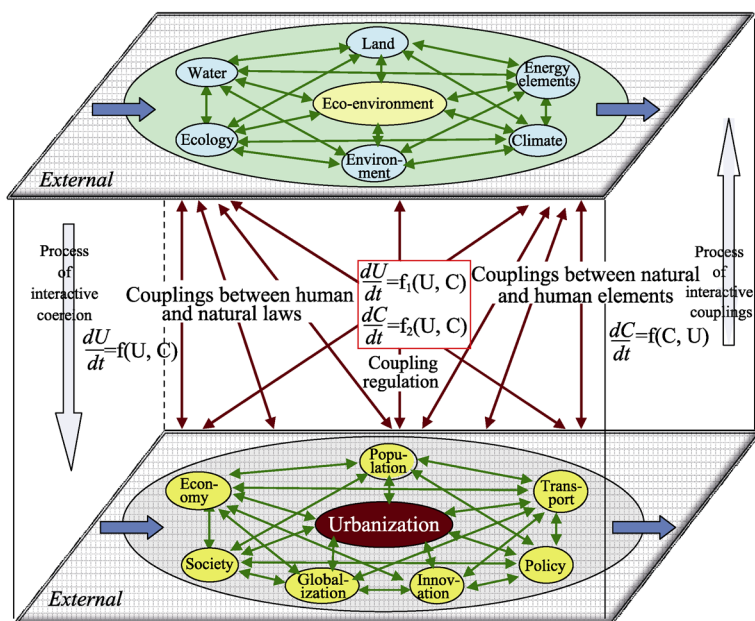
We will further identify the interactive coercion of the key internal and external control elements, construct the interactive coupling matrix, analyze the intensity of interactive coercions, quantify the spatiotemporal coercing characteristics of key control elements and reveal the ecological effects of the interactive coercion of key control elements in different urbanized areas, unveil the spatiotemporal evolution characteristics of key control elements and the interactive coerced eco-environmental effect, and provide fast and slow key control elements to regulate the interactive coercing threshold between urbanization and the eco-environment in mega-urban agglomerations and to assess potential risks to resources and the eco-environment during urbanization (Fang and Wang, 2013).

## **2.2 Interactive coerced local coupling and telecoupling mechanisms, and the pattern of interactive coercing effects between urbanization and the eco-environment**

The urbanization system of mega-urban agglomeration includes 7 elements, which are population, economy, infrastructure, society, innovation, policy and globalization, while the eco-environment system includes 6 elements, which are water resource, land resource, energy, ecology, climate and environment. With respect to inter-regional (external) scale, intra-regional (internal) scale, and the scale of local couplings and telecouplings (Fang and Ren, 2017), we want to explore the interactive coercing and coupled relationships between the mega-urban agglomeration system and the ecosystem ( $Q = \{U, C\} = \{(u_1, u_2, u_3, \dots, u_i), (c_1, c_2, c_3, \dots, c_j)\}$ ) under the influence of internal and external elements. These relationships can be defined as the dynamic coupled relationships between  $U_i$  and  $C_j$ , which will reveal the mechanism, stage, type and coupling pattern of the interactive coerced local couplings and telecouplings between the urban agglomeration system and ecosystem in mega-urban agglomerations.

(1) To reveal the mechanism of the interactive coerced local couplings and telecouplings between urbanization and the eco-environment (Figure 3). Our strategy is to use system coupling models such as correlation analysis, geographical weighted regression (GWR), panel cointegration test, vector error correction model (VECM), KSIM, spatial error model, and spatial lag model to analyze the data generated in the process of urbanization and eco-environmental evolution in mega-urban agglomerations over the past 35 years. At the scales of inter-region, intra-region and coupling, we will explore the mechanism of interactive coercion between urbanization and the eco-environment in mega-urban agglomerations under the influence of internal and external natural and human elements. On one hand, we will perform a “one-to-one” bidirectional analysis of the mechanism of interactive coerced local coupling and telecoupling between a single element of urbanization system and a single element of eco-environmental system, and calculate the interactive coupling coefficient of the element  $U_i$  of urbanization system to the element  $C_j$  of the eco-environmental system.

On the other hand, we will conduct a “many-to-many” multidirectional analysis of the local coupling and telecoupling mechanisms of interactive coercion between urbanization and the eco-environment. We will build a coupling equation of urbanization and the eco-environment ( $UE = f(U_i - C_j)$ ;  $i = 1, 2, 3 \dots, m$ ;  $j = 1, 2, 3 \dots, n$ ) and draw coupling curves of interactive coercion between the urbanization system and eco-environmental system. Our results should provide a quantitative scientific basis to achieve harmonious man-water, man-land, man-energy, man-climate and man-carbon relationships.



**Figure 3** Schematic diagram of the interactive coupling mechanisms between urbanization and the eco-environment

(2) To define the stages and types of interactive coerced local couplings and telecouplings between urbanization and the eco-environment. Based on the study of the interactive coupling mechanisms of single elements and multiple elements, we will construct a model of the dynamic coupling relationships between urbanization and the eco-environment. By using the data generated in the process of urbanization and eco-environmental evolution in mega-urban agglomerations over the past 35 years, we will calculate the coupling degrees of 6 subsystems of the eco-environment and 7 subsystems of urbanization as well as the coupling degree between urbanization and eco-environmental systems. According to the coupling degrees and in reference to the theoretical evolution cycle of the interactive coupling between urbanization and the eco-environment, we can comprehensively evaluate the process, stages and types of couplings between urbanization and the eco-environment in mega-urban agglomerations under the influence of internal and external elements. This evaluation will determine the stages of interactive coercion between urbanization and the eco-environment based on both bidirectional and multidirectional elements, and the types of interactive coercion between urbanization and the eco-environment based on the identification of coupling stages.

(3) To quantitatively reveal the local coupling and telecoupling patterns of the interactive coercion between urbanization and the eco-environment. First, in reference to the research

on mechanisms, stages and types of interactive coercion between urbanization and the eco-environment and the characteristics and laws of subsystems such as water resource, land resource, energy, ecology, climate and environment, we can analyze the coupled boosting effect, coupled reducing effect and coupled constant effect of these subsystems to identify the degree of eco-environment satisfaction to the degree of urbanization demand in mega-urban agglomerations. Second, we can also simulate the dynamic fluctuation process of interactive couplings between urbanization and the eco-environment to reveal the mechanism of stochastic fluctuation in interactive couplings between urbanization and the eco-environment (Fang and Qiao, 2005). Third, we can quantitatively develop the adaptive thresholding algorithm and explore the pattern of interactive couplings between urbanization and the eco-environment (Huang and Fang, 2003; Qiao and Fang, 2006). Fourth, using forewarning methods and forewarning signal models, we can forewarn of potential dangers and report warning signs that are present in the coupling process of urbanization and the eco-environment in mega-urban agglomerations. Lastly, we can also quantitatively unveil the coupling fission law, dynamic hierarchy law, stochastic fluctuations law, non-linear synergetic law, threshold value law and forewarning law of local couplings and telecouplings between urbanization and eco-environmental elements (Fang and Yang, 2006).

### **2.3 Determination of the severity of interactive coercion between urbanization and the eco-environment and risk assessment**

Based on the analysis of the interactive coercion relationships between urbanization and the eco-environment, we can determine the coupling status of key control elements and the interactive coupling status of multiple elements. In addition, we can also identify the degree of dynamic couplings of interactive coercion and the degree of severity of interactive coercion. Furthermore, we can comprehensively evaluate the risks of interactive coercion and build a risk assessment system to predict the severity of interactive coercion between urbanization and the eco-environment in mega-urban agglomerations.

(1) To determine the coupling status of key control elements. Based on the available data, we can separately construct models of interactive coupling status between different single eco-environmental elements and urbanization, including man-water, man-land, man-energy, man-carbon, man-climate and man-ecology relationship (Fang and Bao, 2007). These models can clarify the mutually beneficial or detrimental relationships between urbanization and resources and the eco-environment, and quantitatively express the degree of coercion, synchronicity and dependency, and estimate the trend of the aforementioned coupling status change.

(2) To determine the integrated interactive coupling statuses of multiple elements. Based on the models of interactive coupling status of single elements, we can further establish integrated models of the interactive coupling statuses between urbanization and eco-environmental elements including water, land, climate, energy and carbon in mega-urban agglomerations, and thus create an integrated system of the interactive coupling statuses between urbanization and the eco-environment. Moreover, through multiple approaches, we can analyze the integrated interactive coupling relationships among multiple elements, and quantify the degrees of integrated couplings, coercion and coordination between urbanization and resources and environment (Fang and Xie, 2010; Bao and Fang, 2006; Fang and Sun, 2005). Three analytical approaches include artificial neural network models to determine the inte-

grated interactive coupling statuses of multiple elements, ensemble empirical mode decomposition (EEMD) to analyze the synchronicity between multiple temporal resolutions and the interactive coupling statuses of multiple elements, and computable general equilibrium (CGE) model to define the inherent relationships between urbanization and resources and environmental elements.

(3) To identify the degree of dynamic coupling and the severity of interactive coercion, and comprehensively evaluate the risk of interactive coercion. We can treat a mega-urban agglomeration as a living organism and view its metabolic processes and the ecosystem services provided by the agglomeration as ‘vital signs’. Combined with the degree of coupling of interactive coercion, the severity and causes of “urban agglomeration diseases” can be determined. Specifically, the exergy analysis theory can be introduced into studies of urban agglomeration metabolism (Fang *et al.*, 2017). The net exergy yield rate (NEYR), environment load rate (ELR) and exergy exchange rate (EER) can be used to represent the vitality, structure and resilience of urban systems, respectively. Additionally, based on the simulation of ecosystem services of urban agglomerations, and the results of supply and demand analysis, as well as the structural and functional eco-thermodynamic indices of urban agglomerations, such as metabolic utility, metabolic efficiency, metabolic intensity, metabolic eco-coercion and metabolic environmental impacts, we can comprehensively assess the severity, duration and future trends, and analyze the causes of “urban agglomeration diseases” by establishing the baseline and threshold.

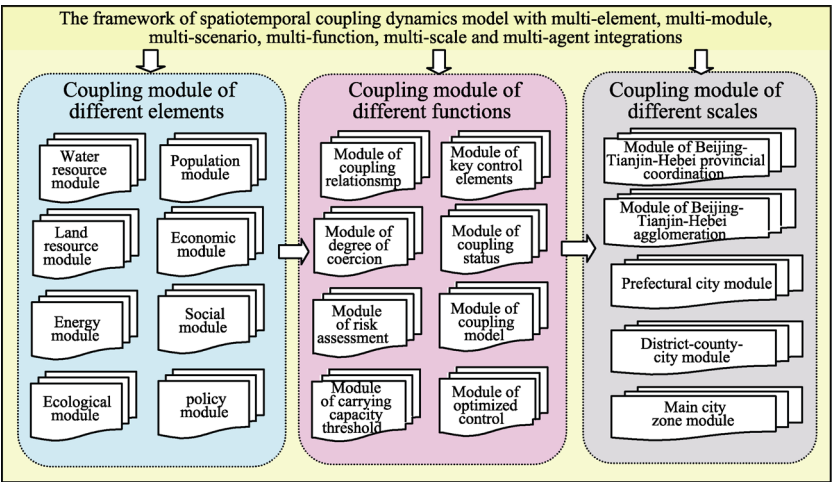
(4) To establish a risk assessment system of the interactive coercion between urbanization and the eco-environment in mega-urban agglomerations. We can view the interactive coercion between urbanization and the eco-environment as the source of risk in an agglomeration, with both living and non-living characteristics. According to the degree and duration of coercion, we can analyze the degree to which an agglomeration is exposed to the coercion. Moreover, based on the urban metabolic analysis from eco-thermodynamics and the supply and demand status of ecosystem services, we can evaluate the health status as well as the vulnerability and the resilience of an urban system. Furthermore, using the Bayesian statistical method, we can decipher the interactive coercion between urbanization and the eco-environment into different types of risks, including social security, resource security and eco-environmental risks, and calculate the probabilities of these risks. Lastly, according to the magnitude and controllable degree of risks in agglomerations, we can establish a forewarning system for real-time monitoring of health status, and forewarn the signs and risks of “urban agglomeration diseases”, and record the long-term health status of urban agglomerations.

## **2.4 The dynamic simulation and elastic threshold of interactive coupling between urbanization and the eco-environment**

In reference to the results of the spatiotemporal characteristics, local coupling and telecoupling mechanisms and patterns, and risk assessment of the interactive coercion between urbanization and the eco-environment in mega-urban agglomerations, and on the basis of the system dynamics model, we can reconstruct a system dynamics model of the interactive coercion between urbanization and the eco-environment in mega-urban agglomerations with multi-element, multi-scale, multi-scenario, multi-function, multi-module and multi-agent integrations. Moreover, we will validate the aforementioned spatiotemporal coupling dy-

namics model, and simulate the thresholds and construct the threshold model of interactive coercion between urbanization and the eco-environment. Consequently, we will build a systematic scientific platform for the quantitative study of urbanization in mega-urban agglomerations. Through adjustments and repeated simulation of critical thresholds, the mid-term to long-term multi-scenario scheme for mega-urban agglomerations can be constructed, which will provide a scientific basis for decision-making to achieve coordinated development of urban agglomerations. Moreover, these critical thresholds can serve as reference parameters for decision-making regarding economic and social development goals, the operation of the economy-population-urban agglomeration system, and the degree of resources and environmental protection in the forthcoming developmental processes of mega-urban agglomerations (Tan *et al.*, 2014; Zhang *et al.*, 2016; Wang *et al.*, 2016).

(1) To construct the system functional modules of interactive coercion between urbanization and the eco-environment. Using models of the carrying capacity threshold and the degree of saturation of ecology-production-life space, we can construct 8 different system functional modules, including water resource and eco-environment, land resource, energy and climate, population and urban system, economic globalization and industrial development, construction and investment of urban and rural areas, transport and logistics, and finally, science and technology innovation, and macro policy. In addition, we can study the core variables and the mathematical expression of each module, use nesting principles to organize these functional modules, and construct a conceptual framework for the dynamics model of the interactive coercion between urbanization and the eco-environment in mega-urban agglomerations (Figure 4).



**Figure 4** The framework of spatiotemporal coupling system dynamics model with multi-element, multi-module, multi-scenario, multi-function, multi-scale and multi-agent integrations

(2) Dynamics analysis of the key control elements in interactive coercion between urbanization and the eco-environment. By means of regression analysis and a macroeconomic model, and using water resource as the key control element, we can construct the functional module of water resource and the eco-environmental system in the presence of interactive coercion between urbanization and the eco-environment. Moreover, using land resource as

the key control element, we will adopt cellular automata (CA) and a multi-agent model to construct the functional module of urbanization and land use change. This model can be used to simulate the expansion of constructional land in mega-urban agglomerations based on single-center, bi-center and multi-center schemes, and to acquire the relevant parameters and threshold of the interaction between land use change and urbanization. Furthermore, the Stochastic Impacts by Regression on Population, Affluence and Technology (STIRPAT) model can be used to simulate the spatiotemporal impacts of quantification of pollutants, affluence and technology on urban energy use and carbon emission, and carry out the life cycle analysis (LCA) of mega-urban agglomerations.

(3) To construct the spatiotemporal coupling system dynamics model with multi-element, multi-scale, multi-scenario, multi-function, multi-module and multi-agent integrations. Based on the existing system dynamics model of urbanization, we will consider key eco-environmental elements, such as water resource, land resource and energy, as the key control elements in the urbanization process of mega-urban agglomerations. Through this approach, we can depict the flowchart of the causal relationship and feedback loop of the spatiotemporal coupling system dynamics model of the interactive coercion between urbanization and the eco-environment with multi-element, multi-scale, multi-scenario, multi-function, multi-module and multi-agent integrations, and we can also reconstruct the aforementioned model.

(4) To conduct computational experiments and determine the threshold of interactive couplings between urbanization and the eco-environment. We will conduct a preliminary simulation of the interactive coercion between urbanization and the eco-environment using the spatiotemporal coupling system dynamics model, test the validity of the model, simulate the thresholds and construct a model of the threshold. Additionally, we will also analyze the interactive coercion between urbanization and eco-environment, and the unhealthy status potential of the urban and eco-environmental systems. The model parameters will be modified and simulated repeatedly until the requirements are fulfilled. Moreover, we will nest and integrate modules, and construct a systematic scientific platform for the quantitative study of urbanization in mega-urban agglomerations.

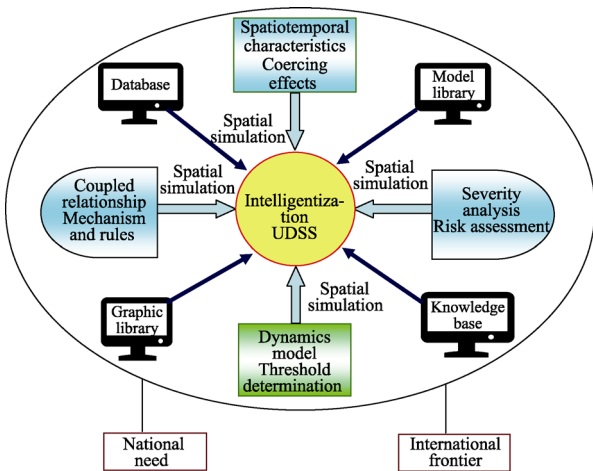
(5) To conduct scenario simulation of the interactive coupling processes and patterns between the urbanization of mega-urban agglomerations and the eco-environment. According to the basic data on mega-urban agglomerations and the goals of counties in the “13th Five-Year Plan” (2016–2020), we will design multiple experimental scenarios, repeat experiments and calculations, and produce a scenario plan of the process of urbanization in mega-urban agglomerations that can adapt to the thresholds, and resources and environmental carrying capacity. In addition, we will be able to a conduct long-term (2030–2050) forecast and simulation in the interactive coercion process between urbanization and the eco-environment through adjustments to coercion thresholds and repeated simulations, which will ultimately form a mid-term and long-term multi-scenario plan for the development of mega-urban agglomerations.

(6) We will adopt a system dynamics model for resources and the environment to construct systems of forewarning indices and forewarning signs for the interactive coercion between urbanization and the eco-environment. In detail, we can determine the contribution rates of forewarning indices as well as simulate the social and economic development goals

and the degree of resources and environmental protection in the recent developmental process of mega-urban agglomerations. Additionally, we can determine the degree of unhealthy urbanization caused by the deviation from the forewarning indices of the coercion between the social and economic development goals and the degree of resources and environmental protection. Collectively, the forewarning response system for the interactive coercion between urbanization and the eco-environment in mega-urban agglomerations can provide a scientific basis for government decision-making.

**2.5 Research and development, and model selection for the intelligent decision support system of the interactive coupling between urbanization and the eco-environment (UDSS)**

Based on space simulation and GIS technology, we can build an integrated intelligent decision support system for the interactive couplings between urbanization and the eco-environment in mega-urban agglomerations (UDSS). The UDSS has the distinctive features of high intelligence, high visualization ability and high sensitivity (Figure 5). By combing the UDSS with typical research areas, we can simulate the impacts of resources and environmental protection, and the relevant optimized regulations to determine the appropriate population sizes, space and economy in an agglomeration at different stages, and we can also propose a sustainable development model and a highly efficient growth model based on resource restrictions and eco-environmental capacity (Fang *et al.*, 2011b). In this regard, our models should provide a systematic scientific decision-making basis for the promotion of healthy and sustainable development of urban agglomerations.



**Figure 5** Schematic diagram of the intelligent decision support system for optimizing the interactive couplings between urbanization and the eco-environment

(1) To implement multi-scale spatiotemporal simulations of the socioeconomic and eco-environmental elements in mega-urban agglomerations. We can obtain information on natural elements (water, land, energy, ecology, climate and environment) in a wide range of spaces by applying spatialization technologies including remote sensing, GIS, sensor networks, spatial distribution information generated from big data, the method of spatial difference and scale conversion of spatial grid, and surface modeling. Moreover, through the

spatialization of the data on human elements (population, economy, society, infrastructure, technology innovation, policy and globalization), we can obtain a wide range of continuous spatial information for these elements. Using the above methods, we can achieve standardization of the multi-source data on urbanization elements as well as the spatialization features and the visualized expression of the spatiotemporal dynamics of socioeconomic and eco-environmental elements. Additionally, under the unified spatiotemporal frame, we can integrate various methods of visualized expressions such as spatial graphs, statistical graphs, flow diagrams and three-dimensional (3D) graphs to show the spatial distribution and statistical results of socioeconomic and eco-environmental elements related to urbanization. In addition, simulated results of urbanization under multiple scenarios can also be generated. Combined with space-time prism, we can achieve four-dimensional multi-scale simulations.

(2) To conduct the visualized scenario simulation of the interaction between urbanization and the eco-environment within the restriction of eco-environmental elements. We will adopt methods such as hierarchy decomposition, cooperation correlation and cascade interaction to construct the coupling model library with a self-organization feature by the standardized assembly method, which can provide highly effective model library support for the visualized scenario simulation of the interaction between urbanization and the eco-environment. Moreover, by using asynchronous evolution, cooperative interaction and feedback network, we will discuss the scenario simulation mechanism of dynamic urban development under multiple interactions and feedbacks. Further, we can complete the scenario simulations in the presence of multiple spatiotemporal dynamic restrictions from the complex eco-environmental elements, and the asynchronous development and asynchronous feedbacks from multi-scale cities. Lastly, by means of spatiotemporal scale conversion and process decomposition, we can explore how to achieve coupled restrictive effects of resources and the environment at the multi-temporal and multi-spatial scales, and also how to achieve dynamic visualized scenarios of the evolution and feedback of urbanization elements.

(3) To develop an intelligent decision support system of the interactive coupling between urbanization and the eco-environment. We will construct an intelligent decision support system of the interaction between urbanization and the eco-environment, which will integrate spatialized environmental elements, systematic dynamic simulations and multi-scale optimized decision-making modules. This system will include a four-dimensional simulation module with multiple scales of population, space and economic size, a scenario simulation module with multi-scale interactions and feedbacks, and a module based on the capacity limit of resources and the environment, and sustainable development. Additionally, we also want to achieve accurate estimation of the multi-scale population and economic sizes of mega-urban agglomerations, achieve simulation of the interactive coercion between eco-environment and urbanization at the scales of county, prefectural city, urban agglomeration and province, and generate an optimized model for the development of highly efficient and sustainable urban agglomerations. Finally, we hope to provide a quantitative decision-making platform for the construction of resource-conserving, environmentally-friendly, ecologically-sustainable and intelligent urban agglomerations.



### 3 Conclusions and discussion

Mega-urban agglomerations are strategic core areas for domestic economic development and the main regions of new urbanization in China. They also play important roles in shifting the global economic center of gravity to China. However, unsustainable high-density aggregation, high-speed expansion, high-intensity pollution and high-risk threats to resources and the environment are emergent in the development of mega-urban agglomerations. With unsustainable urban developments and severe eco-environmental problems, these regions carry the “most affected areas” distinction and face increasing coercion from resources and the environment in their development. How to coordinate the relationships between urbanization and eco-environment in mega-urban agglomerations is a complex problem that needs to be urgently solved by both academia and governmental decision-making departments. The coordinated development of urbanization and the eco-environment has become a global strategic issue. However, research in this field is still at an early stage and has yet to draw much attention from researchers.

Current practical experience on the development of global urbanization shows that urbanization has been producing severe coercing effects and far-reaching influence on the eco-environment. Moreover, there are extremely complex non-linear coupling relationships between urbanization and the eco-environment. As such, research on the interactive coupled effects between urbanization and the eco-environment will be frontiers and high-priority in Earth system science and sustainability science in the next decade. In addition, these research topics will greatly attract the attention of international organizations. Nevertheless, in the field of interactive couplings between urbanization and the eco-environment, much research is still urgently required to achieve sustainable development of mega-urban agglomerations.

In order to theoretically analyze the interactive coupled effects between urbanization and the eco-environment in mega-urban agglomerations, we need to construct a theoretical framework of the interactive couplings between urbanization and the eco-environment. Based on the framework, we can further analyze the non-linear coupled relationships and coupling characteristics of the interaction between various natural and human elements in mega-urban agglomerations, identify the coercing intensities of the interactions between various internal and external elements, present the mechanisms and patterns of local couplings and telecouplings under the influence of internal and external key control elements, summarize the theories of the interactive couplings between urbanization and the eco-environment, construct a spatiotemporal coupling dynamics model with multi-element, multi-scale, multi-scenario, multi-function, multi-module and multi-agent integrations, and develop an optimized intelligent control and decision-making support system for the sustainable development of mega-urban agglomerations. Through the aforementioned efforts, we will be able to propose solutions to mega-urban agglomeration related problems and maintain its sustainable development.

In order to methodically analyze the interactive coupled effects between urbanization and eco-environment in mega-urban agglomerations, it is necessary to consider a mega-urban agglomeration as an open, complex giant system. Based on the establishment of a shared unified standardized database, we can study the interactive couplings between urbanization and the eco-environment with multi-element, multi-target, multi-module and multi-scenario

integrations, and also with big data analysis. Moreover, we will build a framework of the interactive couplings between urbanization and the eco-environment with multi-scale, multi-technology and multi-agent integrations. Overall, we will propose an optimized solution according to the following technical route, which sequentially consists of analyzing the spatiotemporal evolution characteristics, determining the key control elements, identifying the coupling relationships, revealing the mechanisms of coercion, discovering the coupling laws, screening for controlling variables, calculating the thresholds, conducting the tests to regulate and control variables, completing the scenario simulations, proposing the optimized solutions, and finally achieving the national goals.

Considering the extreme complexity of sustainable development of mega-urban agglomerations, we believe that traditional urban geography is not sufficient to reveal the cross-city, cross-boundary, cross-field, cross-disciplinary and even cross-country characteristics of mega-urban agglomerations. The basic functions of cities have exceeded the traditional social and economic functions, and have started to more frequently interact with eco-environmental elements. As such, it is impossible to study the development of mega-urban agglomerations within a single discipline, and hence it is urgent to apply integrated interdisciplinary approaches to realize multi-element couplings, multi-scenario simulations, multi-risk forewarnings and multi-goal decision-makings in the sustainable development of agglomerations, and also to advance the study of human geography to the next level.

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