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Spatio-temporal evolution and influencing factors of urban green development efficiency in China

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Abstract: To resolve conflicts between development and the preservation of the natural environment, enable economic transformation, and achieve the global sustainable development goals (SDGs), green development (GD) is gradually becoming a major strategy in the construction of an ecological civilization and the ideal of building a “beautiful China”, alongside the transformation and reconstruction of the global economy. Based on a combination of the concept and implications of GD, we first used the Slacks Based Model with undesirable outputs (SBM-Undesirable), the Theil index, and the spatial Markov chain to measure the spatial patterns, regional differences, and spatio-temporal evolution of urban green development efficiency (UGDE) in China from 2005 to 2015. Second, by coupling natural and human factors, the mechanism influencing UGDE was quantitatively investigated under the framework of the human-environment interaction. The results showed that: (1) from 2005 to 2015, the UGDE increased from 0.475 to 0.523, i.e., an overall increase of 10%. In terms of temporal variation, there was a staged increase, with its evolution having the characteristics of a “W-shaped” pattern. (2) The regional differences in UGDE followed a pattern of eastern > central > western. For different types of urban agglomeration, the UGDE had inverted pyramid cluster growth characteristics that followed a pattern of “national level > regional level > local level”, forming a stable hierarchical scale structure of “super cities > mega cities > big cities > medium cities > small cities”. (3) UGDE in China has developed with significant spatial agglomeration characteristics. High-efficiency type cities have positive spillover effects, while low-efficiency cities have negative effects. Different types of urban evolution processes have a path dependence, and a spatial club convergence phenomenon exists, in which areas with high UGDE are concentrated and drive low UGDE elsewhere. (4) Under the framework of regional human-environment interaction, the degree of human and social influence on UGDE is greater than that of the natural background. The economic strength, industrial structure, openness, and climate conditions of China have positively promoted UGDE.

Keywords: green development; efficiency; green city; green economy; spatial scale; sustainable development goals (SDGs)

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1 Introduction

The construction of an ecological civilization is a fundamental strategy for sustainable development in China, and the development of a high-quality modern economic system and solving pollution problems are key features of this policy. China's development has undergone an evolution through "disordered development", "black development", "circular development", and "sustainable development", and is gradually transiting toward green development (GD). As an important part of the construction of an ecological civilization, GD can resolve the conflicts between development and the preservation of the natural environment, solve ecological problems, and satisfy the demands of citizens for beautiful environments, such as fresh water, green mountains, and a high quality ecological environment (Huang *et al.*, 2017; Marc, 2018). Green development is consistent with the concept of sustainable development, and this synergy is very important for providing policy guidance to achieve sustainable development. In addition, the construction of an ecological civilization and implementation of a GD strategy are also in line with the strategy of "supply side reform" in China. Under the constraints of the available resources and environmental conditions, the use of the healthy economic growth model has become an important way to transform to a new normal in terms of economic activity (Feng *et al.*, 2017; Che *et al.*, 2018). Under the background of the disappearance of the labor factor dividend at "the Lewis turning point", it is difficult to continue a development paradigm that relies solely on increasing the input of production factors (Kumar *et al.*, 2016). Therefore, there is an urgent need to accelerate the transformation of development methods and use transformation, quality upgrades, and increase efficiency as the main ways to realize a transformation from the growth of factor inputs to a new-type of development through "quality change", "efficiency change", and "driver change" (Teresa, 2018; Zeng *et al.*, 2018).

Green development, as an important way to achieve sustainable economic, social, and environmental development, is gradually becoming the focus of the global sustainable development goals (SDGs) and human development (Zhou *et al.,* 2020). GD has received much research attention from the academic community. United Nations Committee on World Environment and Development report in 1987, *Our Common Future,* raised the issue of sustainable development for the first time (Brundtland, 1987). In 1989, David Pierce's book *Blueprint for a Green Economy* first mentioned the concept of GD, with environmental protection as its core. The United Nations Economic and Social Commission for Asia and the Pacific (UNESCAP) Fifth Asia-Pacific Conference on Environment and Development in 2005 introduced the concept of "green growth" and defined green growth as "environmentally sustainable economic growth". In 2007, the United Nations Environment Program (UNEP) defined the "green economy" as an economy that values people and nature, and that can create decent, high-paying jobs. With the in-depth understanding of the relationship between economic activities, natural resources, and the environment, especially after the international financial crisis in 2008, new concepts of a green economy, green new policy, green growth, green transition, and GD have been successively proposed to address the practical needs of development and sustainable development. In 2011, the Organization for Economic Cooperation and Development (OECD) proposed that GD would be the solution for economic growth and development, and also the key to preventing environmental degradation, loss of biodiversity, and unsustainable use of natural resources (OECD, 2012). At the "Rio+20" summit in 2012, countries around the world further consolidated the consensus on GD, promoted the diversified development of the green economy model, and proposed to reshape our common future. The United Nations Conference on Sustainable Development introduced the theme of "Developing a green economy" in 2012, and explicitly called for a new direction of "global economic transition to green". Through continuous appeals and declarations by international organizations and academia, a broad consensus around GD has formed and has been put into practice globally. In addition, researchers have also started to investigate the relationship between human development and the natural environment as a contribution to research in the field of GD. Continuous criticism and progress has been made by adopting an ecological consciousness, undertaking environmental reflection and awakening, and practicing sustainable growth and balanced development, sustainability, and greenness. Through constant adjustment, innovation and optimization of the development model, the GD concept, which aims to improve the utilization of resources and energy, while maintaining economic growth, and avoiding both excessive damage to the environment and excessive consumption of resources, is gradually becoming a focus of international academic circles in the modern era.

The concept of GD is closely related to the traditional Chinese concept of harmony between man and nature, as well as the modern concept of sustainable development. It also concurs with the mantra of "lucid waters and lush mountains are invaluable assets" and the construction of an ecological civilization in the modern era. Chinese researchers have extensively studied the implementation of GD strategies and policies, as well as the related driving and restricting factors. Through an analysis of the concept and implications, mode of transformation, strategic countermeasures and driving (restricting) factors, measurement and evaluation indexes, theory, and application of GD, a relatively systematic theoretical system has been formed (Huang *et al.*, 2014; Zheng *et al.*, 2014; Gu, 2015; Liu *et al.*, 2015; Choi *et al.*, 2016; Lin *et al.*, 2017). Cyclical and low-carbon development is the key to improving green development efficiency (GDE). Improvements in GDE have mainly occurred through green growth, green technology, green energy, and green innovation. This has been achieved through low energy consumption, and the constant increase in the proportional contribution of human health and environmentally friendly industries to overall GDP. In this way, low resource consumption and low emissions can be achieved, and economic growth can be decoupled from resource consumption and pollution emissions (Feng *et al.*, 2016). Improving GDE is an important way to realize the construction of an ecological civilization and achieve economic transformation and development. While realizing economic growth, GD can also achieve resource conservation and the reduction of environmental pollution, as well as promoting a shift to low inputs, low emissions, and high outputs. Studies of GDE have mainly started from the macro-scale (i.e., region) or micro-scale (i.e., enterprise or industry). Studies have covered aspects of GD, such as measurement models and calculation methods, temporal changes and spatial differentiation, convergence and influencing factors, and efficiency evaluations in different industries (Ray *et al.*, 2014; Ma *et al.*, 2017; Mu *et al.*, 2017; Zhang *et al.*, 2017; Bai *et al.*, 2018). Efficiency was measured by methods such as the data envelopment analysis (DEA), directional distance function (DDF), and total factor productivity (TFP) models (Lin *et al.*, 2014; Li *et al.*, 2016; Song *et al.*, 2018). The Malmquist exponential decomposition, kernel density estimation, and spatial autocorrelation were used to interpret the spatio-temporal dynamic evolution characteristics. Tobit regression, bootstrap truncated regression, and spatial autoregressive models were constructed to determine the effects of fiscal decentralization, technological innovation, and environmental regulation on GDE (Zhang *et al.*, 2018; Zhao *et al.*, 2018; Frick *et al.*, 2019). These empirical studies have consolidated the results of previously established top-level models and systematically evaluated the implementation of Chinese GD patterns, including the regional differences, differences between industrial sectors, and the GD heterogeneity of enterprises.

A city is a complex open giant system, with multiple elements. Studying urban green development efficiency (UGDE) will enable the identification of the development status of "economic-social-natural" factors and enable the effective allocation of the resources used in urban development (Verónica *et al.*, 2019). From the perspective of inputs, previous studies have rarely incorporated technological innovation into the production stage, and have therefore failed to fully consider the impact of technological inputs on production. The input of resource elements has only covered the consumption of fossil fuels because it is difficult to accurately and comprehensively identify the energy consumption in actual production. On the other hand, there is still a lot of room for improvement in the design of social outputs. Researchers have been more concerned about environmental pollution factors, while the ecological benefits brought about by environmental improvements are often overlooked, leading to the effects of environmental improvements being underestimated. Previous studies have mostly started at the province (regional) scale, with few assessments at the urban agglomeration, specific region, and city scale. The multi-scale regional differentiation research paradigm has been relatively well covered, both in part and as a whole, while an analysis from the perspective of "national-regional-urban agglomeration-city" has rarely been considered. The comparison and understanding of UGDE at multiple scales is difficult, and the spatial heterogeneity and correlation characteristics of regional development cannot be clearly reflected. Under the background of multiple factors (e.g., the spread of knowledge and technology across regions, continuous dispersal of environmental pollution, and cross-disciplinary integration), it is necessary to investigate the UGDE of complex urban systems. Therefore, this study integrated cities and urban agglomerations, taking 285 cities at prefectural level and above in China as the main research focus. It systematically evaluated the concepts and implications of GD and its efficiency, and built a UGDE input-output evaluation system. Using the Slacks Based Model with undesirable outputs (SBM-Undesirable) to measure Chinese UGDE from 2005 to 2015. The spatial-temporal evolution characteristics of UGDE were analyzed through a variety of spatial scale analysis methods, and systematic mechanisms were explored by integrating the natural background and human and social factors. The study attempted to determine the pattern of GD, clarify the development mechanism, and provide a decision-making reference for the coordinated GD of the regional economy, society, and environment as three major systems.

2 Data and methods

2.1 Data sources

There were three main data sources used in the study. (1) Natural and environmental data. The annual average temperature and annual precipitation data were obtained from the China

Meteorological Data Service Center (http://data.cma.cn/site). The original data were in the form of monthly data from 756 meteorological stations across the country. After excluding abnormal station values, the annual average of the remaining 703 stations was calculated. Then, the Kriging interpolation method was used to generate the raster data of the time series of annual average temperature and annual precipitation in China from 2005 to 2015. We used the 2004–2016 global atmospheric $PM_{2.5}$ concentration raster data published by NASA as the basic research data (http://earthdata.nasa.gov), which had a resolution of 0.01°. Where data was unavailable, we took the mean value of the three years before and after as the $PM_{2.5}$ concentration in the missing year (Tone, 2001). Moderate resolution imaging spectroradiometer (MODIS) normalized difference vegetation index (NDVI) data were obtained from the International Scientific Data Mirroring Center of the Computer Network Information Center of the Chinese Academy of Sciences. The monthly MODND1M synthetic data from the China regional NDVI vegetation index synthesis product (TERRA) from 2005 to 2015 has a spatial resolution of 500 m. The monthly data were synthesized using the ArcGIS 10.2 platform to generate NDVI data for the corresponding year. (2) Basic geographic information data. The vector administrative boundary map was derived from the 1:4,000,000 basic geographic information data for China, which was provided by the National Basic Geographic Information Center. A total of 285 prefecture-level cities in China were selected (excluding Taiwan Province, Hong Kong, and Macau). To maintain spatial continuity and facilitate analyses, cities that did not have a uniform time series, including Chaohu in Anhui Province, Sansha and Haizhou in Hainan Province, Bijie and Tongren in Guizhou Province, and Haidong in Qinghai Province were excluded. (3) Social and economic data. This included statistical data such as fixed stock, number of employees in a unit, average wage of urban employees, and area of urban green space. It was mainly obtained from the *China City Statistical Yearbook* and *China City Construction Statistical Yearbook* from 2006 to 2016, and the China Economic Network Statistics Database. The number of patent applications authorized in each city was obtained from the China National Intellectual Property Office (SIPO) patent search database. Some missing data were adjusted and supplemented with data from the official website of the corresponding region. Finally, we imported all natural, human, and social elements into ArcGIS, and built a spatio-temporal database of China's UGDE from 2005 to 2015.

2.2 Methods

2.2.1 SBM-Undesirable model

In addition to desirable outputs in the process of urban development, undesirable outputs such as environmental pollution will also be produced. Traditional radial models fail to take into account the invalid decisions making unit (DMU) slack variables, so there is a bias in the efficiency measurements for the presence of undesirable outputs. To correct the slack variable, Tone (2001) proposed the SBM-Undesirable model, which can effectively solve the problem of the slackness of output variables and undesirable output problems, and accurately evaluate the UGDE of Chinese cities. In this study, the SBM-Undesirable model, which considers undesirable outputs and constant returns to scale from an input perspective, was used to measure the UGDE in Chinese cities. The calculation method was as follows:

$$\rho = \min \frac{1 - \frac{1}{N}\sum_{n=1}^{N} s_n^x / x_{k'n}^{t'}}{1 + \frac{1}{M+1}\left(\sum_{m=1}^{M} s_m^y \Big/ y_{k'm}^{t'} + \sum_{i=1}^{I} s_i^b / b_{k'i}^{t'}\right)}$$
$$s.t. \sum_{t=1}^{T}\sum_{k=1}^{K} z_k^t x_{kn}^t + s_n^x = x_{k'n}^{t'}, n = 1, \cdots, N$$
$$\sum_{t=1}^{T}\sum_{k=1}^{K} z_k^t y_{km}^t - s_m^y = y_{k'm}^{t'}, m = 1, \cdots, M \tag{1}$$
$$\sum_{t=1}^{T}\sum_{k=1}^{K} z_k^t b_{ki}^t + s_i^b = b_{k'i}^{t'}, i = 1, \cdots, I$$
$$z_k^t \geqslant 0, s_n^x \geqslant 0, s_m^y \geqslant 0, s_i^b \geqslant 0, k = 1, \cdots, K$$

where ρ is the target efficiency value; N, M, and I represent the number of inputs, desirable outputs and undesirable outputs, respectively; $(x_{k'n}^{t'}, y_{k'n}^{t'}, b_{k'n}^{t'})$ represent the input-output value of the k'th decision making unit at t period; (s_n^x, s_n^y, s_n^b) represent the slack for inputs, desirable outputs, and undesirable outputs, respectively; and z_k^t is the weight vector of a decision making unit.

2.2.2 Regional differences measurement

The Theil Index was used to measure the degree of regional differences in UGDE (Zhang *et al*., 2018). The Thiel index has a decomposable characteristic, That this index can be decomposed into intra-regional differences and inter-regional differences, therefore if can effectively decompose the structure and source of regional differences in UGDE. The Theil Index is calculated as follows:

$$Theil = Theil_W + Theil_B$$
$$Theil_W = \sum_{i=1}^{m}\left(\frac{n_i}{n}\frac{\bar{x}_i}{\bar{x}}\right) Theil_i \tag{2}$$
$$Theil_B = \sum_{i=1}^{m}\frac{n_i}{n}\left(\frac{\bar{x}_i}{\bar{x}}\right)\ln\left(\frac{\bar{x}_i}{\bar{x}}\right)$$

where m represents the number of regional divisions; n_i/n represents the proportion of cities in region; $\bar{x}_i / \bar{x}$ is the ratio of the mean UGDE of each city to the national average; $Theil_i$ represents the Theil index for the UGDE in city i; $Theil_W$ and $Theil_B$ respectively represent the difference in UGDE of cities within and between regions.

2.2.3 Spatial Markov chain

A spatial Markov chain was constructed by combining the methods of Markov with spatial lag, which can effectively analyze the spatial interactions in the change process of UGDE (Pu *et al*., 2005). By comparing the corresponding elements in the spatial and non-spatial matrices, the relationships between the discretized UGDE type transition probability and the surrounding neighboring cities were identified, and the spatial spillover effect of the transfer of UGDE type with different types of neighboring cities was revealed. This was calculated using the following equation:

$$P_{ij,t+1}(k) = P_{ij,t}(k) \times N \times W_k \tag{3}$$

where P is a probabilistic transfer matrix, with a size of $N \times N$; W_k represents the spatial lag term; and $P_{ij,t+1}$ is the probabilistic matrix of the k types in the case of (t+1) years, with k as the spatial lag.

2.3 Construction of an assessment system

An input-output index system of Chinese UGDE was established based on the input-output model (Table 1). We selected capital, labor, technology, resources, and others as input factors. Specifically, the capital stock was selected to represent the capital investment, the total number of laborers in previous years was selected to represent the labor input, and the financial expenditure on science and technology, and education in each location was selected to represent the technical input. The resource input was expressed by the total consumption of water, soil, and energy. In terms of desirable outputs, the GDP of each region was selected to reflect economic benefits, the social benefit index comprehensively reflected social outputs, and the environmental benefit index reflected environmentally "good" outputs. In addition, the loss of ecological and environmental value due to waste emissions during the development process were taken into account. Therefore, the environmental pollution index was established as an evaluation system for undesirable output factors, and the resource and environmental constraints were important factors for evaluating GDE. We used the entropy method to comprehensively calculate the resource elements, social benefit index, environmental benefit index, and environmental pollution of each city. The GDP was adjusted to the constant price in 2005 according to the GDP deflator for each province. The total capital investment of the whole society was used to represent the capital stock because it could not be obtained directly.

Table 1 The evaluation of UGDE in China

<table>
<tr><th>Type</th><th>First level indicators</th><th>Second level indicators</th><th>Third level indicators</th></tr>
<tr><td rowspan="5">Input</td><td>Capital</td><td>Fixed capital stock</td><td>Total social fixed capital investment</td></tr>
<tr><td>Labor</td><td>Number of unit employers</td><td>Number of unit employees at the end of the year</td></tr>
<tr><td>Technology</td><td>Number of patent authorizations</td><td>Number of patent applications granted by region</td></tr>
<tr><td rowspan="2">Resources</td><td rowspan="2">Water, land, and energy consumption</td><td>Total water supply, urban built-up area, total electricity consumption</td></tr>
<tr><td>Artificial and natural gas supply, liquefied gas supply</td></tr>
<tr><td rowspan="4">Output</td><td rowspan="3">Desirable output</td><td>Economic benefits</td><td>GDP (constant price in 2005)</td></tr>
<tr><td>Social benefits</td><td>Average wage of urban employees, total retail sales of consumer goods</td></tr>
<tr><td>Environmental benefits</td><td>Area of urban green space, percentage cover of green space, utilization rate of industrial solid waste centralized treatment rate of sewage treatment plants, treatment rate of harmless domestic garbage</td></tr>
<tr><td>Undesirable output</td><td>Environmental pollution</td><td>Amount of industrial wastewater, amount of industrial SO_2 emitted, amount of industrial dust emitted</td></tr>
</table>

3 Spatio-temporal differentiation of UGDE in China

3.1 Temporal evolution of UGDE in China

Based on the SBM-Undesirable model, the UGDE and its regional difference index (i.e., the Theil index) of 285 prefecture-level cities in China from 2005 to 2015 were measured re-

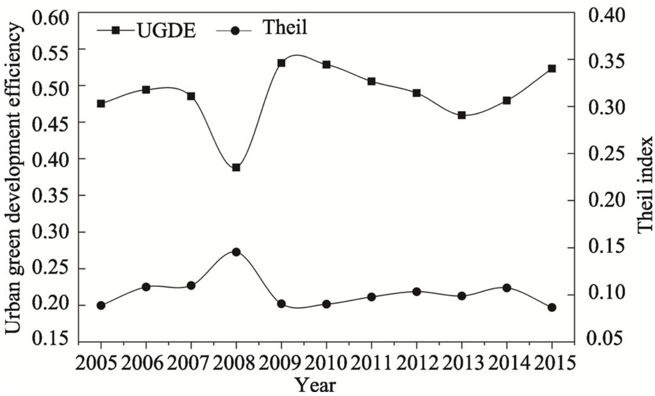

Figure 1 The temporal evolution of UGDE in China from 2005 to 2015

spectively (Figure 1). The results revealed a "W-shaped" pattern of the UGDE of China from 2005 to 2015, with the regional differences shown as the opposite "M-shaped" pattern. The stage change was obvious.

There were three stages of UGDE development. In the first phase (2005–2008), UGDE fluctuated and declined from 0.475 in 2005 to 0.388 in 2008, a decrease of 24%. There was a rapid expansion in the regional differences from 0.089 in 2005 to 0.145 in 2008, an increase of 64%. In the second phase (2008–2009), UGDE rapidly improved from 0.388 in 2008 to 0.531 in 2009, a change of 37%. During this period, regional differences were well controlled and the Theil index fell from 0.145 in 2008 to 0.091 in 2009, a 61% decrease. The low-carbon and green sustainable development path in the post-financial crisis era has led to an increase in UGDE and the reduction of regional differences. In the third phase (2009–2015), the UGDE presented a "V-shaped" change, while the regional difference presented an inverted "V" saddle shape. In the "12th Five-Year Plan" (2011–2015), the Chinese government has given increasing attention to structural adjustment, energy reduction, and coordinated regional development. As a result, UGDE gradually increased after a period of decline caused by the initial adjustment, and the degree of regional difference has gradually eased.

3.2 Spatial differentiation of UGDE in China

To explore the spatio-temporal characteristics of UGDE from multiple perspectives in different regions, at different levels of urban agglomeration, and in cities of different scales, China was divided into three regions, 20 urban agglomerations, and five urban levels. This enabled a systematic analysis according to the patterns of economic and geographic development and regional spatial characteristics. The three major regional blocks were the eastern, central, and western regions. Twenty urban agglomerations were divided into national, regional, and local urban agglomerations based on the national "5+9+6" urban agglomeration planning and construction goals (Fang *et al*., 2015). According to *Green Book of Small and Medium-sized Cities*, Chinese cities can be divided into super, mega, big, medium, and small cities according to the average population of urban districts from 2005 to 2015 (CUES, 2010).

3.2.1 The phenomenon of three major regional differences

From 2005 to 2015, the UGDE in the eastern, central, and western regions all displayed a "W-shaped" pattern, with average values of 0.548, 0.475, and 0.428, respectively. The UGDE followed an "eastern > central > western" stepwise decreasing pattern (Figure 2). Specifically, the UGDE in the eastern region decreased from 0.569 in 2005 to 0.555 in 2015. The UGDE in the central and western regions gradually increased, with growth rates of

18.89% and 19.78%, respectively. These were ultimately significant increases over the period studied. The western region had the largest GDE spatial imbalance (0.033), followed by the eastern region (0.032) and the central region (0.031). The uneven development within the three regions was the key to restricting the improvement of UGDE. The proportion of internal differences in the eastern region continued to rise, the Theil Index increased from 29.64% in 2005 to 30.77% in 2015. The central region had the fewest internal discrepancies, but the proportion of intra-regional discrepancies continued to increase during the study period, accounting for 35.78% of the overall discrepancy by 2015. The overall level of UGDE in the western region was low, with most cities at a low level.

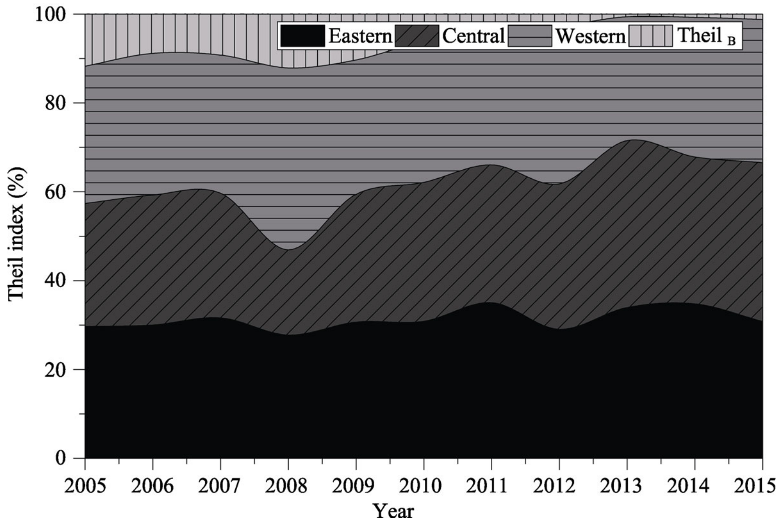

Figure 2 The decomposition of the Theil index of UGDE in different regions of China

The eastern region was dependent on its own resources for development and had a strong ability to effectively manage resources and the environment. During the reform and opening up period, technological innovation and information technology became prominent, and the pressure on resources and the environment gradually decreased. Over time, UGDE maintained a steady medium and high paced growth rate, with the eastern region ultimately having the highest UGDE growth rate of the three regions. With the adjustment and transformation of industry and urbanization, resource depletion gradually became an issue in the development of some industrial cities in the central region. The central region was characterized by early and large scale resource development and many cities became industrially depleted. Structural problems in economic development persisted for a long time, with the weakening of institutions and mechanisms. The lack of innovation and entrepreneurship led to increased difficulties in achieving sustainable development. Because urban development in the western region was dominated by an inward-oriented economy and was greatly influenced by policy, it was not only subject to the constraints imposed by path dependence in the development process but also consumed large amounts of resources. Coupled with the single regional economic model and imperfect market mechanisms, the UGDE was always lower than in the eastern and central regions.

3.2.2 Factors controlling the development of multi-level urban agglomerations

From 2005 to 2015, the UGDE of different urban agglomerations increased, which was also in line with the characteristics of the overall UGDE. The UGDE of each urban agglomeration presented the characteristics of an inverted-pyramid cluster growth, which was specifically represented by the pattern of national-level urban agglomerations > regional urban agglomerations > local urban agglomerations (Figure 3). The highest UGDE was found for national-level urban agglomerations, but during the study period there was a trend for it to initially decrease and then steadily increase. It increased from 0.546 in 2005 to 0.553 in 2015, which represented an overall increase of only 1.20%. Although the UGDE level was higher, there was no obvious improvement. The second highest UGDE was found for regional urban agglomerations, and the increase was significantly higher than that of national-level urban agglomerations. It increased by 16.81% from 2005 to 2015, and displayed a catch-up trend. Regional urban agglomerations had the lowest UGDE in the early stage of the study. However, their growth rate was the largest, with an increase from 0.383 in 2005 to 0.457 in 2015, an increase of 19.20%.

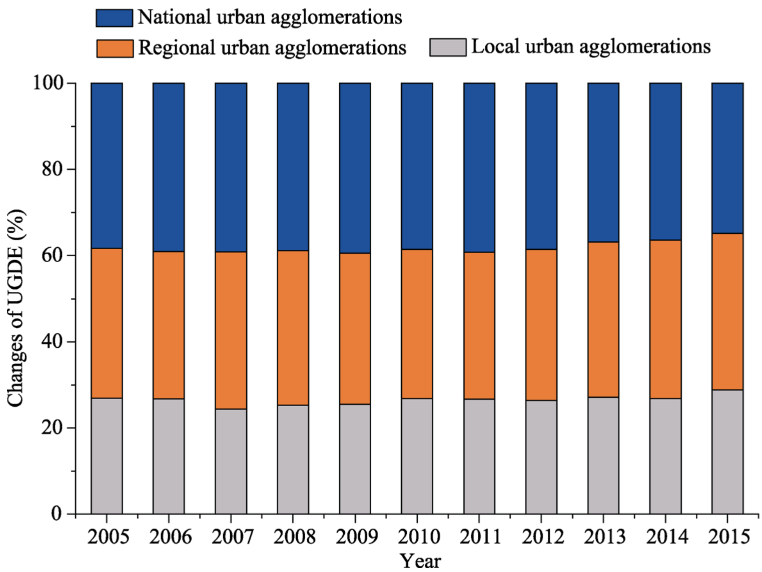

Figure 3 The multi-level evolution of UGDE in urban agglomerations of China from 2005 to 2015

National-level urban agglomerations, as the key development areas of the country, had a high level of resource allocation, but under the constraints of natural resources, social development, and economic growth, the UGDE in national-level urban agglomerations did not significantly improve from its high starting point. In contrast, in regional urban agglomerations and local urban agglomerations, which were composed of non-core cities and regional cities, there was a steady improvement in UGDE as the cities developed. The higher the level of urban agglomeration, the closer the internal cities were in terms of their UGDE, and the better the degree of urban development, the higher the level of UGDE.

Regional urban agglomerations were found to be well placed to meet the state's need to formulate policies for the construction of an ecological civilization and promotion of GD. For example, the Chengdu-Chongqing urban agglomeration initiated a "two-wheel drive" to promote the rapid development of UGDE, with a strategy of western development and the establishment of a “National Demonstration Area for National Urban and Rural Coordinated Reform.” In the middle reaches of the Yangtze River, urban agglomerations have made full use of the strategic opportunities of the rise of the central area of the country, and the development opportunities of the “two-type social reform pilot zone (i.e., a pilot area for the national resource-saving and environment-friendly mechanism)” in Wuhan metropolitan area. As a result, the Changsha-Zhuzhou-Xiangtan urban agglomeration has made great developmental progress. The Yangtze River Delta, Pearl River Delta, and the Beijing-Tianjin-Hebei urban agglomerations have maintained their leading positions in GD due to their advantages in technological progress, industrial infrastructure upgrades, resource utilization, and environmental protection.

3.2.3 Characteristics of the hierarchical structure among cities of different sizes

There was a positive correlation between the UGDE and population, with hierarchical scale characteristics of “super cities > mega cities > large cities > medium cities > small cities” (Figure 4). From 2005 to 2015, the mean UGDEs of super, mega, large, medium, and small cities were 0.617, 0.519, 0.463, 0.435, and 0.426, respectively, with large gaps in the values among cities of different grades and an obvious decrease along the size gradient. The largest increase in UGDE was found in super cities, with an increase of 34.81%. The UGDE of medium, large, and mega cities was relatively stable. During the study period, their values were stable at about 18%, 18%, and 21%, respectively, accounting for about 1/5 of the overall UGDE. The UGDE of small cities decreased by 5% during the study period, with no obvious fluctuations. There was a positive correlation between the UGDE and the size of the population. The larger the size of a city, the more obvious its advantages in terms of resource allocation. A large population provides sufficient labor, which ensures sustainable growth for cities to a certain extent and improves the UGDE. The “potential difference” at different levels will affect the improvement of UGDE through different channels. Therefore, the regulation and management of internal differences is the key approach to improve the UGDE within cities of different sizes.

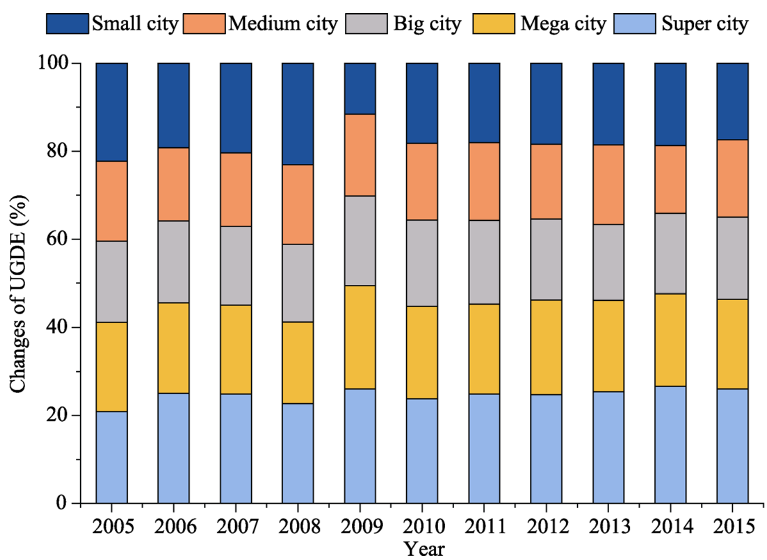

Figure 4 The UGDE in multi-level urban agglomerations from 2005 to 2015

3.3 Spatio-temporal dynamic characteristics of UGDE in China

The traditional Markov transition matrix indicates a change between sample types, but it lacks a spatial perspective and cannot explain the characteristics of spatio-temporal dynamic transfers in the context of different regional interactions. Therefore, a spatial Markov transfer matrix was used to reveal the spatio-temporal dynamic characteristics of UGDE. According to the distribution characteristics of UGDE, it can be divided into four types: low-efficiency, medium-efficiency, relatively high-efficiency, and high-efficiency. The research period was divided into three stages: 2005–2008, 2008–2009, and 2008–2015 (Table 2).

Table 2 The spatial Markov transfer matrix of UGDE from 2005 to 2015

Type		2005–2008				2008–2009				2009–2015			
		1	2	3	4	1	2	3	4	1	2	3	4
1	1	0.847	0.097	0.028	0.028	0.762	0.119	0.071	0.048	0.844	0.131	0.010	0.015
	2	0.292	0.477	0.200	0.031	0.190	0.238	0.476	0.095	0.202	0.551	0.191	0.056
	3	0.167	0.250	0.417	0.167	0.167	0.417	0.250	0.167	0.000	0.275	0.625	0.100
	4	0.111	0.111	0.222	0.556	0.222	0.000	0.000	0.778	0.034	0.052	0.190	0.724
2	1	0.674	0.304	0.022	0.000	0.357	0.500	0.071	0.071	0.805	0.161	0.011	0.023
	2	0.250	0.515	0.176	0.059	0.154	0.346	0.385	0.115	0.167	0.592	0.225	0.017
	3	0.118	0.196	0.549	0.137	0.045	0.091	0.500	0.364	0.016	0.203	0.626	0.154
	4	0.000	0.043	0.087	0.870	0.000	0.000	0.222	0.778	0.010	0.051	0.153	0.786
3	1	0.740	0.260	0.000	0.000	0.455	0.364	0.091	0.091	0.692	0.282	0.013	0.013
	2	0.280	0.480	0.200	0.040	0.176	0.294	0.471	0.059	0.130	0.652	0.174	0.043
	3	0.082	0.219	0.548	0.151	0.077	0.231	0.308	0.385	0.017	0.182	0.645	0.157
	4	0.019	0.074	0.148	0.759	0.000	0.100	0.200	0.700	0.009	0.026	0.183	0.783
4	1	0.833	0.133	0.033	0.000	0.600	0.400	0.000	0.000	0.838	0.162	0.000	0.000
	2	0.207	0.517	0.241	0.034	0.056	0.389	0.556	0.000	0.120	0.652	0.163	0.065
	3	0.049	0.246	0.557	0.148	0.000	0.111	0.500	0.389	0.010	0.286	0.480	0.224
	4	0.000	0.010	0.237	0.753	0.000	0.042	0.042	0.917	0.000	0.031	0.221	0.748

Note: 1. Low-efficiency cities; 2. Medium-efficiency cities; 3. Relatively high-efficiency cities; 4. High-efficiency cities

There was a significant spatial spillover effect in China, with the UGDE of neighboring cities being affected by each other. High-efficiency cities were responsible for a significant positive spillover to neighboring cities. Conversely, inefficient cities had negative spillover effects. Cities adjacent to high-efficiency cities had a higher probability of experiencing an increase in UGDE and a lower probability of experiencing a decrease, and vice versa. Specifically, from 2005 to 2008, the average probability of the upward transfer of UGDE in low-efficiency cities was 0.226. When the neighboring cities had a medium-efficiency or high-efficiency, their transition probability increased to 0.326 and 0.260, respectively. The probability of an upward transfer in UGDE decreased to 0.153 when a city was adjacent to a low-efficiency city. From 2008 to 2009, the probability of upward transfer for a low-efficiency city bordering another low-efficiency city was 0.238. This was lower than the probabilities when bordering a medium-efficiency city, relatively high-efficiency city, and high-efficiency city, which were 0.195, 0.308, and 0.162, respectively. Correspondingly, when a high-efficiency city was adjacent to a low-efficiency city, the probability of a downward transfer was 0.222, which was greater than the probability when a high-efficiency city was adjacent to a high-efficiency city. From 2009 to 2015, the probability of an upward transfer (0.156) for a low-efficiency city adjacent to another low-efficiency city was smaller than the probability (0.162) when it was adjacent to a high efficiency city, and the probability of a downward transfer (0.252) for a high-efficiency city to another high-efficiency city was also smaller than the probability when it was adjacent to a low-efficiency city (0.276). In addition, when a city was adjacent to a different type of city, the probability of the UGDE remaining unchanged was greater than the probability of an upward or downward shift. This shows that there was also a strong "club convergence" phenomenon and a certain spatio-temporal inertia in the various types of spatio-temporal changes.

From 2008 to 2009, the probability of a downward transfer for low-efficiency, medium-efficiency, and high-efficiency cities was higher than in the other two periods, indicating that the regional UGDE had significantly improved. This was in line with the phenomenon whereby the overall UGDE increased from 2008 to 2009, indicating that an increase in the efficiency of specific cities is the key factor influencing the improvement of the overall UGDE. However, the probability of a low-efficiency city being maintained in that state was higher than that of other efficiency types in the three periods, which indicates that under a background of regional spatial dependence, the positive spillover effect between cities is relatively limited in terms of its promotion into underdeveloped areas. In the future, improving the UGDE of low-efficiency cities and promoting the role of positive spillovers should play a large role in the overall improvement of UGDE.

4 Analysis of the UGDE factors influencing in China

There were clear spatio-temporal differentiation characteristics of UGDE, and there were also obvious differences and correlations among different regions, urban agglomerations, and cities. Under the interactive coupling of the "economic-social- environmental" system, the imbalance of natural background conditions and human and social development factors have combined and influenced each other. This has introduced complexity into the process by which the spatial and temporal patterns of the UGDE has changed over time. Therefore, this study started from the regional system of the human-environment interaction, built a model of the factors affecting the UGDE, and systematically quantified the mechanism by which UGDE evolved under the influence of multiple factors (Figure 5).

4.1 Model specification and variable selection

The factors influencing UGDE in China were investigated from the perspective of natural background factors and the development of human and social factors, in an attempt to verify the "Kuznets hypothesis" and "Porter hypothesis". In terms of natural background factors, the initial selection of water, soil, climate, and biological factors were annual precipitation, annual average temperature, $PM_{2.5}$ concentration, and vegetation cover. These factors represented urban hydrological conditions (*pre*), urban temperature (*tem*), ecological suitability

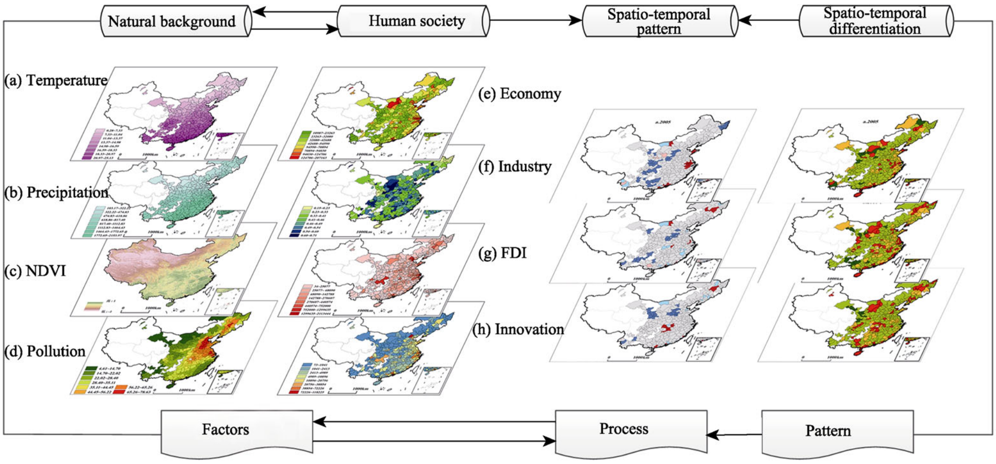

Figure 5 The factors influencing the mechanism of UGDE in China

(*ndvi*), and environmental quality (*eq*), respectively. In the terms of human and social factors, the per capita GDP (*rgdp*) was used to measure the level of macroeconomic development and its regression coefficient was expected to be positive. The environmental Kuznets curve (EKC) effect of UGDE was measured by the square of per capita GDP ($rgdp^2$) (Grossman *et al.*, 1992). The proportion of regional fiscal revenue spent on technological developments was used to reflect technological innovation (*te*), and to test whether there was a "Porter hypothesis" phenomenon in the implementation of GD policies. The total amount of foreign capital actually received in a year (*fdi*) was used to indicate the degree of openness of each city. This was used to assess the existence of the "pollutant shelter effect" and "pollutant paradise" hypotheses, with the expected value of the coefficient being uncertain (Copeland, 1994). In addition, the urban industrial structure (*is*) and the proportion of urban GDP provided by secondary industry were used to measure the degree of rationalization and the level of urban industrial structure. It was expected that the regression coefficient would be negative.Because the UGDE was between 0–1 and there was a significant truncation phenomenon, general econometric models cannot accurately estimate it. Therefore, a panel tobit measurement model was used to estimate and analyze the factors influencing the UGDE of Chinese cities. The formula was as follows:

$$UGDE_i^* = \beta_0 + \beta_1 \ln rgdp_i + \beta_2 \ln\left(rgdp\right)_i^2 + \beta_3 \ln is +_i \beta_4 \ln fdi_i + \beta_5 \ln te_i + \beta_6 \ln temp_i + \beta_7 \ln pre_i + \beta_8 \ln PM_{2.5i} + \beta_9 \ln NDVI_i + \varepsilon_i, \varepsilon_i \sim N(0, \sigma^2) \quad (4)$$

$$UGDE_i = \begin{cases} GDE_i^* & 0 < UGDE_i^* \leqslant 1 \\ 0 & UGDE_i^* \leqslant 0 \end{cases}$$

where $UGDE_i$ is the UGDE of each city; β_0 is the constant term coefficient; β_i is the regression coefficient of each influencing factor; and ε_i is the random error term coefficient. Only $UGDE_i$ can be observed in actual research, while $UGDE^*$ cannot be observed. In the observable range $UGDE_i = UGDE^*$, and the model used a maximum likelihood estimation (MLE) to estimate the coefficient β_i. A multi-collinearity diagnosis, descriptive statistics, and correlation tests of each factor showed that the correlation between explanatory variables was weak and there was no problem of multi-collinearity.

4.2 The mechanisms controlling UGDE in China

Models (1), (2), and model (3) are the regression results for human and social factors, natural background conditions, and natural and humanistic factors (Table 3). Considering all 285 cities as a whole, the most significant impact of human and social factors on UGDE was technological innovation. The coefficient was −0.247, which was significant at the 99% level, and there was a significant negative relationship with GDE. The coefficients of economic strength, industrial structure, and openness were 0.068, 0.016, and 0.015, respectively, which were significant at the 99%, 90%, and 95% levels, respectively. All had a positive impact on UGDE, with the degree of impact decreasing in the order of economic strength > industrial structure > openness. In the case of natural background factors, only urban temperature was significant at the 99% level, with a coefficient of 0.016. For every 1% increase in average annual temperature, the UGDE would increase by 0.016%. Environmental quality and ecological suitability had a positive, but not significant, effect on UGDE. There was a negative relationship between hydrological conditions and UGDE. The greater the average annual precipitation, the more the UGDE was correspondingly suppressed, but this effect was not obvious.

Table 3 The estimation of the factors influencing UGDE in China

	Variable	Model (1)	*Z* value	Model (2)	*Z* value	Model (3)	*Z* value
Human and social factors	*rgdp*	0.025***	3.68			0.030***	4.20
	$rgdp^2$	0.013***	3.68			0.015***	4.20
	is	0.087*	1.55			0.089*	1.58
	fdi	0.007**	2.07			0.005*	1.50
	te	−0.439***	−6.64			−0.453***	−6.84
Natural background factors	*tem*			0.005**	2.32	0.007***	3.21
	pre			−0.004	−0.67	−0.001	−0.40
	eq			0.0001	0.28	0.0004	0.38
	ndvi			0.119*	1.67	−0.027	1.01
	C	0.212***	−3.71	0.723***	−3.62	0.099***	1.01
Correlation test	sigma_u	0.181		0.187		0.178	
	sigma_e	0.139		0.141		0.139	
	rho	0.628		0.638		0.621	
	likelihood ratio test	1305.72		1262.74		1312.67	

Note: ***, **, * indicate a significance of 99%, 95%, and 90%, respectively.

The coefficient of the square of per capita GDP was 0.068, which was significant at the 99% level, indicating that there was a "U-shaped" relationship between economic development and UGDE. Therefore, UGDE can be seen as a means of environmental regulation in the context of the construction of an ecological civilization and GD policies. An increase in efficiency will reduce environmental pollution, and can therefore act as a negative indicator of environmental pollution. Then, the EKC between environmental pollution and economic development could be interpreted based on the "U-shaped" relationship between UGDE and economic development, i.e., there was an environmental "EKC" effect between GD and economic growth in Chinese cities from 2005 to 2015. Opening to the outside world (*fdi*) had a significant role in promoting UGDE, indicating that since 2005 development in China was no longer dependent on foreign investment, and the outward-looking nature of economic and social development gradually weakened. Therefore, it was concluded that China has successfully broken through the stages of the "pollutant shelter effect" and "pollutant paradise hypothesis" that are prevalent in developing countries.

With the continuous introduction of scientific development and the concept of sustainable development, the Chinese government has taken multiple factors into consideration regarding foreign investment. It must meet the needs of economic development but this must not be at the expense of the environment. This phenomenon is a good illustration of the change in the role of the state and the government's use of foreign investment since reform and opening up was initiated in 1978, which is gradually meeting the requirements of constructing an ecological civilization and GD policies. Technological innovation can play an important role in solving environmental problems and maintaining increases in productivity. Using UGDE as a means of environmental regulation has a significant negative effect on technological innovation. The corresponding "Porter Hypothesis" advocates a proactive environmental protection policy and suggests that strict and appropriate environmental regulations can stimulate enterprises to carry out technological innovation. The resulting innovation benefits can offset or even exceed environmental protection costs, thereby ensuring or improving the competitiveness of enterprises. Improving the UGDE as a means of environmental regulation has not only played an active role in promoting technological innovation in cities, but has also greatly inhibited the improvement of technological innovation at the national level. This is an obvious "green paradox", and the "inverted mechanism" of technological innovation has not yet developed to resolve it. According to the Porter hypothesis, environmental regulation has a positive effect on technological innovation and even the competitiveness of enterprises, but this is conditional on the economic level of a country or region having developed to a certain degree. Only then can the situation described by the "Porter Hypothesis" occur.

5 Conclusions and discussion

5.1 Conclusions

(1) From 2005 to 2015, the average UGDE in China has been at an intermediate level, from 0.475 in 2005 to 0.523 in 2015, an overall increase of 10%. Changes of UGDE have occurred over three time periods. From 2005 to 2008, UGDE gradually decreased, while regional differences continued to expand. From 2008 to 2009, UGDE increased rapidly, while regional differences narrowed rapidly. From 2009 to 2015, UGDE development was relatively balanced.

(2) The trend of UGDE was considered in three regions (east, central, and western) and presented a “W-shaped” pattern, with mean values of 0.548, 0.475, and 0.428, respectively. There were stepwise decreasing characteristics of UGDE observed that followed a “eastern-central-western” pattern. The UGDE of multi-level urban agglomerations followed an inverted pyramid pattern of “national level > regional level > local level”, and the hierarchical structural characteristics of “super cities > mega cities > large cities > medium cities > small cities” was prominent.

(3) The UGDE was found to have a significant spatial spillover effect, whereby the UGDE of one city could influence the UGDE of an adjacent city. There was a strong “spatial club convergence” phenomenon and a certain spatio-temporal inertia in the various types of transfers. High-efficiency cities resulted in significant positive spillovers to their neighbors, while low-efficiency cities had negative spillover effects. Cities adjacent to high-efficiency cities had a higher probability of transferring upward and a lower probability of transferring downward.

(4) From the perspective of the regional human-environment interaction system, technological innovation was the core driving factor and had a significant negative effect on the UGDE. Economic strength, industrial structure, and openness had positive impacts on UGDE, but the degree of impact decreased over the study period. Among the natural background factors, the influence of urban temperature was positive, while hydrological conditions, environmental quality, and ecological suitability had no significant effect on UGDE.

(5) It was assumed that UGDE acted as a means of environmental regulation. Economic development and UGDE displayed a “U-shaped” relationship, and there was a clear EKC effect. Openness was significantly positively related to UGDE. There was no obvious pollution transfer effect generated by foreign investment, but investment would improve the environmental quality and a “pollutant shelter” would not be established accordingly. Technological innovation had a significant inhibitory effect on the improvement of GDE. It would be impossible to improve environmental quality by technological innovation at this stage in China’s development.

5.2 Discussion

The UGDE was considered to act as an environmental regulation in this study. The degree of UGDE reflects the quality of the natural environment and the level of urban environmental regulation. Its spatio-temporal pattern and its influencing factors are of significance for the overall control and promotion of Chinese urban GD and the construction of an ecological civilization. It can also be used to verify whether the developmental theories of western developed countries have been incorporated in the actual development of China. At present, China generally displays an EKC effect, i.e., environmental pollution is continuing to increase while the economy is developing. The results of this study will be important in the next stage of supply-side reform, economic restructuring, elimination of primitive production methods, and the development of environmental protection strategies to achieve the decoupling of economic growth and environmental pollution. In addition, a nationwide “pollutant shelter” effect could not be confirmed, which was related to the structural screening of Chinese foreign investment. This also reflects the fact that China is currently faced with economic and environmental problems that are largely a consequence of its own endogenous factors. How to adjust the relationship between internal development and pollution has become the most important issue in achieving GD. The "Porter Hypothesis" could not be verified in China at this stage. The external benefits of technological innovation could not offset the development costs of the current competitiveness of cities in China, resulting in proactive environmental protection policies failing to encourage enterprises to carry out technological innovation, and inhibiting economic growth to a certain extent. There was no conflict between the implementation of environmental protection and economic growth. The key lies in how to resolve the relationship between the cost of externalities and technological innovation. How to effectively handle the relationships between environmental protection, technological innovation, and economic growth will have a major impact on the sustainable development of GD.

The formation of the spatio-temporal pattern of UGDE was found to be affected by the combination of natural backgrounds and human economic factors. The interaction of these factors has resulted in a complex human-environment in China. Each factor through its own evolution or mutual coupling and coercion with other factors, continuously shapes the internal development of the urban system, affects the process of urban greening, and influences the improvement of UGDE. The study attempted to expand the logic of "pattern-process-cause" that is applied in the geographical research framework of human-land relations to provide new ideas for urban "fair", "inclusive" and "green" sustainable development. This goal is consistent with the construction of an ecological civilization and GD, and it provides methodological support to further enrich the theory of human-land relationships and practically solve ecological and environmental problems.

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