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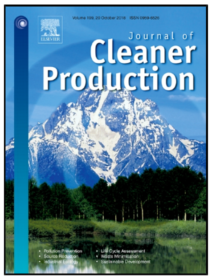

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PII:	S0959-6526(18)32593-9
DOI:	10.1016/j.jclepro.2018.08.244
Reference:	JCLP 14028
To appear in:	*Journal of Cleaner Production*
Received Date:	25 April 2017
Accepted Date:	23 August 2018

Please cite this article as: Wenjie Liu, Fengchao Jiao, Lijun Ren, Xianggong Xu, Jianchun Wang, Xu Wang, Coupling coordination relationship between urbanization and atmospheric environment security in Jinan City, *Journal of Cleaner Production* (2018), doi: 10.1016/j.jclepro.2018.08.244

The wordcount of manuscript (including tables and figure captions):7030

Coupling coordination relationship between urbanization and atmospheric environment security in Jinan City

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Abstract

Constant urbanization growth has seriously increased the influence of urbanization development on atmospheric environment security (AES). Thus, understanding the relationship between urbanization and the atmospheric environment security is necessary for Chinese policymakers to achieve sustainable urbanization development. In this study, we estimated the relationship between urbanization and atmospheric environment security in Jinan City from 1996 to 2004 on the basis of the theory of Environmental Kuznets Curves (EKC). A comprehensive index system for urbanization and atmospheric environment security was used along with statistical data and a coupling coordination degree model (CCDM). The coupling coordination results showed that the urbanization and atmospheric environment security system experienced serious imbalance between low coupling period (1996–1997), moderate disorders of coupling period (1998–2000), imbalance of antagonism period (2001–2002), basic coordinated period (2003–2008), and good coordination of highly coupled period (2008–2014). The spatial urbanization and efficiency subsystems are essential determinants of urbanization in the coupling relationship between urbanization and atmospheric environment security. We determined the main factors that influence the system to provide a basis for creating scientific urban development strategies and atmospheric environment protection measures. The findings of this study held a profound significance for further work on urbanization and provided essential data for planning in the future.

Keywords: Jinan City; urbanization; atmospheric environment security; coupling coordination degree

1 Introduction

China has experienced rapid urbanization growth since its post-reform (Hubacek, Guan, Barrett, & Wiedmann, 2009), and the urbanization levels increased from 19.39% in 1980 to 53.73% in 2013 according to the China Statistical Yearbook.

The country's rapid urbanization in the past several decades has captured the world's attention as its effects in the global scope became apparent (He, Xu, Shen, Long, & Chen, 2017). According to Northam's division of the urbanization process, the urbanization levels between 30% and 70% are considered to indicate accelerated development, which requires considerable resources, such as fossil fuels, land resource, and water resource (Li, Li, Zhou, Shi, &Zhu, 2012). Such development may also reduce the environmental carrying capacity because of the excessive use of resources (Wang, Da, Song, & Li, 2008). China is currently undergoing urbanization that is classified as accelerated development (Zhan, Huang, Zhao, Geng, & Xiong, 2013). This accelerated development has incurred a heavy price locally, thereby resulting in ecological and environmental impacts, natural resource depletion, and damage to existing ecosystem service functions in many of China's high-growth regions (Oliveira et al., 2013). Ultimately, the capability to achieve "sustainable development" in the future is highly threatened (Wei, Bao, Wu, He, & Zeng, 2015).

In a broad sense, atmospheric environment security (AES) means that the atmospheric environment on which man relies for survival and development should be in a safe and sound state without any pollution and damage. Moreover, AES indicates the risks to survival and development in the natural ecological environment and human ecological sense. In this study, AES is defined as a kind of state in which the structure and function of the atmospheric environment system are integrated, healthy, and stable to provide reliable eco-services for supporting human living and socioeconomic activities. Undoubtedly, rapid urbanization considerably threatens the AES. According to the Environmental Kuznets Curves (EKC) hypothesis, environmental pollution and degradation will become worse with economic growth during the early stage of development. However, the trend of environmental degradation slows down with continuous economic growth, and environmental quality improves over a certain level of economic development. Given that China has not yet completed the historical tasks of urbanization and industrialization, the "accelerated" urbanization levels currently being observed in the country are predicted to increase for many years to come. Therefore, thorough research into the precise relationship between urbanization and AES is critically needed. Against this backdrop, the research conducted in detail in the present study thus appears to be urgent and meaningful and will hopefully assist policymakers in coordinating development and achieving future sustainable development.

Jinan is the capital city of Shandong Province and is located in the northwestern part of Shandong Province at 36°40′ N latitude and 116°57′ E longitude of the Greenwich meridian (Fig. 1). The average level of urbanization (i.e., the composite index of several aspects, including land expansion, population growth, and economic development) has been approximately 1.5% over the past 10 years, whereas that in China was only 0.9% (Wang, Yuan, Zhang, Mu, Yang, & Ma, 2013). Meanwhile, Jinan has experienced continuous growth in the nonagricultural population (i.e., a key indicator for identifying urbanization). Compared with other large-sized and medium-sized Chinese cities, Jinan exhibited rapid urbanization and economic development.

Jinan covers an area of 8177.21 km^2 and is located in the transition belt between Luzhong south low hills and Lu northwest alluvial plain regions. Jinan is a semi-enclosed city surrounded by the Yellow River and Taishan Mountain (Zhou et al., 2016). The unique landform provides Jinan with a shallow saucer shape that is unsuitable for the spread of pollutants (Liu, Wang, Fan, Xiao, & Wang, 2016). Jinan is characterized by a typical subhumid continental monsoon climate. Given that the climate is cold in winter, the heating period is long in the region. Consequently, soot pollution of the atmospheric environment becomes the main problem. Moreover, the frequency of adverse weather, such as calm wind, temperature inversion, and fog, is high. The special meteorological conditions result in the obvious seasonal characteristics of air quality (Zhang et al., 2014). In recent years, rapid urbanization has increased the number of building construction sites and motor vehicles. This growth is an important factor leading to air pollution. Under the combined effect of the unique landform and meteorological conditions and the rapid growth in the number of building construction sites and motor vehicles, Jinan has suffered from severe air pollution and is listed as one of the major haze regions in China (Song, Yang, & Chahine, 2016).

Based on the rapid urbanization and severe air pollution problems Jinan is now facing, this study has two main purposes, i.e., (i) identifying the relationship between urbanization and AES through the coupling coordination degree model (CCDM) and (ii) determining suitable and available methods to achieve the coordinated development of urbanization and atmospheric environment and providing policy support. In response to these purposes, we established a comprehensive index system for urbanization and AES on the basis of the theory of EKC and the pressure–state–efficiency–response framework model. The entropy method was used for the calculation of the weight of each indicator. The CCDM was then used for the analysis of the coupling relationship between urbanization and AES. Finally, we used the regression model to analyze the relationships between urbanization system–AES subsystem and AES system–urbanization subsystem indicators.

In the context of sustainable development, this study is not only helpful in promoting the coordinated development of urbanization and AES but is also critical to achieving the sustainable development of what has been termed China's "new urbanization." The findings of this study hold significance for further work on the sustainable development of Jinan, providing essential data for planning. From the perspective of coordinated development, this study improves the role of AES in combating rapid urbanization so that cities can become more livable and sustainable.

In the remainder of this paper, we provide a brief literature review in Section 2. Then we present the methods in Section 3. We report the results and further analyze the coupling relationship between urbanization and AES in Section 4. Finally, we provide implications and conclusions of this study in Sections 5 and 6, respectively.

2 Literature review

This study was based on the theory of EKC, which illustrates the relationship between environment and economy. The EKC hypothesis, which states that environmental quality worsens with economy growth during the early stage of development, was first reported by Grossman and Krueger in 1991 (Liu, Zhang, & Bae, 2017). Inspired by this theory, an increasing number of scholars have attempted to determine whether the "urbanization and environment relationship" exhibits similar characteristics. A number of these researchers have reported the existence of a curve similar to that described by the EKC hypothesis. Wang, Ma, & Zhao (2014) observed a double-exponential curve between urbanization and environment. Wang, Zhang, Kubota, Zhu, & Lu (2015) conducted a similar study and obtained strong evidence for an inverted U-shaped relationship between urbanization and carbon emissions in Organization for Economic Co-operation and Development countries. Wan & Wang (2014) stated that urbanization is not only a cause of but also a solution to environmental degradation. Just as a coin has two sides, the development of urbanization accelerates the emission of pollutants, and a series of measures has been implemented to control pollution (Cheng, Jiang, Fajardo, Wang, & Hao, 2013). Similar conclusions were also drawn by Zhong et al. (2013) and Li et al. (2016). Overall, scholars have begun to focus more attention on the relationship between urbanization and environment.

Basing on the previously mentioned studies, we employed the ideology of AES to evaluate and determine whether the basic structure and function of the atmospheric environment system are threatened by urban expansion and economic development (Hassan, Afridi, & Khan, 2017). AES is considered the significant component of ecological security and can satisfy the demands of ecological security and air environment (Shi, Wang, Huisingh, & Wang, 2014). In physics, coupling refers to the phenomenon in which two or more systems or movement forms influence one another through various interactions (Li et al., 2012). Given the nature of the relationship between urbanization and AES systems, the analysis of the coupling between the two systems will provide effective support for facilitating the coordinated evolution of population, resources, environment, and development.

However, most of the existing studies have concentrated on the relationship between economic growth and environment, and few of them considered urbanization rather than economic growth. Even among the empirical studies of urbanization and environment, focus has been placed on the investigation of the EKC hypothesis, and only a few researchers assessed the coupling relationship. In addition, existing research has tended to address the spatial scale of a province, such as Shandong (Wang, Yuan, Lai, Ma, & Ren, 2012) or Jiangxi (He, Pan, Wang, & Lei, 2013); a basin, such as Huai River Basin (Guo, Wang, Nijkamp, & Xu, 2015); or an interregional area, such as Yangtze River Delta (Zhao, Wang, & Zhou, 2016), Beijing–Tianjin–Hebei region (Wang et al., 2014), or southern Brazil (Pagliosa, 2006). A single city has hitherto been neglected in existing literature. Furthermore, only a few studies of the coupling relationship between urbanization and AES systems have been conducted. Therefore, more in-depth studies of the coupling relationship between urbanization and AES systems should be conducted. The findings of this study hold broad significance for further work on urbanization, providing essential data for planning.

3 Methods

3.1 Index system design

This study aimed to measure the AES condition in the process of urbanization using an objective, comprehensive, and scientific method. For this purpose, the following general selection criterion has been adopted: (1) choose the most cited indicators; (2) cover the components of urbanization sustainability and the pertinent predetermined categories and (3) choose the simplest indicators to facilitate data collection, understanding and dissemination (Liu, Yao, Wang, & Bao, 2011). Given the criterion, an evaluation index system from four aspects of demographic, economic, social, and spatial urbanization was established. According to the status quo and existing problems of AES of Jinan City, the Pressure–State–Efficiency–Response framework model was adopted to set up the evaluation index system of AES. The model was selected because it can clearly express the complex relationship within the system. Then, frequency analysis was used to determine the main indexes of the urbanization and AES system. The expert consultation method was used to further determine the selected indicators for optimizing the selected indicators. Finally, 15 evaluation indexes of the urbanization system and 12 evaluation indexes of the AES system were determined.

3.2 Data sources and preprocessing

The relevant statistical data were collected from the Statistical Yearbook of Shandong and Jinan (1997–2015) from the China Statistical Yearbooks Database by the National Knowledge Infrastructure of China. Other environmental quality data were obtained from the Annual Environmental Report by Jinan Environmental Protection Agency. The Statistical Yearbook of Shandong and Jinan were compiled according to the Statistics Law of The People's Republic of China. The statistical data were collected from the Bureau of Statistics of Shandong Province, Bureau of Statistics of Jinan City, and National Bureau of Statistics of the People's Republic of China. Therefore, the data are reliable and credible. Considering that the raw data of the selected indicators differ in dimension and that the indicators differ in orders of magnitude, the data were standardized using Formulas (1) and (2) and the influence of dimension, magnitude, and positive and negative orientations were eliminated (Ren, Cui, & Sun, 2014).

Positive indicator: $$x'_{ij}=\frac{x_{ij}-x_{minj}}{x_{maxj}-x_{minj}} \tag{1}$$

Negative indicator: $$x'_{ij}=\frac{x_{maxj}-x_{ij}}{x_{maxj}-x_{minj}} \tag{2}$$

In the above-mentioned formulas, x_{ij} represents the value of indicator j in year i; x_{maxj} and x_{minj} indicate the maximum and minimum values of indicator j among all years.

3.3 Evaluation of urbanization and AES

The levels of urbanization and AES quality were analyzed using the entropy method (Zou, Yun, & Sun, 2006). The entropy method is initially devoted to the study of the convergence to equilibrium (Chen, Zhang, Chen, & Nie, 2015). Although the theory of entropy belongs to thermodynamic category, different disciplines have applied the concept of entropy to specific areas according to their requirement. The entropy principle is a general rule of nature, and all the phenomena of nature follow the principle of entropy. The value of entropy reflects the degree of order of one system. Therefore, the theory of entropy can be used to analyze the effect of urbanization on atmospheric environment and find the methods that can coordinate the relationship between urbanization and atmospheric environment (Wang, Yuan, Ma, Zhang, & Zuo, 2012). The weight of each indicator was calculated on the basis of the information entropy and variations in the indicators. The steps were as follows (Formulas (3)–(8)):

The proportion of the indicator *j* in year *i*: $P_{ij} = x'_{ij} \Big/ \sum_{i=1}^{m} x'_{ij}$ (3)

Information entropy of indicator: $e_j = -\frac{1}{\ln m}\sum_{i=1}^{m}(P_{ij} \times \ln P_{ij})$, $(0 \le e_j \le 1)$, when $P_{ij} = 0$, $e_j = 0$ (4)

Entropy redundancy: $g_j = 1 - e_j$ (5)

Weight of the indicator: $W_j = g_j \Big/ \sum_{j=1}^{n} g_j$ (6)

Evaluation of a single indicator: $S_{ij} = W_j \times x'_{ij}$ (7)

Comprehensive level in year *i*: $S_i = \sum_{j=1}^{n} S_{ij}$ (8)

In the afore-mentioned formulas, n is the number of indicators and m is the number of years.

Small entropy value means the difference among the indicators is significant and the evaluation indexes are important. The original data (1996–2014) describing the 27 indicators of Jinan City were processed using these steps on a time scale, and the relevant values were subsequently calculated. The calculation results are shown in Table 1.

3.4 Coupling coordination degree model

The CCDM is significant for cities in their future development plans (Ding, Zhao, Huang, Cheng, & Liu, 2015). In physics, coupling refers to the phenomenon in which two or more systems or movement forms influence one another through various interactions (Li et al., 2012). Coupling degree (*C*) is the measurement of coupling relation and describes the degree of which systems or system elements interact with each other. Coupling coordination degree (*D*) determines the sequence and structure of the system when it reaches the critical region, or determines the trend that the system is from disorder to order (Zhou, Li, & Zhang, 2016). CCDM is given in Formulas (9)–(11) as follows:

The comprehensive evaluation index: $T = \alpha U(x) + \beta A(y)$ (9)

The coupling degree: $C = U^k(x) \times A^k(y) / T^{2k}$ (10)

The coupling coordination degree: $D = \sqrt{C \times T}$ (11)

In the said formulas, *T* represents the comprehensive evaluation index of the urbanization and AES system; *U(x)* is the level of the urbanization subsystem and *A(y)* is the AES subsystem; α and β represent the contribution of urbanization and AES, respectively. Let α = β = 0.5 (Ai, Feng, Dong, Zhu, & Li, 2016), where *C* represents the degree of coupling and *K* is the regulation factor. Let *K* = 2 (Zhou, Xu, & Lin, 2016). When the sum of *U(x)* and *A(y)* is constant, *C* represents the degree of coupling between urbanization and AES. In this study, *U(x)* and *A(y)* can be calculated by S_i described in Formula (8). *D* is the degree of coupling coordination. The determination of these values is described in detail in Table 2.

Following domestic and foreign scholars on the research achievements of coordinated development between urbanization and environment quality (Wang, Fang, Wang, Huang, & Ma, 2015), the coupling coordination degree between urbanization and AES was obtained. The results are shown in Table 3.

3.5 Regression analysis

Regression models were used to analyze the relationships between urbanization system–AES subsystem and AES system–urbanization subsystem indicators. The parametric goodness of fit (R^2 value) was used to check the applicability of the model

(Huang, Li, Pontius, Klemas, & Hong, 2013). The non-parametric correlation statistic was employed because it can account for non-linear relationships. The exponential regression model can be expressed as follows:

$$Y = A + BC^{Dx} \tag{12}$$

Where x is an independent variable (urbanization index value) and Y is a dependent variable (AES index value). A, B, and C are all model coefficients.

4 Results

4.1 Main influence indicators of urbanization and AES systems

In Table 1, economic urbanization had the maximum weight and was therefore an indicator with the most significant influence on the comprehensive level of urbanization at the subsystem level, followed by spatial and demographic aspects, and finally by social aspects. In the urbanization process of Jinan City, the geographical scope of the city has expanded, the level of economic development has continued to improve, and urban population density has continued to increase. These phenomena show that economic development represents the foundation, migration and geographic expansion represent the performance, and living standard improvement represents the final result of the target in the urbanization process.

In the AES subsystem, the most significant influence indicator was state subsystem, followed by pressure, efficiency, and response subsystems. The continuous development of urbanization from 1996 to 2014 has continuously changed the industrial structure of Jinan City and decreased the proportion of industries. The strengthening of the city environmental protection investment and the vigorous promotion of the enterprise clean production system have improved the industrial soot and dust removal rates, thereby decreasing the emissions of industrial SO_2, soot, and dust. Consequently, the AES degree has improved constantly.

4.2 Trends of the comprehensive level of the urbanization and AES systems

Fig. 2 shows the changing trend of the comprehensive level of the urbanization system. The overall level of urbanization increased from 1996 to 2014. Obviously, the upward trend of spatial aspects was significant. Other systems showed no significant fluctuation in each year.

Fig. 3 shows the changing trend of the comprehensive level of the AES system. The comprehensive level of the AES system initially decreased and subsequently obviously increased from 1997 to 2001. Thereafter, the comprehensive level of the AES system stabilized but largely fluctuated from 2010 to 2014. The fluctuation of the comprehensive level of the AES system is mainly attributed to the decline in the pressure and state subsystem security degrees in 2011 and 2013, respectively. The state subsystem security degree decreased markedly from 1996 to 1997 along with the increase in the ambient air concentrations of SO_2 and NO_2. From 1997 to 2000, the ambient air concentrations of SO_2, NO_2, and PM_{10} showed a significant downward trend. Accordingly, the security of the state subsystem continued to increase. From 2000 to 2012, the ambient air concentrations of SO_2, NO_2, and PM_{10} changed to a lesser extent, and the state subsystem security degree remained stable. However, the state subsystem security degree declined sharply after 2013 mainly because the new ambient air quality standards (GB3095-2012) were enforced after 2013. The requirements of valid monitoring data of GB3095-2012 are stricter than those of GB3095-1996. Consequently, the air pollution composite index and annual average ambient air concentrations of SO_2, NO_2, and PM_{10} increased after 2012. Therefore, the state subsystem security degree declined after 2013.

Pressure subsystem security declined in the periods 1996–1997, 2002–2005, and 2010–2011 because of the increased emissions of industrial SO_2, soot, and dust. In 1997–2002 and 2011–2014, industrial SO_2, soot, and dust emissions showed a significant downward trend, thereby increasing the pressure subsystem security degree. From 1996 to 2012, per 10,000 yuan of industrial added value, SO_2, soot, and dust emissions showed a downward trend. As a result, efficiency subsystem security exhibited an upward trend in the said period. From 1996 to 1997, the industrial dust and soot removal rates decreased briefly because of the development of environmental air treatment facilities. However, with the strengthening of environmental protection investment after 1997, industrial soot and dust control intensified. The industrial soot and dust removal rates also increased and resulted in the good state of the AES response subsystem security. In general, the atmospheric pressure factor was insufficient to influence the overall quality of the AES system because of the continued adoption of atmospheric environment and industrial control measures, and the AES system status was good.

4.3 Coupling relationship between urbanization and AES systems

The quantitative evaluation of the coupling relationship and coordination degree between urbanization and AES is shown in Table 2. The coupling coordination degree evolution curves of the two systems were drawn. The purpose was to test the influence of urbanization and AES on the coordinated degree of coupling and to clearly reflect the coupling evolution trend in time series (Fig. 4).

The coupling coordination degree between urbanization and AES indicated an overall increasing trend during the course of the study period, producing an S-shaped curve. Combined with the data shown in Tables 2 and 3, the development of coupling in the following four stages was analyzed:

(1) 1996–2001: The coupling coordination degree between the two systems was poor. In 1996–1997, the two systems were in a low coupling state. Their development showed a serious imbalance state, the atmospheric quality decreased rapidly because of the low level of urbanization, and the urbanization stress effect on the atmospheric environment was obvious. In 1997–2001, the two systems remained at a low coupling coordination degree but in a moderate imbalance state in the development process. The urbanization development stress effect on atmospheric environment weakened, and the quality of atmospheric environment was within the recoverable scope.

(2) 2002–2004: During this period, the development of the two systems was in the antagonism period and in a state of disorder. The energy demand and consumption were large as a result of the growth state of urbanization development. Therefore, a large volume of air pollutants were discharged and the atmospheric environment quality was affected obviously by urbanization development. By contrast, worse atmospheric environment quality would affect urbanization development seriously.

(3) 2005–2007: During this period, a turnaround seemed to occur and resulted in urbanization and AES undergoing basic coordination. The urbanization and AES systems were in the stage of run-in. Meanwhile, urbanization entered a rapid development period. During this period, a series of measures was implemented, such as increasing the investment in environmental protection, promoting clean production, and strengthening the control of atmospheric pollution. Therefore, the atmospheric environment quality significantly improved.

(4) 2007–2014: During this period, the urbanization and AES systems were in the highly coupled phase. The development of the two systems was in a good coordination state. Not only the urbanization level but also the atmospheric environment quality enhanced unceasingly. Urbanization entered the benign development stage with atmospheric environment protection.

4.4 Coupling relationship between urbanization subsystem and AES system

We imported the regression curve between AES and urbanization subsystems to analyze the coupling relationship between urbanization subsystem and AES system. Fig. 5 shows the coupling diagram of the relationship between urbanization subsystem and AES system. Table 4 lists the relevant regression curve parameters.

The coupling correlation coefficient of spatial urbanization and AES was the highest and therefore had the most significant influence on the AES system. Demographic, economic, and social aspects came in second. Air pollution mainly concentrated in the urban built-up regions. The city industrial zone, industrial resident mixed area, and downtown business gathering area air pollutions were heavy, whereas those from other areas were light. In the urbanization of Jinan City, the city region and urban built-up areas have expanded and the urban industries and population distribution have changed along with the change of the spatial structure. Urban structure, morphology, industrial enterprises, living area, and road traffic planning exert a certain influence on the atmospheric environment. Therefore, this finding indicates that the urban spatial layout should be planned reasonably by the government during the development of urbanization and urban development policies for rapidly urbanizing cities, such as Jinan.

4.5 Coupling relationship between urbanization system and AES subsystem

The coupling diagram of the relationship between urbanization system and AES subsystem is shown in Fig. 6, and the relevant regression curve parameters are shown in Table 5.

The coupling correlation coefficient of efficiency subsystem and urbanization was the highest and therefore had the most significant influence on the urbanization system. This finding indicates that more attention should be focused on the "per 10,000 yuan of industrial added value industrial pollutant emissions" in atmospheric governance, which also shows that reductions in the emissions of industries should be enforced and industrial structure should be optimized to achieve the goal of sustainable development.

5 Implications

The historical and current data compiled and analyzed in this study present a unique case study on the AES of Jinan City. The CCDM is significant and meaningful for the future development of Jinan. As the capital city of Shandong Province, Jinan should explore the coupling relationship between urbanization and AES and identify the key factors influencing future sustainable and healthy urbanization. The results of this study indicate that the rapid development of urbanization placed significant pressure on the atmospheric environment in the initial development stage of Jinan. During this period, urbanization and AES were seriously imbalanced and brought about adverse effects in relation to one another. With the implementation of useful environmental protection plans, the level of coupling between urbanization process and AES system increased rapidly, shifting from a stage of "low coupling" to a stage of "high coupling." Given the sustainable development of urbanization, the results indicate that the urban spatial layout should be planned reasonably by policymakers and government leaders. From the AES aspect, policymakers and government leaders should focus more attention on the adjustment of the industrial structure to achieve sustainable development. In addition, the introduction of advanced technology, highly efficient resource consumption, and less environmental pollution emissions should be emphasized during economic policymaking.

6 Conclusions

In this study, a CCDM was developed to evaluate the degree of coupling between urbanization and AES quantitatively, with Jinan City as the case. In the context of rapid urbanization, the relative analysis described herein was applied to investigate the dynamic change of the coupling coordination degree between urbanization and AES. In general, the coupling coordination degree between urbanization and AES initially decreased and subsequently increased in a straight-line trend from 1996 to 2014. The results in Jinan City changed from low coupling period to the imbalance of the antagonism period, the basic coordination period, and the good coordination of the high coupling period. This empirical work can provide a useful evidence base for future attempts to improve urbanization and AES, which also for the better realization of sustainable development.

This study indicates that economic urbanization has the maximum weight at the urbanization subsystem. In extension, the coupling correlation coefficient of spatial urbanization and AES was the highest. In other words, spatial urbanization was the most important determinant of urbanization in the coupling relationship between urbanization and AES in Jinan from 1996 to 2014. This finding indicates that urban planners and government decision makers must focus more attention on the layout of urban space to achieve the coordinated development of urbanization and atmospheric environment. Moreover, urban planners and government decision makers must emphasize sustainability in the formulation of urban development policies for rapidly growing and urbanizing areas, such as Jinan.

The state subsystem has the maximum weight at the AES subsystem, which indicates that the strengthening of the city environmental protection investment helps in increasing the level of urbanization to some extent. In extension, reductions in the emissions of industries should be enforced and industrial structure should be optimized to achieve the goal of sustainable development. Furthermore, a circular economy should be vigorously developed, and resources should be efficiently utilized to improve the quality of life and create a livable region.

According to the theory of EKC, the relationship between urbanization and environment exhibits an inverted U-shaped curve. However, in this study, the coupling coordination degree between urbanization and AES indicated an overall increasing trend during the course of the study period, producing an S-shaped curve. This finding can be mainly attributed to the fact that the theory of EKC only focused on the effect of urbanization on the environment, neglecting the effect of the environment on urbanization. In this study, a CCDM, which illustrated that urbanization and environment influence each other through various interactions, was established and found that the coupling coordination degree between urbanization and AES presented an overall increasing trend.

On the management aspect, government departments should plan the urban spatial layout reasonably and reduce the adverse planning effects on AES. Meanwhile, policymakers and government leaders must focus more attention on the worsening air quality in Jinan, which can influence the achievement of sustainable urbanization in the long term and is admittedly a considerable challenge for government decision makers to maintain a balanced development between urbanization and AES. As we have discussed previously, optimizing the industrial structure and improving the resource utilization rate based on technological advancement are the most effective measures for accelerating the transformation of the city's economic development.

Acknowledgements

We would like to thank the reviewers for their valuable comments and suggestions. We thank Erqian Cui for her valuable contributions to this research. We thank shinewrite.com for its linguistic assistance during the preparation of this manuscript. This research is supported by China National Natural Science Foundation (no. 41301649).

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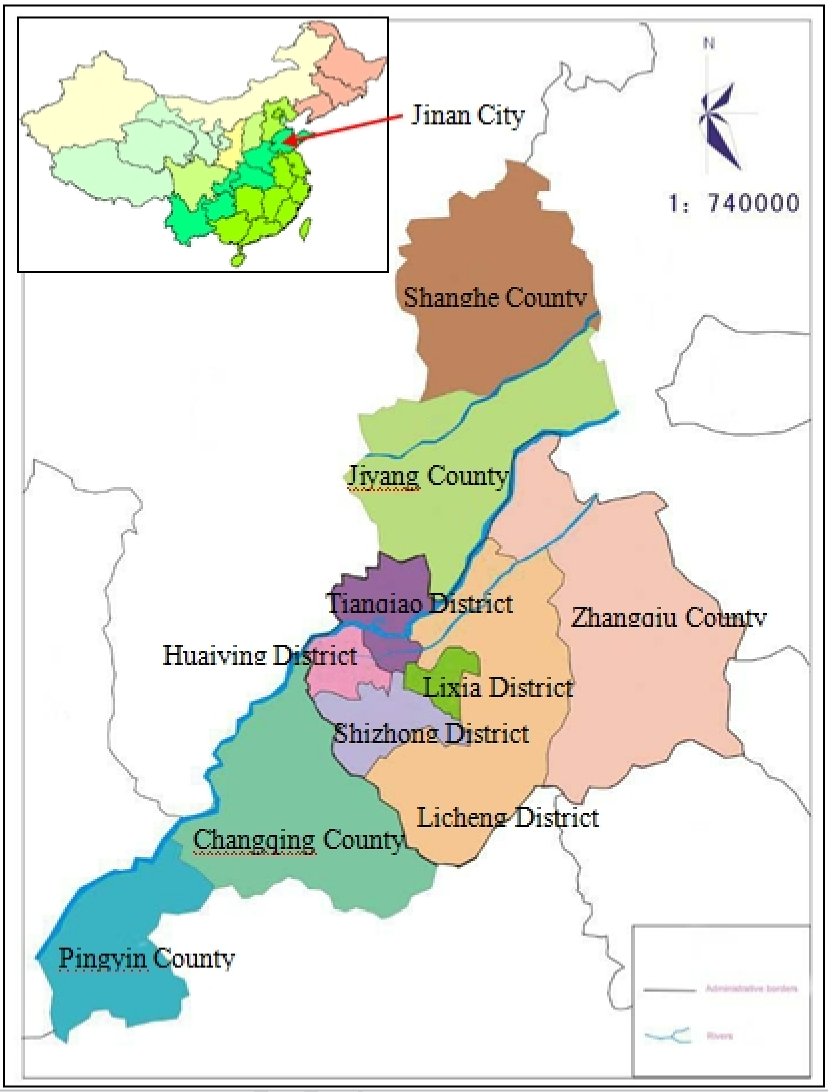

Fig. 1 Study area

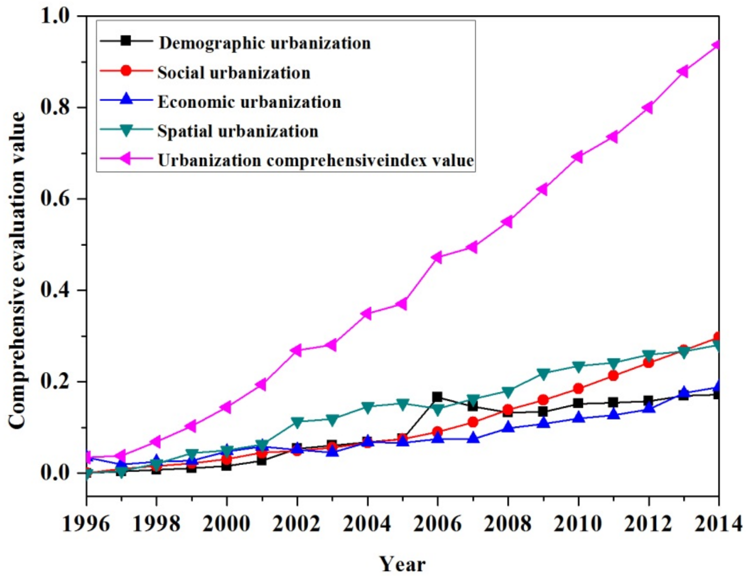

Fig. 2 The changing trend of comprehensive level in the urbanization system

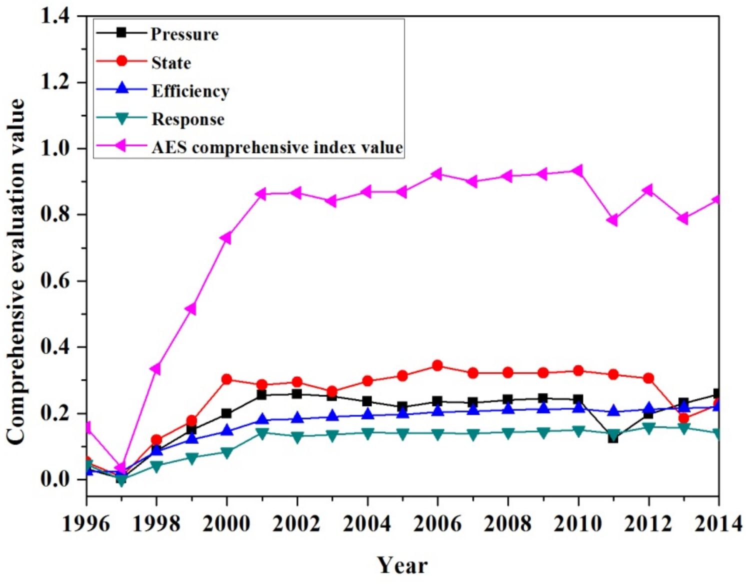

Fig. 3 The changing trend of comprehensive level in the AES system

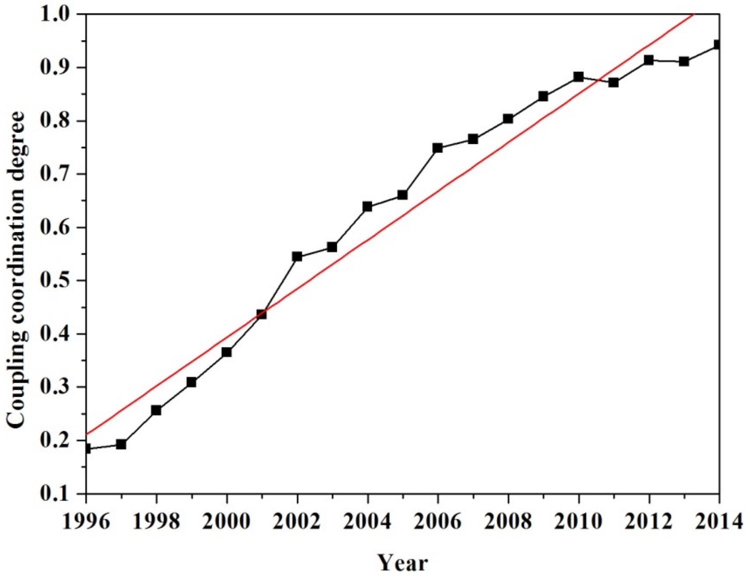

Fig. 4 Coupling coordination degree evolution curve of urbanization and AES systems

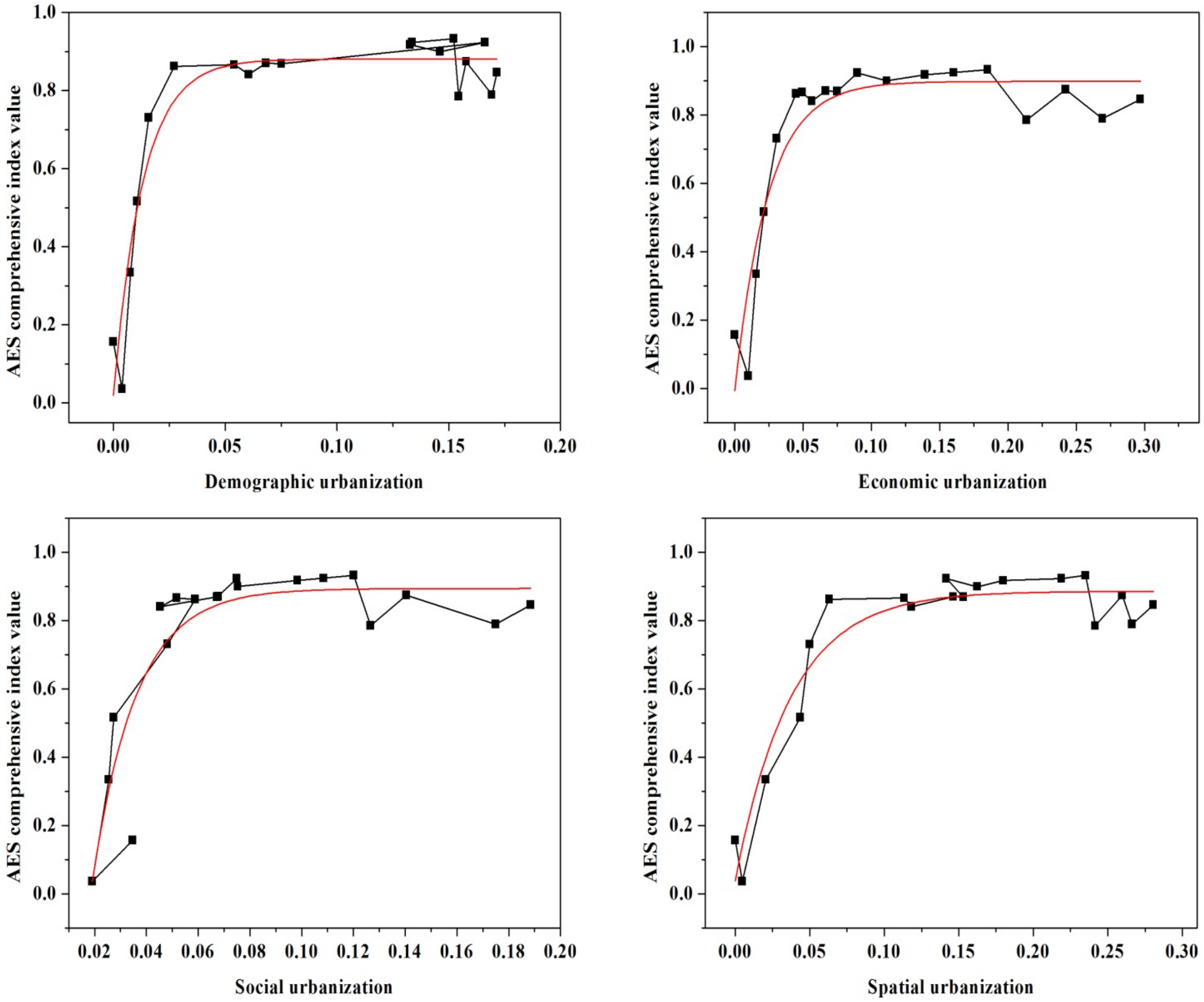

Fig. 5 Urbanization subsystem and AES system coupling curve during 1996-2014 in Jinan

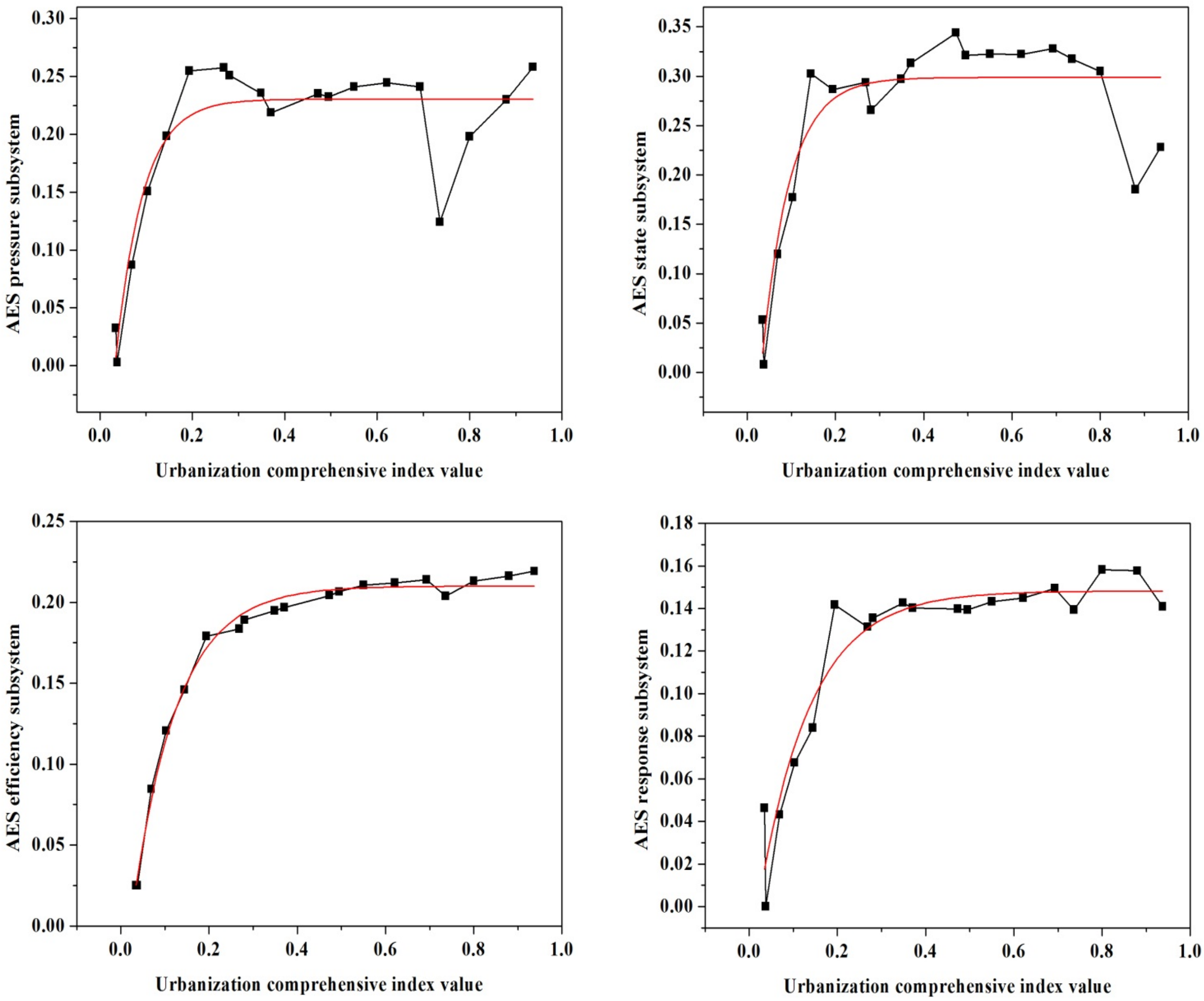

Fig. 6 Urbanization system and AES subsystem coupling curve during 1996-2014 in Jinan

- Comprehensive index evaluation system of urbanization and AES was constructed.
- The Entropy Method was employed to determine the index weight of the system.
- Coupling coordination degree model between urbanization and AES system was established.

Table 1

Index system used for evaluation of the relationship between Urbanization and the AES and the index weights

Target layer	Subsystem layer	Index layer	Index type	Entropy weight	Subsystem weight
urbanization	U1 Demographic aspects	U11 Non-agricultural population rates (%)	+	0.0758	0.2305
		U12 Percentage of the tertiary industry employed population to total employed population (%)	+	0.0526	
		U13 Urban population density (People/km^2)	+	0.1021	
	U2 Economic aspects	U21 Per capital GDP (yuan/people)	+	0.0781	0.2970
		U22 Percentage of GDP of added value of tertiary industry (%)	+	0.0314	
		U23 Per capita disposable income of urban people (yuan/people)	+	0.0858	
		U24 Per capita total retail sales of social consumer goods(yuan/people)	+	0.1017	
	U3 Social aspects	U31 Number of doctors per 10000 people (people/10000 people)	+	0.0857	0.1920
		U32 Number of public transportation vehicles per 10000 people(M/ten thousand)	+	0.0380	
		U33 Number of college students per 10000 people(people/10000 people)	+	0.0683	
	U4 Spatial aspects	U41 Per capita road area(People / m^2)	+	0.0752	0.2805
		U42 Urban residents per capita living space (m^2/people)	+	0.0640	
		U43 Urban per capita public green area (m^2/people)	+	0.0423	
		U44 Built up area greening coverage (%)	+	0.0269	
		U45 Percentage of the urban built up area of total land area (%)	+	0.0721	
AES	A1 Pressure	A11 Industrial SO_2 emissions (t)	-	0.1110	0.2731
		A12 Industrial soot emissions (t)	-	0.1027	
		A13 Industrial dusk emissions (t)	-	0.0594	
	A2 State	A21 Air pollution composite index in Jinan city	-	0.0923	0.3468
		A22 Annual average ambient air concentrations of SO_2（mg/m^3）	-	0.0925	

	A23 Annual average ambient air concentrations of PM_{10}（mg/m^3）	-	0.0943	
	A24 Annual average ambient air concentrations of NO_2（mg/m^3）	-	0.0677	
A3 Efficiency	A31 Per 10,000 yuan of industrial added value industrial SO_2 emissions（t/10000yuan）	-	0.0783	0.2192
	A32 Per 10,000 yuan of industrial added value industrial soot emissions（t/10000yuan）	-	0.0763	
	A33 Per 10,000 yuan of industrial added value industrial dust emissions（t/10000yuan）	-	0.0646	
A4 Response	A41 Ratio of industrial soot removed (%)	+	0.0903	0.1609
	A42 Ratio of industrial dust removed (%)	+	0.0706	

Table 2

Coupling results of urbanization and AES system

Year	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Urbanization comprehensive index value (U)	0.0347	0.0377	0.0693	0.1031	0.1445	0.1940	0.2686	0.2808	0.3489	0.3707	0.4727	0.4953	0.5502	0.6213	0.6927	0.7363	0.8003	0.8799	0.9375
AES comprehensive index value (A)	0.1567	0.0359	0.3342	0.5160	0.7307	0.8622	0.8660	0.8410	0.8700	0.8689	0.9232	0.8995	0.9172	0.9236	0.9323	0.7848	0.8740	0.7890	0.8463
Comprehensive index value (T)	0.0957	0.0368	0.2018	0.3095	0.4376	0.5281	0.5673	0.5609	0.6095	0.6198	0.6979	0.6974	0.7337	0.7725	0.8125	0.7606	0.8371	0.8344	0.8919
Coupling degree (C)	0.3521	0.9988	0.3235	0.3081	0.3042	0.3596	0.5224	0.5634	0.6678	0.7030	0.8025	0.8391	0.8788	0.9249	0.9570	0.9980	0.9961	0.9941	0.9948
Coupling coordination degree (D)	0.1835	0.1917	0.2555	0.3088	0.3648	0.4358	0.5444	0.5621	0.6380	0.6601	0.7484	0.7650	0.8030	0.8452	0.8818	0.8712	0.9132	0.9108	0.9419

Table 3

Coupling coordination degree classification level of urbanization and AES

Coordination level	Serious imbalance	Moderate imbalance	Imbalance	coordinate	Basic coordination	Good coordination
Coupling state	Low coupling	Low coupling	Antagonism stage	Running-in stage	Running-in stage	Highly coupling stage
coupling coordination degree	D≤0.25	0.25<D≤0.45	0.45<D≤0.55	0.55<D≤0.65	0.65<D≤0.8	0.8<D≤1

Table 4

Urbanization subsystem and AES system coupling regression curve parameters

Urbanization subsystem and AES system coupling	Fitting curve equation	regression curve parameters R^2
Demographic urbanization and AES system coupling	$y = 0.881 - 0.862\exp(x/ - 0.01$	0.904
Economic urbanization and AES system coupling	$y = 0.898 - 0.906\exp(x/ - 0.0$	0.860
Social urbanization and AES system coupling	$y = 0.894 - 2.695\exp(x/ - 0.01$	0.793
Spatial urbanization and AES system coupling	$y = 0.886 - 0.848\exp(x/ - 0.03$	0.921

Table 5

Urbanization system and AES subsystem coupling regression curve parameters

Urbanization system and AES subsystem coupling	Fitting curve equation	regression curve parameters R^2
Urbanization system and pressure subsystem coupling	$y = 0.231 - 0.405\exp(x/ - 0.0$	0.814
Urbanization system and state subsystem coupling	$y = 0.299 - 0.484\exp(x/ - 0.0$	0.810
Urbanization system and efficiency subsystem coupling	$y = 0.210 - 0.260\exp(x/ - 0.1$	0.991
Urbanization system and response subsystem coupling	$y = 0.148 - 0.176\exp(x/ - 0.01$	0.920