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A Theoretical Analysis of Interactive Coercing Effects Between Urbanization and Eco-environment

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Abstract: Objectively, a complex interactive coercing relationship exists between urbanization and eco-environment, and the research of this relationship is primarily divided into three schools, i.e., interactive coercion theory, interactive promotion theory and coupling symbiosis theory. Harmonizing the relationship between urbanization and eco-environment is not only an important proposition for the national development plan but also the only way to promote healthy urbanization. Based on an analysis of urbanization process and its relationship with the eco-environment, this article analyzes interactive coercing effects between urbanization and eco-environment from three perspectives of population urbanization, economic urbanization and spatial urbanization, respectively, and analyzes risk effects of the interactive coercion. Further, it shows six basic laws followed by interactive coercion between urbanization and eco-environment, namely, coupling fission law, dynamic hierarchy law, stochastic fluctuation law, non-linear synergetic law, threshold value law and forewarning law, and divides the interactive coercing process into five stages, namely, low-level coordinate, antagonistic, break-in, ameliorative and high-grade coordinate. Based on the geometric derivation, the interactive coercing relationship between urbanization and eco-environment is judged to be non-linear and it can be explained by a double-exponential function formed by the combination of power and exponential functions. Then, the evolutionary types of the interactive coercing relationship are divided into nine ones: rudimentary coordinating, ecology-dominated, synchronal coordinating, urbanization lagging, stepwise break-in, exorbitant urbanization, fragile ecology, rudimentary break-in and unsustainable types. Finally, based on an interactive coercion model, the degree of interactive coercion can be examined, and then, an evolutionary cycle can be divided into four phases, namely rudimentary symbiosis, harmonious development, utmost increasing and spiral type rising. The study results offer a scientific decision-making of healthy urbanization for achieving the goal of eco-environment protection and promoting urbanization.
Keywords: urbanization process; eco-environment; interactive coercing relationship; interactive coercing rules; interactive coercing degree

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1 Introduction

An extremely complex interaction exists between the process of urbanization and eco-environment. How to harmonize this relationship has become an important issue that holds the attention of academic circles and government departments. At the same time, it is also a global strategic issue because urbanization is an actual or potential threat to the surrounding eco-environment with global urbanization accelerating. As early as 1991, the World Health Organization noted that the world was facing two problems: serious deterioration of the natural environment and an accelerated decline of living quality in urban areas. Urbanization has an important impact on global environmental change, which threatens human life in the future. Endao, the former secretary-general of

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the United Nations, said 'Urbanization is perhaps full of hope, but is perhaps full of disaster. Therefore, the future will be decided by our doing' (Fang *et al*., 2008a). McMichael (2000) also noted that urbanization will be an important threat to the eco-environment and human health. At present, academic circles focus on applied studies of urban development, eco-environmental evaluation of city interiors and evaluation of urban ecosystem stability. However, few basic studies addressed the coupling law in the process of interaction between urbanization and eco-environment from the perspective of eco-environmental constraints, and few researches discussed the interactive impacts of urbanization and eco-environment from the perspective of a large spatio-temporal scale. Given this, the article analyzes the interactive coercing relationship between urbanization and eco-environment, reveals basic laws and stage rules of interactive coercion, derives the double-exponential curve and evolution types based on geometric principles, and finally analyzes and recognizes the coercing degree. By doing so, this article will have great practical significances to impel forming major function-oriented zone and a structural system of urban agglomerations with rational hierarchy and orderly division, to synchronously promote regional industrialization and ecological progress of the national economy, and to build environment-friendly cities.

2 Urbanization Process and Its Relationship with Eco-environment

Harmonizing the relationship between urbanization and eco-environment is not only an important proposition for the national development plan, but also the only way to promote healthy urbanization. Research has shown that the dynamics of coordination between urbanization and environment exhibited a U-shaped curve (Li *et al*., 2012).

2.1 Basic content of urbanization

Urbanization is a population transformation process in which the population migrates from rural areas to urban areas and it is also a regional transformation process in which some rural areas become urban areas. The degree of urbanization is usually measured by the proportion of the regional population composed of the urban population (or non-agricultural population). In fact, urbanization is not only a population concentration from rural to urban areas and a population transformation from agricultural to non-agricultural sectors, but also an expansion in the number of cities and urban land area. Urbanization is not only a shift from agricultural activities to non-agricultural activities and an upgrade of industrial structure, but also a process in which urban lifestyles, values, and culture influence spread to rural areas. Therefore, based on its definition and manifestation, urbanization can be divided into four processes: population urbanization reflecting the distribution of the urban population; economic urbanization reflecting urban economic growth; spatial urbanization reflecting the urban spatial expansion; and social urbanization reflecting the proliferation of urban civilization. Based on strategic need analysis, urbanization is not only a process in which the degree of optimal allocation of resources, the degree of population concentration and infrastructure conditions are improved, but also a process of fostering new economic growth points, effectively increasing regional per capita income, solving employment problems, adjusting the economic structure, protecting the eco-environment and building a moderately prosperous society.

2.2 Interactive coercing relationship between urbanization and eco-environment

At present, some studies of the interactive relationship between urbanization and eco-environment primarily focused on two aspects. First, the coercing effect of urbanization on the eco-environment is analyzed from three perspectives, i.e., urban population agglomeration, economic growth and spatial expansion. Pouraghniaei (2012) considered that, from a macro perspective, urbanization distorted eco-environmental conditions, which caused pollution and ecological crisis. On the other hand, from a micro perspective, urbanization altered the coverage status of the underlying ground surface, which accelerated runoff and caused peak flow to arrive early, and it also altered water utilization structure, which influenced urban development. In Tunisia, an inverted-U relationship between SO_2 emissions and GDP has been observed (Fodha and Zaghdoud, 2010). In Taejon area of South Korea, the groundwater chemistry is more influenced by land use and urbanization than by aquifer rock type (Chan, 2001). In the city of Merida, Yucatan, Mexico, the groundwater quality is most affected by urbanization and the most affected (contaminated) areas coincide with that of urbanization (Graniel *et al*., 1999). In Shanghai, China, study results reveal that rapid urbanization corresponds with rapid degradation of water quality and that urban land uses are positively correlated with the decline of water quality (Ren *et al*., 2003). Turkey has to face congested population problems because of fast urbanization. Increasingly urbanized coastal cities have encouraged tourism investment, which leads to loss of agricultural land, overexploitation, environmental pollution and ecological deterioration (Burak *et al*., 2004). The urbanization process has usually resulted in an expansion of impermeable areas, an increase in water demand, an increase in industrial and domestic waste water and a reduction of water surface areas and green lands (Imbe *et al*., 1997).

Second, eco-environmental limits on urbanization are analyzed from the perspectives of ecological condition, resource status and environmental pollution. For example, Ruth and Paul (2001) analyzed the economic benefits of different water use patterns including for domestic, industrial, agricultural and leisure purposes, and discussed the restrictions of water resources on urban development. Jurdi *et al*. (2001) analyzed the restraint of eco-environment on urbanization and industrial and agricultural development, based on the analysis of environmental, institutional and financial issues in Lebanon. Based on Kuznets Curve, many researchers explored the interactive relationship between urban economic development and the eco-environment by analyzing economic structure, international trade, the scientific and technological progress, national policy, *etc*. (Grossman and Kreuger, 1995; Panayotou, 1997; Martínez-Fernández *et al*., 2000; Khanna and Plassmann, 2004). Ducrot *et al*. (2004) adopted a multi-agent model prototype to represent the relationship between urbanization dynamics and land and water management in a peri-urban catchment area.

It is clear that the relationship between urbanization and eco-environment is extremely complex. According to environmental Kuzents Curve Theory, Ecological Economics Theory, Critical Natural Capital Theory and Sustainable Development Theory (Fang *et al*., 2004), the interaction between urbanization and eco-environment can be summarized into three theories: interactive coercion, interactive promotion and coupling symbiosis (Fang, 2004).

2.2.1 Interactive coercion theory

An interactive coercing relationship exists between urbanization and eco-environment when urbanization exacerbates regional resource shortages and accelerates eco-environmental deterioration, and meanwhile the fragile eco-environment further constrains urbanization. This perspective is known as interactive coercion theory. The eco-environment is a fundamental necessity for human survival and an important requirement for urban development. Therefore, a fragile eco-environment will restrict urbanization significantly. At the same time, urban development and urbanization inevitably damage the already fragile eco-environment, and the degraded eco-environment further constrains urban development and urbanization; thus, a vicious circle arises (Prinz, 2001). Liu *et al*. (2011) introduced the aggregated index system representing the coupling relationships between urbanization and eco-environment and developed an integrated sustainable development approach (ISD) to simulate and evaluate the integrative effects.

2.2.2 Interactive promotion theory

Urbanization leads to optimal allocation of resources and sound development of the eco-environment, and at the same time, favorable eco-environment and resource conditions support rapid urbanization. Urbanization and eco-environment promote one another, which is known as interactive promotion theory. In this process of interactive promotion, resources are allocated more efficiently in cities than in villages and are used more effectively in industry than in agriculture. Urbanization further improves the eco-environment; and meanwhile, favorable eco-environment promotes urbanization. Furthermore, urban socio-economic development creates advantages for both environmental protection and investment. As urbanization progresses, the relationship between urban development and eco-environmental protection will move in the direction of harmonious co-existence and virtuous circle (Portnov and Safriel, 2004; Song and Fu, 2005).

2.2.3 Coupling symbiosis theory

Along with the evolution of urbanization and socio-economic development, both an interactive coercing process and a mutual promotion relationship exist between urban development and the eco-environment. This perspective is known as coupling symbiosis theory. Urbanization influences the eco-environment through population agglomeration, spatial expansion, economic growth and structural optimization; the eco-environment responds to urbanization by the changes of resources, atmospheric environment and biological environment (Qiao *et al*., 2005). This interactive coercing effect between urbanization and eco-environment leads to further optimization of resource allocation and improvement of economic structure. The relationship between urbanization and eco-environment moves in the direction of harmony, and finally, promotes the evolution of urbanization and eco-environment system from low-level harmonious co-existence to high-level harmonious coupling (Fang, 2003).

2.3 Interactive coercing effects between urbanization and eco-environment

The interactive coercing effects between urbanization and eco-environment were caused by population urbanization, economic urbanization and spatial urbanization (Fig. 1).

2.3.1 Interactive coercing effect caused by population urbanization

Population urbanization reflects a process in which people move into cities and population transform from agricultural to non-agricultural sectors. During this process, the eco-environment is influenced by increasing urban domestic water consumption, residential land, domestic sewage and garbage, *etc*. Taking the effect of population urbanization on the eco-environment in Hexi Corridor, Gansu Province as an example, when the non-agricultural population increases by 1×10^5 persons, urban domestic water, residential land, urban domestic sewage and urban domestic garbage will increase by 3.0×10^6 m^3, 5.14 km^2, 4.54×10^6 t/year and 5.76×10^4 t/year, respectively. However, this process of human migration into cities also has positive effects on the eco-environment apart from increased productivity. It effectively avoids estrepement and indiscriminate logging, decreases the pressure on resources and the environment in rural areas and reduces possible damage to eco-fragile zones caused by the dispersed pattern of rural habitation. With economic development and the progression of urbanization, surplus labor forces staying in rural areas begin leaving the village to participate in non-agricultural employment. Urban development will play an active role in rural urbanization and agricultural labor force transfer.

2.3.2 Interactive coercing effect caused by economic urbanization

Economic urbanization is a process of urban economic growth. It represents not only a shift from agricultural to non-agricultural activities but also raising the level of urban economy and optimizing and upgrading industrial structure. The effect of economic urbanization on the eco-environment is primarily reflected by intensifying water shortages, groundwater tables declining, and generating pollution caused by industrial and agricultural production such as wastewater, waste gas and trash. Taking Hexi Corridor as an example, when the value of gross industrial output increases by 1.0×10^9 yuan, industrial water and land use will increase by 4.2×10^6 m^3

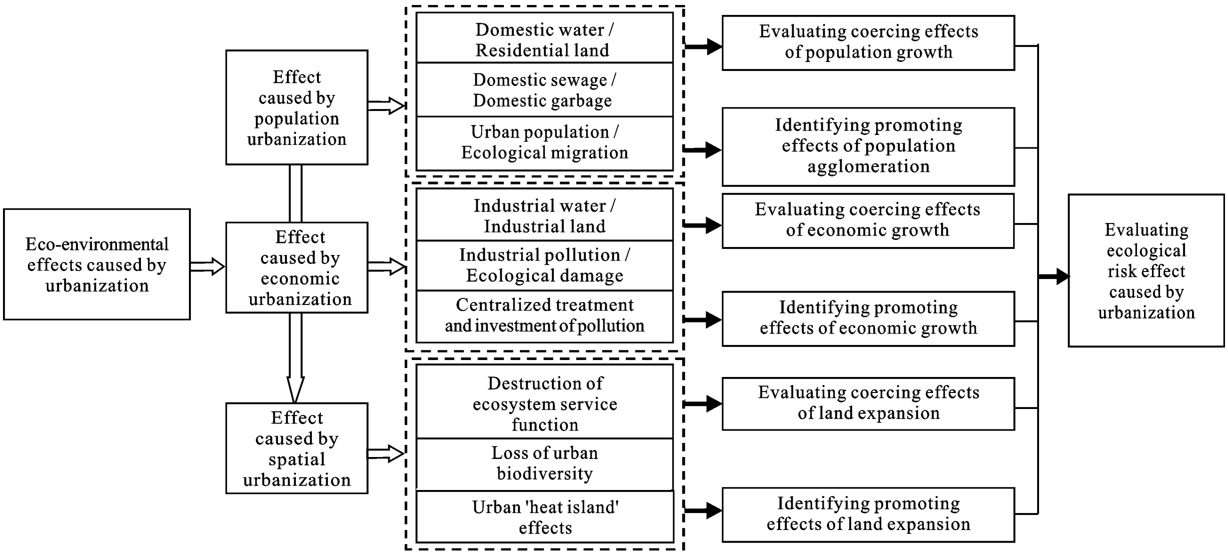

Fig. 1 Interactive coercing effects between urbanization and eco-environment

and 0.36 km^2, respectively, and SO_2 and powder generated by industrial production will increase by 500 t and 170 t, respectively. However, in addition to various negative coercing effects on the eco-environment, urban economic development also has positive impacts, including highly efficient and intensive resource use as well as the potential for increasing ecological investment and pollution treatment. Economic urbanization is accompanied by technological advancement and the optimization and upgrading of industrial structure. It benefits the application of advanced ecological technology. In addition, economic development is accompanied by increased investment in ecological construction and environmental protection, supporting gradual improvement in eco-environment conditions.

2.3.3 Interactive coercing effect caused by spatial urbanization

Spatial urbanization is a process in which the number of cities in a region continuously increases and urban areas continuously expand into rural areas. The effect of spatial urbanization on eco-environment include the occupation of cultivated land, forest land, grassland, *etc*., the destruction of ecosystem service functions, the alteration of biodiversity in oases, and the intensification of the urban 'heat island' effect. In Hexi Corridor, when urban land increases by 1 km^2, 0.79 km^2 of cultivated land, 0.10 km^2 of grassland and 0.11 km^2 of unused land are occupied for urban development, the value of ecosystem service worth 3.70×10^7 yuan (RMB) is lost, and the spatial distribution of species diversity exhibits an obvious decline from suburban areas to city centers (Wang, 1996). In the process of urban land expansion, the original natural surface, which has a high specific heat due to coverage by grassland and water, is replaced by surfaces with low specific heat such as cement and asphalt. The changes alter not only reflective and absorptive properties of the ground surface, but also the heat exchange of the near-surface layer and the surface roughness of the ground. The dense aggregation of buildings in cities blocks air flow, which concentrates urban heat and affects physical conditions of the atmosphere (Zhan *et al.*, 2003). Each of these effects of urban expansion exacerbates the urban heat island effect.

2.3.4 Risk effect in process of interactive coercion between urbanization and eco-environment

During the process of urbanization, because previously agricultural ecosystems are rapidly replaced by urban ecosystems, an inevitable and negative consequence for sustainable development of rural urbanization appears (Zhou and Zhu, 1990). Thus, urbanization causes urban ecological risk which arises largely from production practices and socio-economic development. It includes some risks imposed by the traditional management model and technology and some risks from resource development and utilization. Moreover, urban ecological risk is affected by other risk factors such as financial markets, capital input and output, commodity circulation and marketing, industrial structure upgrades as well as the functional conversion of various production factors in the process of urbanization (Xiao *et al.*, 2002). Therefore, as urbanization progresses, the problem of urban ecological risk becomes particularly prominent. We indicated different degrees of ecological risk based on single-factor and comprehensive evaluation modeling of urban ecological risk. Firstly, the degree of ecological risk of urbanization, arranged in order, is as follows: economic urbanization > population urbanization > social urbanization. Secondly, the degree of ecological risk associated with industry is as follows: primary industry > secondary industry > tertiary industry. Thirdly, the degree of ecological risk of water utilization is as follows: agricultural water > industrial water > water for tertiary industry. In addition, Najem *et al*. (1985) indicated the degree of ecological risk with respect to the basin: upper reaches < middle reaches < lower reaches. It is clear that the ecological risks caused by economic urbanization, primary industry development, agricultural irrigation and the lower basin development are high. Therefore, to manage urban ecological risk, it is necessary to promote intensive economic growth, develop the secondary and tertiary industries, speed the process of industrialization, reduce the proportion of agricultural irrigation in total water use, and highlight the will to develop eco-environmental construction of the lower basin.

3 Basic Laws and Periodic Rules of Interactive Coercion Between Urbanization and Eco-environment

3.1 Basic laws of interactive coercion between urbanization and eco-environment

Relying on Dissipative Structure Theory and the Ecosystem Need Laws (Si, 2001), the interactive coercing relationship between urbanization and eco-environment can be considered an open and non-equilibrium dynamic fluctuating system with non-linear interactions and self-organizing ability; it is therefore known as an interactive coercing system (Fang, 1989). Theoretically-based analysis indicates that this coupling system accords with coupling fission law, dynamic hierarchy law, stochastic fluctuation law, non-linear synergetic law, threshold value law and forewarning law. The six fundamental laws are basic ones that the coupling process must follow (Fang and Yang, 2006).

3.1.1 Coupling fission law

The coupling system of urbanization and eco-environment fully reflects the interactions between humans and nature. It is a typical ecological-economic-social complex system. To be clear, this article addresses only the coupling relationship caused by the interaction among urbanization, eco-environment and economy. Let v_e, v_{eq} and v_u represent the economic growth rate promoted by resource development and utilization, the eco-environment quality change rate caused by economic development and resource utilization, and the urbanization change rate, respectively. Then, eight status categories of interactive coupling among urbanization, ecological environment and economic development are presented in Table 1. Coupling fission law is the first law to drive the interactive coupling between urbanization and eco-environment.

3.1.2 Dynamic hierarchy law

The degree of urbanization demands on eco-environment is an indicator of ecosystem balance. Based on a theoretical analysis, the degree of eco-environment meeting the demand of urbanization development can be divided into five levels, namely, more satisfied, satisfied, basically satisfied, less satisfied and unsatisfied. Therefore, coupling status between urbanization and eco-environment can be divided into stronger coupling, strong coupling, moderate coupling, weak coupling, and weaker coupling. Evaluation grades of the coupling status, arranged in order, are better, good, moderate, tolerable, and bad; and the development trend orderly are stronger sustainable development, strong sustainable development, standard sustainable development, weak sustainable development, and unsustainable development (Table 2). Dynamic hierarchy law is the second law followed by interactive coupling between urbanization and eco-environment.

3.1.3 Stochastic fluctuation law

According to Dissipative Structure Theory, the interactive coupling between urbanization and eco-environ-

Table 1 Eight status categories of interactive coupling among urbanization, eco-environment and economic development

Category	Eco-environmental quality change rate (v_{eq})	Economic growth rate (v_e)	Urbanization change rate (v_u)	$(v_e / v_{eq}) / v_u$	Coupling results and statuses
1	>0	>0	>0	>1	Strong-economic-sustainable coupling status
2	>0	>0	>0	<1	Strong-ecological-sustainable coupling status
3	>0	<0	<0	<1	Ecological-sustainable coupling status
4	>0	<0	<0	>1	Ecological-sustainable coupling status
5	<0	<0	<0	>1	Unsustainable non-coupling status
6	<0	<0	<0	<1	Unsustainable non-coupling status
7	<0	>0	>0	<1	Economic-sustainable coupling status
8	<0	>0	>0	>1	Economic-sustainable coupling status

Table 2 Coupling hierarchy and intensity between urbanization and eco-environment

Coupling hierarchy	Degree of E meeting demand of U	Evolutionary direction	Coupling degree	Evolutionary direction	Evaluation grade of coupling status	Evolution direction	Evaluation of development trend	Evolution direction
First grade	More satisfied		Stronger		Better		Stronger sustainable	
Second grade	Satisfied		Strong		Good		Strong sustainable	
Third grade	Basically satisfied		Moderate		Moderate		Standard sustainable	
Fourth grade	Less satisfied		Weak		Tolerable		Weak sustainable	
Fifth grade	Unsatisfied		Weaker		Bad		Unsustainable	

Notes: E, eco-environment; U, urbanization ment is a dynamically fluctuating process. The character of time organization determines that this process is a dynamic system and its important evolutionary mechanism is occasional stochastic fluctuation. Because of the hierarchical and inclusive characteristics in the system, eco-environmental factors in a limited coupling system always change randomly, leading to various stochastic disturbances to the system, i.e., 'external fluctuations'. External and internal fluctuations overlap, synchronize and resonate. Then it brings about the complex fluctuations of the system and further increases the complexity of system evolution. The main representations are as follows: the co-existence of multiple fluctuations determines that the coupling system co-evolution is a process predominated by the eco-environment; the random fluctuations determine the occasional coupling direction; the cooperation and competition among several fluctuations result in the complex evolution of the coupling system.

3.1.4 Non-linear synergetic law

According to Dissipative Structure Theory, the coupling between urbanization and eco-environment is a system with non-linear interactions among urbanization factors, among eco-environment factors, and between urbanization and eco-environment factors. It is also a complex system characterized by integrity and rapidity. In this coupling system, the eco-environment system is considered the 'nutrition source', i. e., outputting energy, and the urban system is considered the 'nutrition collector', i. e., absorbing nutrition. The two systems mutually promote and restrain one other, and there exists a rather complex non-linear interaction between them (i.e., feedback, self-catalysis, self-organization, self-copy). Meanwhile, the non-linear interactions among factors inside each system get stronger. This non-linear interaction causes the micro-behavior of numbers of geographic elements to get 'synergy' and 'cooperation' and produce a macro-'sequence' and thus it forms a complex system with a multi-level structure.

3.1.5 Threshold value law

According to the basic principle of logistic process and Kuznets Curve, the dynamic change process of interaction between the urbanization level and the eco-environmental capacity largely conforms to logistic curve and Kuznets' inverted U-shaped curve.

The eco-environmental capacity of a given location has its own threshold value. In the initial period of urban development, the threshold value trends to the static maximum, and with the urbanization progress, environmental capacity gradually approaches the threshold limit value. The inflection point A_1 is the first threshold value. When the eco-environment is improved, the threshold value of eco-environmental capacity changes from A_1 to A_2 and urbanization continues. The third threshold value A_3 will then appear, and so on. This form of stepped curve essentially follows the composite curve of the Logistic Equation (Fig. 2).

In the initial period of urbanization, urbanization change rate v_u, rises following eco-environmental quality change rate v_e. However, urbanization change rate does not increase and even declines when eco-environmental quality change rate reaches or exceeds a certain threshold B. Finally, an inverted U-shaped curve forms (Fig. 3). Based on the variation, the best threshold or the elastic threshold interval of urbanization can be identified in the process of eco-environmental capacity change.

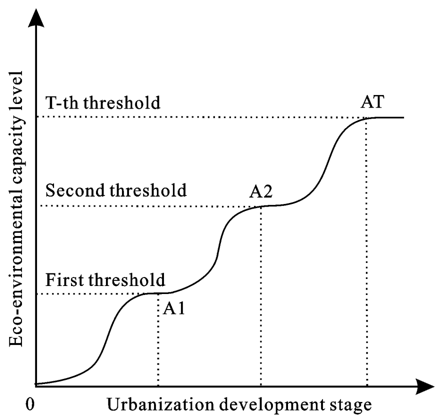

Fig. 2 An analysis of logistic process and thresholds in process of interactive coercion between urbanization and eco-environment

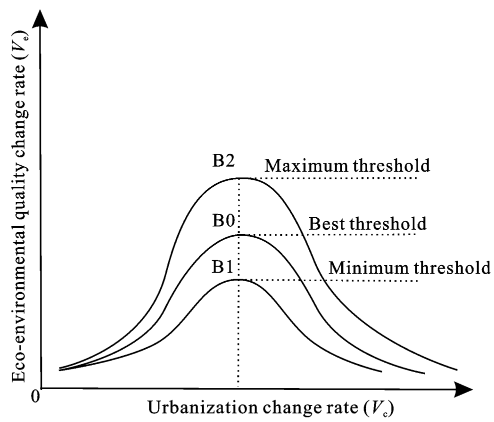

Fig. 3 An analysis of inverted U-shaped curves and thresholds in process of interactive coercion between urbanization and eco-environment

3.1.6 Forewarning law

The forewarning system of coupling between urbanization and eco-environment is a warning based on deviation of the coupling relationship from its expected state. The coupling forewarning system is divided into two patterns: current warning and future warning. The current warning is to ascertain whether the current coupling state has overstepped the expected scope, i.e., an inspection of the current coupling state. The future warning is to ascertain when and what type of crisis will appear according to the current speed of urbanization, i.e., a dynamic comprehension of the future development trend. The forewarning process includes: choosing a reference system, establishing a forewarning index system, building a forewarning model, and defining the forewarning limit, forewarning light and forewarning degree (Yu and Lu, 2001). 'Green light' represents that the coupling system is coordinate; 'yellow light' represents that the coupling system is not very coordinate, with the possibility of changing to be uncoordinated or trending to be coordinate in a short time; 'red light' represents a serious warning that the coupling system is very uncoordinated and effective countermeasures should be taken to promote recovery and avoid system breakdown. The change from 'red light' to 'yellow light' indicates that the coupling system is changing from incoordination to coordination and further measures should be taken to improve system coordination. The change from 'green light' to 'yellow light' is a warning to adjust control measures quickly to reverse the evolution trend.

3.2 Periodic rules of interactive coercion between urbanization and eco-environment

The urbanization process can also be divided into stages. Through studying on the progression of urbanization in countries around the world, Ray (1975) summarized that the path of urbanization is like a small, flat, S-shaped curve and can be divided into three development stages. After being modified and taking full account of the stages of economic growth, urbanization is divided into four stages (Fang *et al.*, 2008b), namely the initial (urbanization level stands at 1%–30%), middle (urbanization level stands at 30%–60%), later (urbanization level stands at 60%–80%) and final stages (urbanization level stands at 80%–100%) (Fig. 4).

The research on interactive coupling mechanism and regularity between urbanization and atmospheric environment in Shandong Province showed that the relationship between them was in break-in stage and its sustainability has been an upward trend (Wang *et al.*,

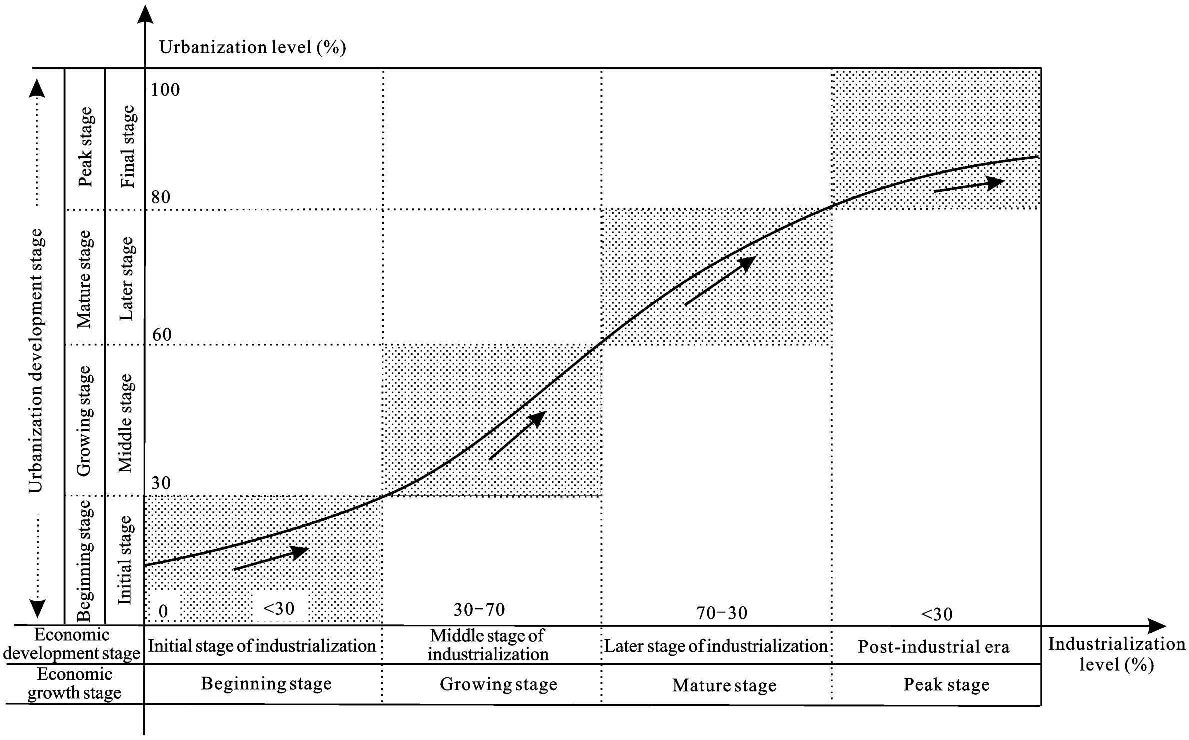

Fig. 4 Corresponding relationship between urbanization and economic development stages

2012; Wang *et al*., 2013). According to the urbanization stages and dynamic mechanisms as well as changes of the interactive coercing relationship between urbanization and eco-environment, this article divides the interactive coercing process into five stages, shown in Fig. 5.

3.2.1 Low-level coordinate stage

This stage usually occurs during the initial stage of urbanization. During this stage, agglomerating production factors to the central city and centripetal urbanization are observed. Due to the relatively slow urbanization and economic development, the degree of eco-environmental deterioration never reaches the threshold. Therefore, ecological pressure is not high and the coercing effect of urbanization on eco-environment is weak. Eco-environmental degradation can usually be reversed through natural processes.

3.2.2 Antagonistic stage

This stage usually occurs during the initial stage of urbanization or during the initial and middle growing stage of urbanization. It is marked by rapid urbanization and ecological pressure increasing. Urbanization is primarily in the form of agglomeration and agglomeration-diffusion. From a spatial perspective, it is a period of centripetal urbanization and suburbanization. With the rapid development of urbanization and industrialization, the coercing effect of urbanization on eco-environment increases greatly, ecological pressures rise sharply and the conflict between urbanization and eco-environment gets intensified. There exist complex cooperative or antagonistic effects between urbanization and eco-environment, and cumulative environmental effects increase rapidly.

3.2.3 Break-in stage

This stage usually occurs in the final growing stage of urbanization. It is marked by the slowdown of urbanization and ecological pressure. Urbanization is primarily in the form of diffusion-agglomeration. From a spatial perspective, it is a period of counter-urbanization. Due to rapid urbanization, ecological pressure gradually approaches the ecological threshold and the elastic threshold law takes effect, such that the conflict between urbanization and eco-environment oscillates between alleviation and intensity. With the progression of urbanization, urbanization and eco-environment influence and adapt to one another continuously and cumulative environmental effects fluctuate.

3.2.4 Ameliorative stage

This stage usually occurs during the mature stage of urbanization. It is marked by continually easing ecological pressure. Urbanization during this stage is primarily in the form of diffusion-agglomeration and diffusion. From a spatial perspective, this is a period of reurbanization. Due to a shift to tertiary industry in economic structure transformation, the wide application of high-tech and cleaner production technologies, the strengthened human awareness of environmental protec-

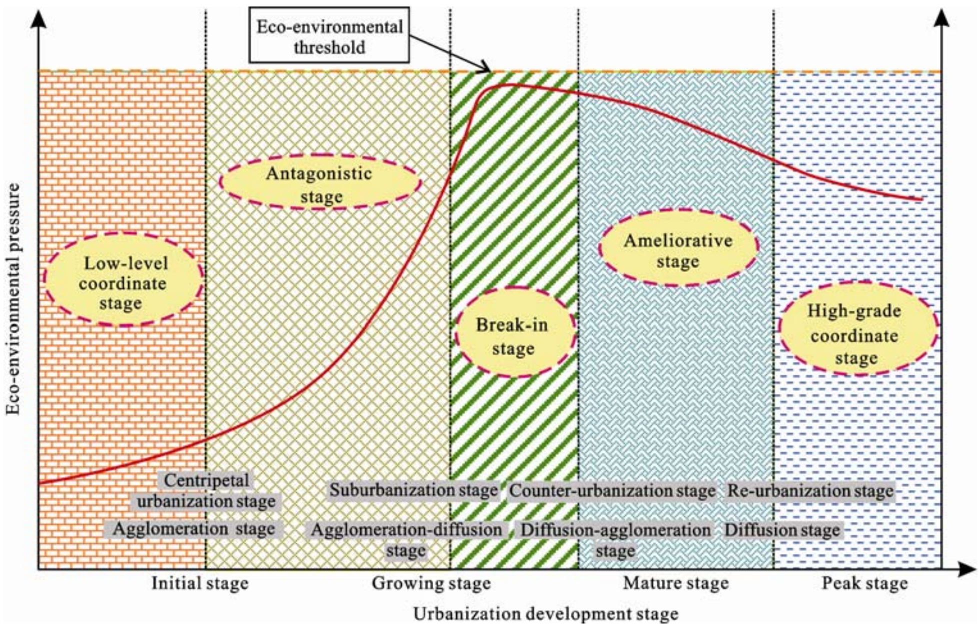

Fig. 5 Stages of interactive coercion between urbanization and eco-environment

tion and the increased ecological investment, the eco-environment is improved, ecological pressure gradually diminishes, the conflict wanes, and cumulative environmental effects decline smoothly.

3.2.5 High-grade coordinate stage

This stage often occurs during the peak stage of urbanization. The eco-environment, degraded by urbanization, has been restored since the ameliorative stage. Ecological pressure falls to the lowest level, the conflict between urbanization and eco-environment has essentially disappeared, urbanization and eco-environment co-exist harmoniously, and cumulative environmental effects decreased gradually.

4 Double-exponential Curve and Evolutionary Types of Interactive Coercion Between Urbanization and Eco-environment

4.1 Double-exponential function and curve of interactive coercion between urbanization and eco-environment

4.1.1 Double-exponential function

The relationship between urbanization and economic development is curved logarithmically (Zhou, 1995). Eco-environmental conditions and economic development level exhibit an inverted U-shaped relationship. Based on the two aforesaid relationships, it can be deduced that the coupling relationship between urbanization and eco-environment is a double-exponential function (Huang and Fang, 2003):

$$z = m - n[10^{\frac{y-b}{a}} - p]^2 \quad (1)$$

where, z represents the degree of eco-environmental deterioration; y is urbanization level; m, n, a, b, p are undetermined parameters.

When $y < a\lg P + b$, the eco-environment deteriorates gradually with the progression of urbanization.

When $y = a\lg P + b$, the degree of eco-environmental deterioration reaches the maximum value m.

When $y > a\lg P + b$, the eco-environment is improved gradually with the progression of urbanization.

The double-exponential function relationship indicates that as urbanization progresses, ecological pressure theoretically rises and then declines. In other words, phenomena such as eco-environmental deterioration and pollution may appear; however, such phenomena will diminish predictably with further urbanization. This is a common rule and a general tendency to which the interaction between urbanization and eco-environment adheres.

4.1.2 Double-exponential curve

First, a logarithmic curve and an environmental kuznets curve (EKC) curve are put into the first and third quadrants of the same coordinate system, respectively. The former represents urbanization changing with economic development while the latter represents eco-environment changing with economic development. Next, horizontal and vertical lines are drawn out from the two curves in the first and third quadrants to the second quadrant. Finally, a curve in the second quadrant is formed, which describes the coupling relationship between urbanization and eco-environment, shown in Fig. 6. This curve is divided into two parts by the middle inflection point, each an exponential curve. The front part (below the middle inflection point) is a monotonically increasing curve; the other is a monotonically decreasing curve. Prior to the inflection point, the degree of eco-environmental deterioration increases with the progression of urbanization; after the inflection point, the degree of eco-environmental deterioration decreases. Combined with a mathematical model, it may be determined that the urbanization level at the inflection point is $y = a\lg P + b$

4.2 Evolutionary types of interactive coercion between urbanization and eco-environment

Based on the analysis of the double-exponential curve, in different regions and under different backgrounds of eco-environmental conditions and urbanization, there are nine types in the process of interactive coercion between urbanization and eco-environment (Qiao *et al.*, 2006) (Fig. 7).

4.2.1 Rudimentary coordinating type

Regional ecological conditions are relatively good and the pace of urbanization is slow. Both the coercing effect of urbanization on eco-environment and the constraining effect of eco-environment on urbanization are weak. Due to low ecological pressures and smooth changes, the inflection point is not obvious.

4.2.2 Ecology-dominated type

Regional ecological conditions are relatively good and the pace of urbanization is somewhat slow. The coercing effect of urbanization on eco-environment is weak, but it

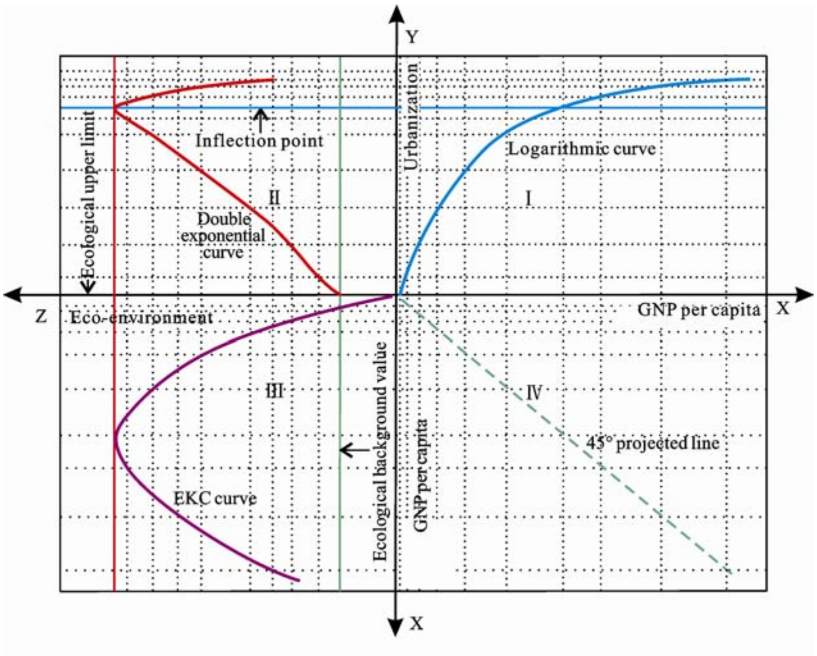

Fig. 6 Double-exponential curve of interactive coercing relationship between urbanization and eco-environment

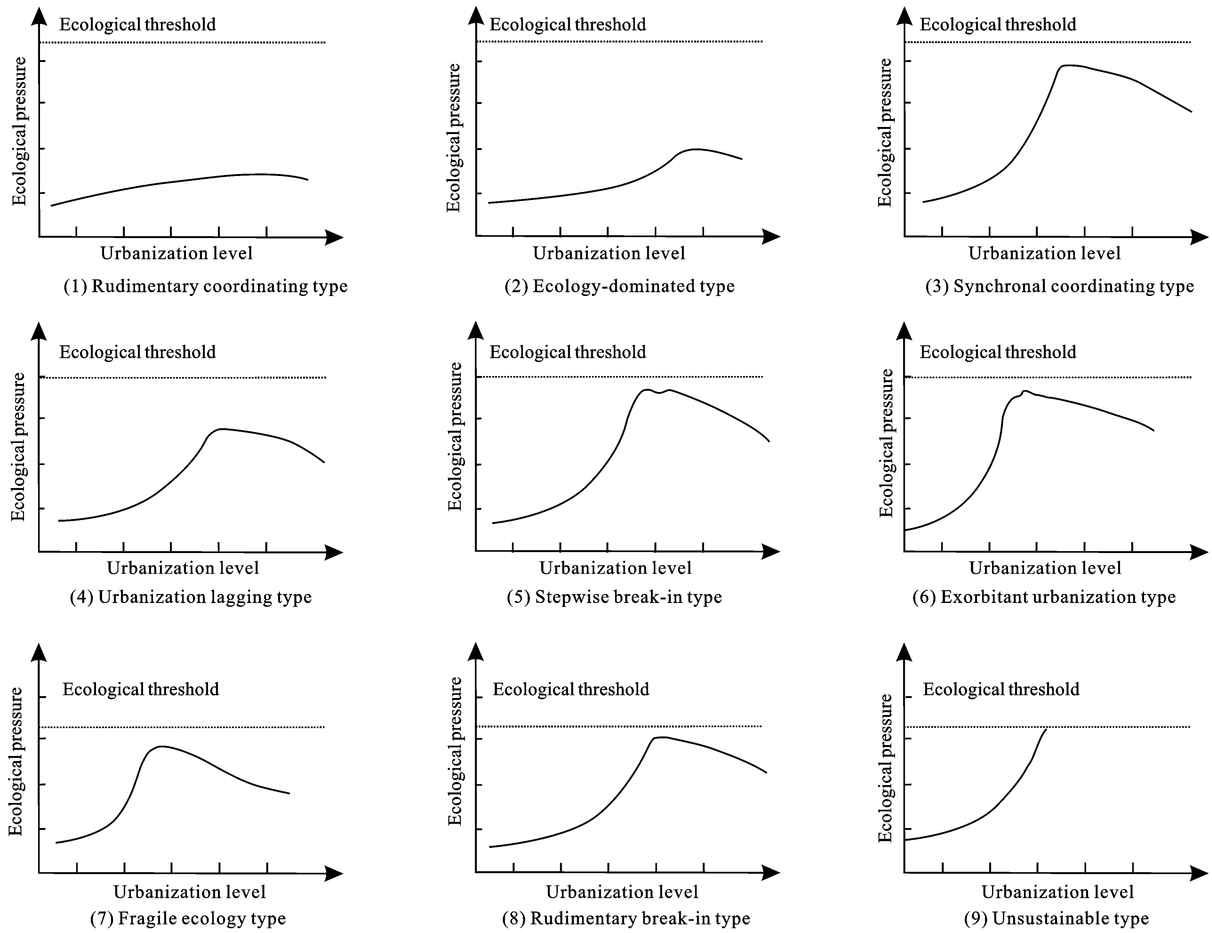

Fig. 7 Nine types of coupling between urbanization and eco-environment

is stronger than the effect in the rudimentary coordinating type. Ecological pressure is low all along and far from the ecological threshold. Therefore, the inflection point of ecological pressure appears somewhat later.

4.2.3 Synchronal coordinating type

Regional ecological conditions are relatively good and the pace of urbanization is rapid. As ecological pressure gradually approaches a maximum threshold, by way of regulation, the progression of urbanization slows, and some problems are alleviated. The inflection point in ecological pressure appears earlier.

4.2.4 Urbanization lagging type

Regional ecological conditions are neither good nor poor and the pace of urbanization is very slow. The coercing effect of urbanization on eco-environment is not strong, and the eco-environment deteriorates slowly. With technological progress and investments increasing, ecological pressure gradually decreases. The elastic threshold law does not perform any function, because the eco-environment does not yet reach the maximum threshold of ecological capacity. The inflection point of ecological pressure appears somewhat earlier.

4.2.5 Stepwise break-in type

Regional ecological conditions are neither good nor poor and the pace of urbanization is somewhat slow. With the progression of urbanization, eco-environment deteriorates and gradually approaches the maximum threshold of ecological capacity. Due to increased ecological pressure, urbanization and economic development are forced to adjust and to slow. After increasing investments in ecological protection, the eco-environment is improved and ecological pressure is gradually reduced. Therefore, under the control of the ecological threshold, the progression of urbanization follows a 'slow-rapid-slow' path and ecological pressure undergoes a 'strong-weak-strong' process. During this process, there may be multiple inflection points of ecological pressure; however, each point value will not exceed the range of threshold value.

4.2.6 Exorbitant urbanization type

The regional ecological condition is neither good nor poor, while the pace of urbanization is rapid. Due to low ecological threshold and rapid deterioration of eco-environment, the eco-environment quickly approaches the ecological threshold. Then, urbanization growth may become negative, which follows the elastic threshold law. During this process, there may be multiple inflection points of ecological pressure; however, each point value will be in the range of the maximum threshold value. As urbanization progresses, ecological pressure moderates gradually, while the degraded eco-environment will be difficult to restore.

4.2.7 Fragile ecology type

Regional ecological conditions are poor. Both the coercing effect of urbanization on eco-environment and the constraining effect of eco-environment on urbanization are strong. Therefore, the pace of urbanization is very slow and human regulations play an important role in the process of urbanization. As urbanization and eco-environment influence and adapt to one another continuously, ecological pressures decrease. The inflection point of ecological pressure appears somewhat earlier.

4.2.8 Rudimentary break-in type

Regional ecological conditions are poor and the pace of urbanization is somewhat slow. With the progression of urbanization, ecological pressure increases gradually, approaching a maximum threshold of ecological capacity. Therefore, urbanization and economic development are forced to adjust and to slow. After investing in ecological protection, the eco-environment is improved and ecological pressure is reduced. Overall, urbanization and ecological pressures fluctuate constantly, and through human regulation, ecological pressure decreases. During this process, the inflection point of ecological pressure appears a little later.

4.2.9 Unsustainable type

The regional ecological condition is poor while the pace of urbanization and economic development is too rapid. The coercing effect of urbanization on eco-environment is very strong. It causes a sharp increase of ecological pressure which exceeds the threshold of ecological capacity. This level of conflict is irreconcilable, and the eco-environment is badly deteriorated by urbanization, setting back civilization. This situation is beyond the limits of human psychological endurance and the rule of social development, and thus, theoretically, it does not occur in the real world.

5 Analysis and Judgment of Interactive Coercing Degree Between Urbanization and Eco-environment

5.1 Calculation of interactive coercing degree

Both interactive coercion between urbanization and eco-environment and the evolution of interactive coercion are non-linear processes (Li and Ding, 2004). Interactive coercing degree between urbanization and eco-environment (α) could be represented by the following formula:

$$\alpha = \text{arctg}\left(V_A / V_B\right)$$

$$A = \frac{\mathrm{d}f(\mathrm{E})}{\mathrm{d}t} = \alpha_1 f(\mathrm{E}) + \alpha_2 f(U) \qquad V_A = \frac{\mathrm{d}A}{\mathrm{d}t}$$

$$B = \frac{\mathrm{d}f(U)}{\mathrm{d}t} = \beta_1 f(\mathrm{E}) + \beta_2 f(U) \qquad V_B = \frac{\mathrm{d}B}{\mathrm{d}t}$$

$$V = f(V_A, V_B)$$

where A and B are evolutionary states of urbanization and eco-environment subsystems, respectively, affected by themselves and external factors; V_A and V_B are evolutionary speeds of the two subsystems. In the overall compound system, A and B affect one another, and any changes of each subsystem will lead to the change of the entire system. V is the evolutionary speed of the entire system; E is eco-environmental system; U is urbanization system.

Due to the evolution of entire system according with development mechanism of combined S-shaped path (Xu *et al.*, 2003), it can be assumed that the dynamic synergistic relationship between urbanization and eco-environment indicates cyclical changes. During every cycle, given that the changes of V are caused by V_A and V_B, V can be analyzed by a two-dimensional plane with the projection of the evolutionary path of V_A and V_B on it. This changing path of V is an ellipse in the coordinate system, shown in Fig. 8. The angle α between V_A and V_B accords with tg $\alpha = V_A/V_B$ and α can be considered the coercing degree. According to the value of α, the evolutionary state of entire system and the degree of coordinating development between urbanization and eco-environment can be confirmed. Some scholars developed other relative researches and get some progresses. Wang *et al.* (2011) build a model evaluating coupling coordination degree in Beijing. Zhang *et al.* (2011) analyzed the coordination degree of urbanization and water ecological environment in Shayinghe River Basin using the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method.

5.2 Judgment of interactive coercing degree

In an evolutionary circle, the interactive coercing system between urbanization and eco-environment will contain four phases, namely rudimentary symbiosis (I), harmonious development (II), utmost increasing (III) and spiral type rising (IV) (Fig. 8).

When $-90° < \alpha \le 0°$, the system is in a rudimentary symbiosis phase. The pace of urbanization is slow, and urbanization is essentially free from constraints of the eco-environment. Therefore, urbanization has nearly no impact on the eco-environment.

When $0° < \alpha \le 90°$, the system is in a harmonious development phase and at the stage of slow urbanization. Urbanization starts to coerce eco-environment and the eco-environment restrains urbanization gradually. The conflict between urbanization and eco-environment arises but is not obvious yet.

When $90° < \alpha \le 180°$, the system is in an utmost increasing phase and at the stage of high-speed urbanization. Because of rapid urbanization, socio-economic development utilizes more resources and severely degrades the environment. The conflict between urbanization and eco-environment is intensified, and the carrying capacity of resources and eco-environment is approach-

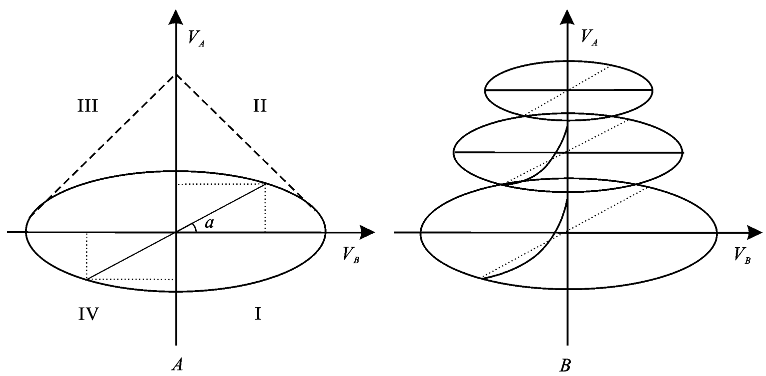

Fig. 8 Process of coupling between urbanization and eco-environment

ing the maximum and crisis is in an incubation period. During this phase, there are two evolutionary paths: 1) the conflict between urbanization and eco-environment is irreconcilable. When eco-environmental deterioration surpasses the threshold, the entire system collapses and degradation of civilization occurs. 2) A variety of engineering, economic, biological, technical and legal measures are taken to diminish the conflict, and finally, the high-grade harmonious symbiosis between urbanization and eco-environment is achieved.

When $-180° < \alpha \leq -90°$, the system is in a spiral type rising phase. The interactive coercing relationship between urbanization and eco-environment is restructured and changes from a relationship of coercing to promoting one another. The entire system will eventually reach the state of high-grade harmonious symbiosis between urbanization and eco-environment.

6 Conclusions

Objectively, a complex interactive coercing relationship exists between urbanization and eco-environment. The process of this relationship can be divided into five stages: low-level coordinate, antagonistic, break-in, ameliorative and high-grade coordinate. Through geometric derivation, it is found that this interactive coercing relationship can be explained by a double-exponential function formed by the combination of power and exponential functions. The curves can be divided into nine evolutionary types. Based on the interactive coercion model, the degree of interactive coercion can be examined. The article further summarizes the theory and method of interactive coercion between urbanization and eco-environment. In the future, more attention should be paid to the technical measure to identify the best coupling point of interactive coercion between urbanization and eco-environment, which could maintain the best distance and the homeostasis between urbanization and eco-environment. And finally, it could help us to put forward the proper urbanization models.

From the perspective of national strategic needs, a method for finding a coordinated and sustainable development pathway based on the interactive coercion between urbanization and eco-environment is an urgent research need. An important approach is to regulate the speed of urbanization between over- and under-urbanization by adopting methods from the fields of business, economics, technology, engineering, law and management. Then, the state will go toward a direction of moderate urbanization, and in this process, urbanization will be in harmony with industrialization, modernization and the eco-environment. That is a healthy urbanization road. Therefore, the future researches into practical applications include: seeking coordinated development models between urbanization and eco-environment; carrying out moderate type, ecological type, environmental protection type, saving type and healthy type urbanization models; building ecological, resource-conserving, environment-friendly, healthy cities.

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