

Finding a more efficient green transformation path for resource-exhausted cities: Evidence from China

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資源枯渇都市における効率的なグリーン転換経路の模索：中国からの実証

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The efficiency of green transformation in resource-exhausted cities is affected by many factors, so it is necessary to analyze the status of UGTE under different combinations of conditions. In this study, five influencing factors, including society, economy, space, environment and infrastructure, were extracted from previous research, and eight representative indicators were selected. Based on the data of 39 resource-exhausted cities in China, the UGTE of the research samples under different combinations of conditions was quantitatively analyzed using fuzzy set qualitative comparative analysis (fsQCA). The main conclusions of this paper are as follows: (1) Four paths can achieve a high level of transformation effect, and six paths can lead to a low level of transformation effect. (2) Among the paths leading to a high level of transformation effect, the two paths are characterized by compact space and efficient operation. The two paths are characterized by economic development and scientific and technological progress. (3) Among the paths leading to the low level transformation effect, the two paths ignore the high level of input of almost all condition variables. Both approaches neglect the construction of urban infrastructure. Both paths ignore per capita disposable income, investment in science and innovation, or high levels of GDP. (4) The realization of high-level green transformation effects should rely on high-level urban infrastructure or high-level economic and social development.

Keywords : Resource-exhausted city, combination of conditions, development path, fsQCA

資源枯渇都市, 条件の組み合わせ, 発展経路, 集合質的比較分析

1. Introduction

The rise of resource-exhausted cities stems from the exploitation and processing of natural resources such as minerals and forests (State Council, 2014). In the stage of rapid development of China's industrial system and steady improvement of the national economy, resource-exhausted cities have made great contributions by virtue of their resource advantages and development foundation (Chen et al., 2019). However, resource extraction and processing industries are generally characterized by high energy consumption, high

pollution and high input (Li and Zou, 2018). Therefore, resource-exhausted cities inevitably suffer from problems such as low resource utilization efficiency, high development intensity, ecological environment destruction and low level of industrial development (Zhang Rongguang et al., 2017) (Zhang Juan, 2017) (Jiang et al., 2024), and fall into a historical cycle of "prosperity due to resources" to "decline due to resources". If resource-exhausted cities want to achieve sustainable development, they must carry out urban green transformation.

In the context of the continued green transformation of resource-exhausted cities, the Chinese government has elevated it to a national strategy and given full support at the

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policy level. In 2013, The State Council initiated the "Sustainable Development Plan (2013-2020)", which aims to promote the industrial transformation of resource-based cities, so as to realize the revitalization of industries and cities. In 2016, the "Industrial Green Development Plan (2016-2020)" emphasized the implementation of the concept of green development in all fields and the whole process of industry, based on green manufacturing, to form a new engine of national economic growth. By 2020, the green industry promotion mechanism will be basically established, and the development level of urban green industry will be significantly improved. In 2021, the Outline of the 14th Five-Year Plan outlined a development vision for 2035. First of all, to ensure that during the 14th Five-Year Plan period, social life, economic development and industrial manufacturing and other aspects of green transformation results are significant. Second, we will basically achieve a new type of industrialization by 2035, enter the stage of carbon emission reduction after the carbon peak, and widely promote green production and lifestyle, so as to basically achieve the goal of a beautiful China. With the strong support of the policy, some resource-exhausted cities actively promote green transformation, such as Tongling and Anshan, and have formulated detailed implementation plans for green transformation.

The efficiency of green transformation in resource-exhausted cities is affected by many factors. Finding the combination of conditions that can achieve high-level green transformation is an important basis for resource-exhausted cities to make sustainable development planning. What are the factors affecting UGTE in resource-exhausted cities? What combination of conditions can achieve a high level of resource-exhausted urban UGTE? Can different combinations of conditions achieve the same transformation effect? The study of resource-exhausted UGTE under different combinations of conditions can provide guidance for the formulation of sustainable development planning.

The previous researches have discussed the influencing factors and the transformation path. In terms of influencing factors, it mainly includes single influencing factors and comprehensive influencing factors. Related studies on single influencing factors mainly include: Scientific and technological innovation (Deng et al., 2013), government governance (Yuan and Zhou, 2012), human input (Wang et al., 2010), environmental governance (Fan, 2011), capital input (Qiu and Liu, 2015) and location factors (Xu, 2012), The above scholars respectively discussed the relationship between

different influencing factors and the level, efficiency and prospect of urban green transformation, and proved that the above factors are positively correlated with urban green transformation. In the relevant researches on comprehensive influencing factors, different scholars mainly discussed the relationship between different combinations of influencing factors and urban green transformation. For example, Dong et al. (2013) believe that the comprehensive impact of economic development level, industrial structure and regional heterogeneity on urban transformation is positive. Tian Hesun (2016) believes that the industrial transformation of resource-based cities is comprehensively affected by low-carbon regulations, technological innovation, human capital, market demand and other factors. However, most of the above studies are based on the current green transformation results of the research samples, and are only based on correlation analysis to study the relationship between different influencing factors and urban green transformation. In terms of the transformation path, most of the previous studies start from the urban development dilemma to clarify the driving mechanism of urban green transformation. Further, on the basis of the driving mechanism of green transformation, combined with the influencing factors, the green transformation path is proposed. For example, Zhou et al. (2022) believe that urban green transformation can be carried out from the aspects of low-carbon energy supply, clean energy consumption, efficient use of urban space, naturalization of urban design and coordination of urban governance. However, the above studies ignore the coordination among different elements, lack the attention to the transformation effect, and lack the prediction and prospective exploration of the urban green transformation effect under different situations.

The innovations and contributions of this paper are as follows. First of all, this paper focuses on the resource-exhausted city UGTE under different combination of conditions, and studies the combination of conditions that can obtain the best green transformation effect. Secondly, this paper focuses on resource-exhausted cities and chooses more microscopic research samples, which can provide more targeted suggestions for the cities most in need of green transformation.

2. Literature review

2.1 Influencing factors of green transformation of resource-exhausted cities

The previous researches on the influencing factors of urban green transformation mainly include the study of single

influencing factors and the study of comprehensive influencing factors. In terms of single influencing factors, it mainly includes: scientific and technological innovation, government governance, human input, environmental governance, capital input and location factors. First, technological innovation. Deng et al. (2013) took coal resource-based cities in China as research samples and argued that the performance of government functions was influenced by the level of scientific and technological innovation and the degree of urban openness. However, China's resource-based cities are dominated by the government in the whole development cycle, and the management system should be classified as the integration of government and enterprise. Therefore, the green transformation of resource-based cities needs to start from the source, improve the level of scientific and technological innovation and urban openness. Based on the questionnaire survey results of resource-based enterprises in Shanxi Province, China, Chen et al. (2014) proposed that there is a gap in innovation performance between resource-based enterprises and non-resource-based enterprises, and it is urgent to improve the scientific and technological innovation capability of resource-based enterprises. Second, governance. Yuan Hezhou (2012) believes that the sustainable development of mineral resource-based cities needs to rely on the overall coordination between resource-based enterprises and the government. Wang (2012) Government, enterprises and industry are the main bodies of urban green transformation, while government governance is of more significant significance. Third, human input. Wang et al. (2010) concluded through empirical research that the level of human resources and the number of employees in the tertiary industry are the main factors affecting urban green transformation. Zhang (2014) believes that human resource input performance is positively correlated with the green transformation effect of resource-based cities. Fourth, environmental governance. Fan (2011) took Pingdingshan City as a research sample, explored its sustainable development by constructing an evaluation index system, and believed that its sustainable development was constrained by environmental pollution. Fifth, capital investment. Qiu and Liu (2015) believe that the integrated input of technological innovation and finance can effectively help resource-based cities get rid of the growth dilemma and reduce their dependence on resource development. Sixth, location factor. Based on the panel data of resource-based cities in China from 2005 to 20083, Xu (2012) studied the influencing factors of urban competitiveness and believed that location factors had the most significant impact on urban competitiveness. Huang and Li (2015) analyzed the

relationship between urban remoteness and urban economic development, and found a significant negative correlation between the two.

In the comprehensive influence factors research. Yan Hema (2012), starting from the industrial sustainability of resource-based cities, believes that the influencing factors include economic and industrial structure, resources and environment, regional planning, economic system, etc. Dong et al. (2013) classified resource-based cities and assessed their urban transformation performance, arguing that the comprehensive impact of economic development level, industrial structure and regional heterogeneity on urban transformation is positive. Wang et al. (2013) took coal resource-based cities in China as research samples and argued that the comprehensive factors affecting urban sustainable development included economy, society, employment, environment and resources. Based on the panel data of 33 resource-based cities in China, Guo et al. (2014) empirically analyzed the impact of factors such as economic level, city size, export dependence, city type, proportion of tertiary industry and environmental protection input on urban sustainable development. Xu Hegao (2014) summarized seven driving factors for sustainable transformation of resource-based cities: policies and regulations, ecological system, low-carbon concept, management innovation, technological innovation, low-carbon investment and market demand. Pan Hebai (2015) summarized eight factors affecting the industrial upgrading and transformation of resource-based cities: market, resources, environment, technology, economy, etc., and comprehensively analyzed the mechanism of different influencing factors. Tian Hesun (2016) believes that the industrial transformation of resource-based cities is comprehensively affected by low-carbon regulations, technological innovation, human capital, market demand and other factors. According to Zhou et al. (2016), low level of economic development, large population size and unreasonable industrial structure are negatively correlated with urban sustainable development, while environmental regulation, good employment structure and science and education level are positively correlated with sustainable development efficiency.

To sum up, previous studies have analyzed the influencing factors of urban green transformation from a single perspective and a comprehensive perspective. Most studies start from the assessment of the effect and efficiency of urban green transformation, and based on correlation analysis, study the influencing factors and mechanism of urban green transformation performance.

2.2 Green transformation path of resource-exhausted cities

To promote the green transformation of resource-exhausted cities, it is necessary to clarify the driving mechanism of urban green transformation, and the driving mechanism mostly stems from urban development difficulties, such as resource depletion, declining human settlements and unsustainable economic growth. Cheng et al. (2019) believe that urban green transformation is a necessary condition to achieve clean production, low energy consumption and low pollution. In the process of rapid urbanization, urban construction and industrial structure with high carbon emissions have exacerbated resource depletion and pollution in cities, making ecological problems increasingly serious. An important way to solve the above problems is urban green transformation. Rondinel-Oviedo and Keena (2023) believe that urban environmental problems are mainly caused by excessive emission of atmospheric pollutants, and the intensifying contradiction between sustainable economic development and urban environmental problems is the main reason for urban green transformation. Ma et al. (2018) took Panzhihua City in China as a research sample and proposed that the main reason for promoting urban green transformation was the stagnation of economic development and resource depletion. On the basis of clarifying the driving mechanism of urban green transformation, previous studies have carried out research on the path of urban green transformation. Most studies start from the influencing factors to explore the path of urban green transformation. Common influencing factors are as follows: Economy, infrastructure, government input and technological innovation (Liu et al., 2022) (Zhang et al., 2022) (Li et al., 2021) (Zhao et al., 2021). In terms of transformation path, some scholars believe that China's urban green transformation can be started from the following aspects: Low-carbon energy supply (Huang and Yu, 2021), clean energy consumption (Yang et al., 2021), efficient use of urban space (Fu et al., 2020), naturalization of urban design (Feng et al., 2020), and coordination of urban governance, etc. At the same time, most previous studies focus on the impact of a single influencing factor on urban green transformation, and prove the positive or negative effects of influencing factors on urban green transformation through regression models and other methods, and then propose the path of urban green transformation (Xu, 2018) (Zhang et al., 2021). Komninos (2022) proposes that industrial digitalization can optimize urban ecosystem and innovation environment, thus promoting urban green transformation. Rolf (2021) believes that the improvement of urban green infrastructure can promote urban sustainable development by incorporating suburban farmland

into the category of urban green infrastructure.

In summary, previous studies have conducted in-depth research on the driving factors and influencing factors of urban green transformation, and based on this, the path of urban green transformation is proposed. However, most studies only start from a single factor, ignoring the coordination and interaction between different elements, and can not comprehensively put forward the path of urban green transformation. At the same time, there is a lack of prediction and prospective exploration of the effect of urban green transformation under different situations.

3. Methodology

3.1 Method selection

From the perspective of configuration, as a complex giant system, the composition of a city is not a loose combination of various components, but interrelated, and results are produced under their joint action (Fiss, 2011). Therefore, for the promotion of UGTE in resource-exhausted cities, it is necessary to start from the influencing factors and find a better combination of conditions in a holistic and combined way. Based on the above considerations, this paper intends to use fuzzy set qualitative comparative analysis (fsQCA) to find the path of UGTE promotion. The specific reasons are as follows: First, fsQCA is not looking for the only best path to improve UGET, but seeks a combination of different paths with equivalence, which can provide multiple ways for urban green transformation decision-making. Second, fsQCA can handle "asymmetrical" correlations that are widespread in the real world. Third, fsQCA uses set relation to analyze the relationship between variables, which has a wider range of application scenarios (Ragin, 2000). QCA mainly includes csQCA, mvQCA and fsQCA. csQCA can only handle variables of binary type. mvQCA is developed based on csQCA and is suitable for processing multi-class information. However, they cannot handle continuous variables.

3.2 Fuzzy Set Qualitative Comparison Analysis (fsQCA)

In the 1980s, Ragin first proposed case-based qualitative comparative analysis (QCA) to analyze causality in small and medium-sized study samples (less than 50 cases). QCA has gone through a process from simple to complex to assign values to variables. At first, researchers only used 0 and 1 to assign values to variables. The binary assignment of 0 and 1 has great limitations and can not meet the wider research needs. Ragin introduced the idea of fuzzy set and extended the assignment method to arbitrary values. In 2005, Berg-Schlusser and Cronqvist further expanded QCA and

proposed qualitative comparative analysis of multi-valued sets, while comparing traditional regression analysis with qualitative comparative analysis of multi-valued sets. It is thought that the latter can contain more comprehensive correlation information (Berg-Schlosser and Cronqvist, 2005). In terms of the field of use, fsQCA is more commonly applied to small-scale samples (less than 15 samples) and medium-sized samples (15-50 samples). Ragin and Fiss et al. argue that the same applies to samples larger than 100. At present, fsQCA is mainly applied in political science and management, and gradually expands to economics and other fields. In terms of using steps, first, fsQCA needs to select the result variable and the condition variable. Secondly, the data is calibrated based on variables and the truth table is established. Third, fsQCA software was used for necessity analysis and configuration analysis to study the influence of different conditional configurations on the outcome variables, and potential development strategies were proposed based on the optimal conditional configurations (Zeng Zhaoyun and Cheng Xiaokang, 2016).

3.3 Model construction

3.3.1 Selection of result variables and condition variables

The objective of this study is to propose a scientific and feasible path for the promotion of UGTE in resource-exhausted cities. Therefore, UGTE is selected as the only result variable. In the fsQCA model, the selection of condition variables should be determined according to the number of research samples and should be maintained at a reasonable level. Ragin believes that the number of

urban green transformation in the previous studies. At the same time, in the previous study, PLS-SEM, MICMAC and DEMATEL-ISM methods were used to determine the five influencing factors and action paths of UGTE in resource-exhausted cities (Appendix A). Therefore, based on previous studies, this study selects conditional variables (Table 1) from the five influencing factors of society, economy, space, environment and infrastructure.

In the social aspect, this study selects the scientific and technological innovation investment as the conditional variable. The improvement of scientific and technological innovation level is closely related to urban green and high-quality development (Feng et al., 2022). The restructured scientific and technological innovation investment effectively supports the continuous improvement of scientific and technological innovation level, and also reflects whether the society attaches importance to the development potential of the country and the city. In economic terms, GDP is the embodiment of the overall economic strength of a country and a city. Per capita disposable income comprehensively reflects the quality of life of urban residents, per capita income level and the distribution of economic development achievements (Xue, 2008). In terms of space, social sustainability (Banai and Antipova, 2016) and economic sustainability (Irwin and Bockstael, 2007) show positive feedback with built space density. Greenhouse gas emission (Alberti, 2005), ecosystem (Ding et al., 2014) and air quality (Ikin and Beaty, 2013) are related to the ratio of urban average perimeter area. In terms of the environment, the frequent natural disaster events in recent

Table 1 Selection of condition variables

Influencing factors	Variables	Ref
Society	Technology & Innovation Investments	Yang et al., 2022; Gu et al., 2023
Economic	GDP	Ma et al., 2019
	Disposable Income Per Capita	Gu et al., 2023
Space	Built-up Space Density	Irwin and Bockstael, 2007
	Perimeter-area Ratio of Patches	Alberti, 2005
Environment	Carbon Emission	Xu and Liu, 2023
Infrastructure	Urban Infrastructure	Jin et al., 2019
	Internet Penetration Rate	Jin et al., 2019

conditional variables for medium-scale research samples should be between 5 and 9 (Ragin, 2009). The sample size of this study is 39, so 8 conditional variables are to be selected. As a complex system, city is composed of social system, industrial system, other system and spatial system (Li Dehua, 2011). The above system corresponds to the society, economy, environment, infrastructure and space influencing factors of

years are mainly due to the continuous increase of urban carbon emissions. In terms of infrastructure, the main measure of the "old" infrastructure is the per capita road area, and the main measure of the "new" infrastructure is the popularization of digital infrastructure such as ICT and Internet.

In the indicator system for measuring urban infrastructure development, per capita road area performs a critical role

(Cervero & Murakami, 2010). Moderate road density can effectively enhance traffic operational efficiency and reduce carbon emissions associated with transportation activities, thereby directly driving the city's green transition process. On the other hand, a well-developed infrastructure system creates

determined as the quantile values of 95%, 5% and 50% of the corresponding variables respectively in this paper. After calibration, each variable is shown in the table (Table 2).

3.3.3 Necessity Analysis of a Single Condition

Necessity indicates that the presence of a condition

Table 2 Calibration Anchors for Result Variables and Conditional Variables

Variables	Influencing factors	Indicators	Completely unaffiliated	Intersection point	Fully Affiliated
Results variable	UGTE	UGTE	1.009	1.035	1.061
	Society	Technology & Innovation Investments	1408.768	17506.740	72524.080
		GDP	211.969	634.517	2307.140
	Economic	Disposable Income Per Capita	17433.620	23012.660	28462.140
Condition variable	Space	Built-up Space Density	0.001	0.009	0.032
		Perimeter-area Ratio of Patches	4.182	8.428	14.483
	Environment	Carbon Emission	5.713	21.732	48.068
	Infrastructure	Urban Infrastructure	15.320	18.130	24.552
		Internet Penetration Rate	20.110	28.500	43.877

favorable conditions for the efficient flow and integration of key production factors such as labor, capital, and technology, strengthening synergistic effects among these factors. This contributes to reducing resource consumption and improving the comprehensive benefits of energy utilization. Furthermore, the construction and application of new-generation digital infrastructure, represented by ICT and the internet, contain immense potential for driving cities toward a low-carbon transformation pattern. Relevant studies indicate that ICT profoundly influences the pathways for achieving urban green transition through means such as optimizing energy supply network structures and significantly enhancing energy efficiency in industrial production processes (Berkhout & Hertin, 2004). In summary, the aforementioned indicators provide an effective analytical basis for exploring how the infrastructure dimension affects UGTE.

3.3.2 Data Calibration

The analysis using fsQCA requires the calibration of the result and conditioning variables. Common calibration methods include direct calibration method and indirect calibration method. Indirect calibration method requires researchers to assign each variable within the range of 0 to 1 according to their own experience, which is highly subjective. The direct calibration rule is based on the three qualitative anchor points of full membership, complete unmembership and crossing point, and transforms each variable into a value from 0 to 1 with the help of the algorithm (Ragin, 2000). Based on the existing studies, the three anchor points are

variable is a necessary condition for the production of the result, and when the condition variable is missing, the result cannot be produced. fsQCA mainly determines the condition variable according to its consistency. When the consistency is greater than 0.9, the condition variable can be determined as a necessary condition. Coverage represents the degree of interpretation of the results by conditional variables, and coverage is positively correlated with the degree of interpretation. Consistency and coverage methods are as follows:

$$\text{Consistency}(x_i \leq y_i) = \sum [\min(x_i, y_i)] / \sum x_i \quad (1)$$

$$\text{Covergae}(x_i \leq y_i) = \sum [\min(x_i, y_i)] / \sum y_i \quad (2)$$

In the above formula, x_i represents the membership of sample i in the x combination, and y_i represents the membership of sample i in the y result. Consistency ranges from 0 to 1, where 0 indicates no membership at all and 1 indicates full membership.

3.3.4 Condition combination analysis

After the necessity analysis of the condition variable is completed, the condition combination analysis of the result variable and the condition variable is needed. Conditional combination analysis needs to build a truth table, which should follow three principles. First, the minimum case frequency is selected according to the number of samples. The case frequency for small and medium-sized samples is usually set to 1 or 2. Second, the standard for consistency is usually

0.8. Thirdly, the PRI consistency values are screened, and only

Table 3 Research samples

Samples of research in the first group of resource-exhausted cities	① Fuxin, ② Panjin, ③ Liaoyuan, ④ Baishan, ⑤ Yichun, ⑥ Pingxiang, ⑦ Jiaozuo, ⑧ Baiyin, ⑨ Shizuishan
Samples of research in the second group of resource-exhausted cities	⑩ Xiahuayuan district (Zhangjiakou), ⑪ Yingtanyingzi mining district (Chengde), ⑫ Fushun, ⑬ Gongchangling district (Liaoyang), ⑭ Yangjiazhangzi (Huludao), ⑮ Qitaihe, ⑯ Huabei, ⑰ Tongling, ⑱ Jingdezhen, ⑲ Zaozhuang, ⑳ Huangshi, ㉑ Dongchuan district (Kunming), ㉒ Tongchuan
Samples of research in the third group of resource-exhausted cities	㉓ Jingjin mining district (Shijiazhuang), ㉔ Wuhai, ㉕ Shiguai district (Baotou), ㉖ Erdaojiang district (Tonghua), ㉗ Hegang, ㉘ Shuangyashan, ㉙ Jiawang district (Xuzhou), ㉚ Xinyu, ㉛ Dayu county (Ganzhou), ㉜ Zibo district (Zibo), ㉝ Puyang, ㉞ Shaoguan, ㉟ Pinggui Management District (Hezhou), ㊱ Luzhou, ㊲ Yimen county (Yuxi), ㊳ Tongguan county (Weinan), ㊴ Honggu district (Lanzhou)

the PRI greater than 0.75 can be analyzed later. Based on the above three principles, three cases of complex solution, intermediate solution and simple solution can be analyzed. Complex solutions often contain more types of combinations of conditions and are analyzed solely on the basis of raw data. The complexity of the intermediate solution is moderate, experience and theory are included in the analysis framework, and simple counterfactual analysis is carried out in the analysis process, so the analysis results are relatively reasonable. The simple solution contains the least type of combination of conditions, while incorporating both simple and complex counterfactual analysis. In the formal result analysis, it is necessary to combine the intermediate solution and the simple solution for comprehensive analysis. Variables appearing in the simple solution are regarded as core conditions, while variables appearing in the intermediate solution and not in the simple solution are regarded as edge conditions.

3.4 Research samples and data

3.4.1 Research samples selection

According to the official list of resource-exhausted cities published by the Chinese government and the complete statistical data, 39 resource-exhausted cities represented by Shizuishan, Huangshi and Luzhou are selected as research samples (Figure 1) (Table 3).

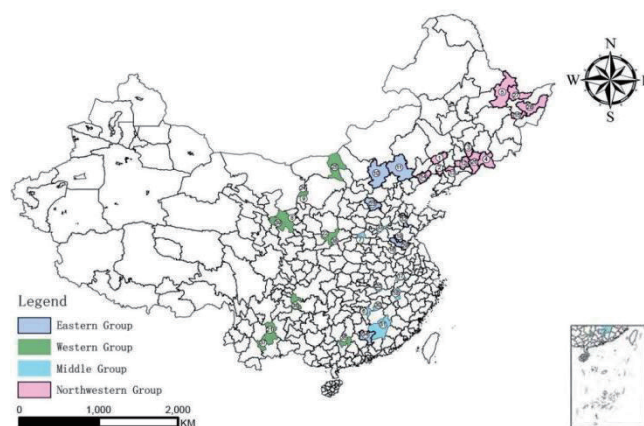


Figure 1 Research samples

Source: drawn by the author

3.4.2 Indicators and data sources

The indicators involved in this study mainly include 1 outcome variable and 8 condition variables. The result variable is the UGTE of the study sample. In the previous study, this paper used the super-efficiency SBM model to evaluate the UGTE of the study sample in 2020. For specific evaluation indicators, calculation methods and specific values, refer to Appendix B. The data of the above eight condition variables mainly use the cross-sectional data of 2020, and the sources mainly include: yearbook, development bulletin, statistical database, etc. Due to the lack of statistical data of some cities, or the small scale, it is impossible to obtain accurate data and other reasons, this study mainly uses: the value of the previous year, the average value, and the statistical data of higher administrative units to supplement. For some data that still cannot be supplemented, linear interpolation is carried out based on the panel data of the study sample for 20 years.

4. Results and discussion

4.1 Results

4.1.1 Single condition necessity Result

According to the above analysis process, this study analyzes the necessity of the condition variables that affect UGTE in resource-exhausted cities. Based on the threshold values and principles described above, the condition variables that exceed the threshold are removed from the truth table. In this study, fsQCA4.1 software was used to analyze the necessity of condition variables, and the results were shown in the table (Table 4). According to the results shown in the table, the consistency of the eight condition variables in the two scenarios of high transformation effect and low transformation effect is no more than 0.9. Therefore, all the single condition variables alone will not lead to the increase of UGTE in resource-exhausted cities. At the same time, the influence of all condition variables on resource-exhausted cities' UGTE is combinatorial, and the combination of different condition variables will present the same green transformation effect. The following is a detailed analysis of different types of condition combinations.

which are all greater than 0.8. All the four paths are sufficient conditions for the study sample to produce high transformation effect, but the coverage of each path is different. Path 2 has a coverage of 0.19, which explains the results the most, and path 4 has a coverage of 0.13, which explains the results the least. Path 1: With compact urban spatial structure, high level of urban infrastructure, non-high-tech innovation investment, non-high per capita disposable income, non-high built-up space density, non-high Internet penetration, and non-high urbanization level, a high level of urban green transformation can be achieved. Path 2: With a high level of GDP, a high level of per capita disposable income, a non-high level of built-up spatial density, a non-compact urban spatial structure, a high level of investment in scientific and technological innovation, a high level of urban infrastructure, and a non-high level of Internet penetration, a high level of urban green transformation can be achieved. Path 3: With a high level of investment in scientific and technological innovation, a high level of per capita disposable income, a non-high level of carbon emissions, and a non-compact urban spatial structure, complementing a high

Table 4 Single condition necessity Result

Variables	High transformation effect		Low transformation effect	
	Consistency	Coverage	Consistency	Coverage
Technology & Innovation Investments	0.566873	0.594378	0.594226	0.599177
~Technology & Innovation Investments	0.617725	0.612855	0.59773	0.570288
GDP	0.60168	0.631173	0.615095	0.620515
~GDP	0.638247	0.632931	0.634395	0.604998
Disposable Income Per Capita	0.693677	0.658564	0.59365	0.541999
~Disposable Income Per Capita	0.51758	0.569799	0.626027	0.662772
Built-up Space Density	0.549369	0.582165	0.575815	0.586802
~Built-up Space Density	0.61008	0.599288	0.589989	0.55734
Perimeter-area Ratio of Patches	0.596097	0.618141	0.608348	0.606666
~Perimeter-area Ratio of Patches	0.620693	0.622352	0.617082	0.595017
Carbon Emission	0.562949	0.631531	0.543438	0.586277
~Carbon Emission	0.631206	0.589764	0.658455	0.591644
Urban Infrastructure	0.589507	0.646763	0.511585	0.539761
~Urban Infrastructure	0.580504	0.552756	0.665202	0.609129
Internet Penetration Rate	0.615261	0.641392	0.613473	0.615017
~Internet Penetration Rate	0.630703	0.629184	0.642293	0.616188

4.1.2 Condition combination result

In this study, fsQCA4.1 software was used to analyze the research samples, and four paths with high transformation effect and six paths with low transformation effect were calculated. The results are shown in Table (Table 5).

For the four paths with high transformation effect, the consistency of the four paths is 0.96, 0.94, 0.93 and 0.91,

level of GDP, a high level of built space density, a high level of urban infrastructure, and a high level of Internet penetration, a high level of urban green transformation can be achieved. Path 4: With a high level of per capita disposable income, a high level of built-up space density, a high level of urban infrastructure, a non-high level of GDP, and a non-compact urban spatial structure, complementing the non-high level of

scientific and technological innovation investment, a high coverage is 0.37. The six paths account for the low

Table 5 Combined paths

Conditional Variables	High transformation effect				Low transformation effect					
	Path 1	Path 2	Path 3	Path 4	Path 1	Path 2	Path 3	Path 4	Path 5	Path 6
Technology & Innovation Investments	●	⊗	⊗	●	●	●	⊗	●	⊗	⊗
GDP		⊗	⊗	●	●	●	⊗	⊗	●	⊗
Disposable Income Per Capita	●	⊗	⊗	⊗	●	●	●	●	●	⊗
Built-up Space Density	●	●	⊗	⊗	●	●	⊗	⊗	⊗	⊗
Perimeter-area Ratio of Patches	⊗	●	●	●	●	●	●	●	⊗	⊗
Carbon Emission	●		●	⊗	●	●	⊗	⊗	⊗	⊗
Urban Infrastructure	⊗	⊗	⊗	⊗	⊗	●	●	⊗	⊗	●
Internet Penetration Rate	●	●	⊗	⊗	●	⊗	●	⊗	⊗	⊗
Original Coverage	0.18	0.19	0.17	0.13	0.14	0.19	0.15	0.13	0.13	0.15
Unique Coverage	0.07	0.06	0.02	0.03	0.02	0.06	0.03	0.02	0.02	0.02
Consistency	0.96	0.94	0.93	0.91	0.94	0.91	0.97	0.96	0.94	0.93
Overall Consistency	0.92				0.93					
Overall Coverage	0.35				0.37					

Note:

●Condition Present ; ⊗ Condition Absent ; ●Core Present ; ⊗ Core Absent

level of carbon emissions, and a high level of Internet penetration, the green transformation of cities can be realized.

Based on the above, there is a causal asymmetry between the condition variable and the result variable when fsQCA method is used for analysis. This study further analyzes the combination path of the effect of transformation from the ground, and the results are shown in Table (Table 5). The intermediate solution gives 6 paths, whose consistency is 0.94, 0.91, 0.97, 0.96, 0.94 and 0.93, all greater than 0.8. The overall consistency of the six paths is 0.93, and the overall

transformation effect.

4.2 Robustness test results

The commonly used robustness testing methods of fsQCA include: increasing the consistency threshold, increasing or decreasing samples, etc. (Du Yunzhou et al., 2020). This study intends to test the stability of the research results by raising the consistency threshold. In the previous study, the threshold was set at 0.8. Therefore, this paper increases it to 0.85 to test the stability, and the results are shown in the table (Table 6). According to the results in the

table, the data before and after threshold adjustment are basically consistent, indicating that this study has good robustness.

4.3 Discussion

In the process of analysis, fsQCA tends to amplify the

4.3.1 Discussion on the path of high transformation effect

There are four combinations of conditions to achieve high transformation effect. The whole can be divided into the path oriented by compact space and efficient operation and the path oriented by economic development and scientific and

Table 6 Combined paths

Conditional Variables	High transformation effect				Low transformation effect					
	Path 1	Path 2	Path 3	Path 4	Path 1	Path 2	Path 3	Path 4	Path 5	Path 6
Technology & Innovation Investments	●	⊗	⊗	●	●	●	⊗	●	⊗	⊗
GDP		⊗	●	●	●	●	⊗	⊗	●	⊗
Disposable Income Per Capita	●	⊗	⊗	⊗	●	●	●	●	●	⊗
Built-up Space Density	●	●	⊗	⊗	●	●	⊗	⊗	⊗	⊗
Perimeter-area Ratio of Patches	⊗	●	●	●	●	●	●	●	⊗	⊗
Carbon Emission	●		●	⊗	●	●	⊗	⊗	⊗	⊗
Urban Infrastructure	⊗	⊗	⊗	⊗	⊗	●	●	⊗	⊗	●
Internet Penetration Rate	●	●	⊗	⊗	●	⊗	●	⊗	⊗	⊗
Original Coverage	0.18	0.19	0.17	0.14	0.14	0.18	0.14	0.12	0.12	0.19
Unique Coverage	0.07	0.05	0.02	0.03	0.02	0.04	0.01	0.02	0.02	0.04
Consistency	0.96	0.94	0.94	0.91	0.94	0.91	0.92	0.96	0.94	0.91
Overall Consistency	0.92				0.88					
Overall Coverage	0.35				0.47					

Note:

●Condition Present ; ⊗ Condition Absent ; ●Core Present ; ⊗ Core Absent

subtle differences between research samples (Wu Chao et al., 2018), which leads to case duplication. This study is based on the core conditions, combined with the previous research, a comprehensive discussion of different conditions combination.

technological progress.

Path 1 and Path 4 are paths oriented towards compact space and efficient operation. Both pay attention to high-level urban infrastructure. Path 1 emphasizes that cities should have compact urban spatial form, while path 4 emphasizes that cities should have high-density built-up space. This is

consistent with existing research. From the perspective of resource integration, the "old" infrastructure represented by road transportation can achieve efficient integration of raw materials, products, labor and other elements at the practical level by reducing logistics costs (Wang et al., 2022). Lv et al. (2023) believe that loose urban space is closely related to low-level and low-quality urban infrastructure, and weakens the benefit utilization rate of urban public service facilities (Fang and Bai, 2022). In resource-depleted cities, governments need to increase investment in public services, which increases fiscal pressure. Path 2 and Path 3 belong to the path oriented by economic development and scientific and technological progress. Both focus on high-level economic and social development. This is also consistent with existing research. Zhou et al. (2024) believe that high-level scientific and technological innovation plays a positive role in promoting urban green economy and transformation development. Zhou et al. (2020) believe that economic strength and industrial structure are important factors to promote the efficiency of urban green development. Compared with the existing studies, this study proposes a path that can achieve high transformation effect in the form of conditional combination, and quantitatively proves the adequacy and explanation degree of different conditional paths for high transformation effect. However, there are still some limitations in this study. First, the degree of high and non-high levels of condition variables in different paths cannot be quantified. Based on the fsQCA method, this study analyzed whether the research samples could achieve high-level UGTE under different combination conditions. However, the fsQCA method can only derive different conditions combination scenarios in a high-level or non-high-level form. It is not possible to quantify the amount and degree of input into specific condition variables. Second, fsQCA has a limit on the number of condition variables. The research sample in this paper is a medium-sized research sample, so the number of conditional variables should be between 5 and 9. Although the conditional variables selected in this paper represent different influencing factors of UGTE to a certain extent, they still cannot comprehensively cover the influencing factors of each dimension. Therefore, it has a negative effect on the coverage in the results of different combinations of conditions. In the future, based on the combination of potential conditions given in this paper, further quantitative studies can be conducted to quantify the degree of high and non-high level inputs. At the same time, other research methods can be further used to cross-verify with fsQCA method to find the optimal condition combination

path.

4.3.2 Discussion on the path of low transformation effect

There are 6 combinations of conditions to achieve low transformation effect. The whole can be divided into: ignoring the path of urban infrastructure and ignoring the path of economic and social development.

Path 1 and path 2 have been invested and developed in a non-high-level form in almost all condition variables. Therefore, paths 1 and 2 inevitably lead to low transformation effects. Path 3 and path 6 ignore urban infrastructure construction, reduce the mobility of production factors, and lead to low transformation effect. Path 4 and Path 5 ignore per capita disposable income, an important indicator of economic and social development, as well as high level development of scientific and technological innovation investment or GDP, resulting in low transformation effect. This is consistent with existing research. Cheng et al. (2019) used the panel data of prefecture-level cities to study the impact of low-carbon city construction on urban green transformation, and believed that smaller city scale, better infrastructure and lower level of scientific and technological development would have a negative impact on urban green growth. Vona and Patriarca (2011) believe that inequality of per capita disposable income and economic development harms the development of environmental technology and environmental innovation, which in turn has a negative impact on urban green transformation. Compared with the existing studies, this study integrated the influencing factors of urban green transformation efficiency and proposed a path leading to low transformation effect. However, there are still some limitations in this study. fsQCA uses cross-section data rather than panel data, and for study samples at different stages of development, it may not be possible to identify the combination of conditions that lead to low transformation effects at different stages. Follow-up research can extend the time span, conduct in-depth research on the data of different stages or different years of research samples, and then put forward more targeted suggestions. Second, the indicators selected for this study are all intrinsic urban attributes, without incorporating external factors of cities into consideration. For instance: the radiating influence of neighboring cities, the guiding role of national-level transportation corridors, etc. Consequently, for cities that derive substantial benefits from external environmental factors, the role of their internal elements may be overestimated, thus limiting the generalizability of the conclusions across cities with diverse geographical contexts.

5. Conclusions and policy recommendations

5.1 Conclusions

In this study, 39 resource-exhausted cities in China were taken as research samples. Based on the factors influencing UGTE in previous studies, fsQCA method was used to study the path of UGTE enhancement in resource-exhausted cities under different combination of conditions.

The main conclusions are as follows:

At the level of combination of conditions that lead to a high level of transformation effect. There are four paths in total. Path 1: compact urban spatial structure + high-level urban infrastructure + non-high-tech innovation investment + non-high per capita disposable income + non-high built-up spatial density + non-high Internet penetration + non-high urbanization level. Path 2: High level of GDP+ high level of per capita disposable income + non-high level of built-up spatial density + non-compact urban spatial structure + high-level investment in scientific and technological innovation + high-level urban infrastructure + non-high level of Internet penetration. Path 3: High level of scientific and technological innovation investment + high level of per capita disposable income + non-high level of carbon emissions + non-compact urban spatial structure, complementing high level of GDP+ high level of built-up spatial density + high level of urban infrastructure + high level of Internet penetration. Path 4: High level of per capita disposable income + high level of built-up spatial density + high level of urban infrastructure + non-high level of GDP+ non-compact urban spatial structure, complementing non-high level of scientific and technological innovation investment + high level of carbon emissions + high level of Internet penetration. Path 1 and Path 4 are paths oriented towards compact space and efficient operation. Path 2 and Path 3 belong to the path oriented by economic development and scientific and technological progress. The above four paths can achieve a high level of green transformation in cities.

At the level of combination of conditions that lead to low level transformation effects. There are six paths. Paths 1 and 2 ignore the high level of input for almost all condition variables. Path 3 and Path 6 ignore urban infrastructure construction. Path 4 and Path 5 ignore per capita disposable income, an important indicator of economic and social development, as well as high-tech innovation investment or high level of GDP development. All of the above six paths lead to a low level of green transformation in cities.

5.2 Policy recommendations

Based on the analysis of different combinations of conditions, resource-exhausted cities should formulate

policies in line with their actual conditions to achieve high-level urban green transformation.

5.2.1 Differentiated Policy Design Based on fsQCA Paths

Based on the paths leading to high-level transition, policies for spatial efficiency, economic-technology orientation, and inclusive transformation can be formulated. For paths resulting in low-level transition, corrective policies can be designed.

(1) Spatial Efficiency: Compact structure and infrastructure prioritization are core tenets. First, delineate urban growth boundaries to curb inefficient sprawl, mandating mixed-use development—e.g., integrating commercial, residential, and service functions (Ewing et al., 2016). Second, implement transit-oriented development (TOD) strategies, concentrating high-density clusters around transit stations with increased floor area ratios. Simultaneously, mitigate heat island effects via vertical greening and permeable paving. Third, upgrade infrastructure by renovating utility tunnels, expanding recycled water systems, and establishing distributed energy stations.

(2) Economic-Technology Orientation: Innovation-driven growth and green development are core tenets. First, enable land-use conversion mechanisms (e.g., research-to-industrial land) to accelerate tech commercialization. Impose carbon intensity reduction targets ($\geq 5\%$ for industrial zones). Second, develop innovation corridors by integrating industry-academia-research complexes and tech parks along BRT routes. Third, establish green tech funds allowing corporate tax deductions based on emission reductions, while levying energy consumption taxes on high-income/high-carbon groups to supplement funding.

(3) Inclusive Transformation: Spatial optimization and social welfare are core tenets. First, promote socially inclusive spaces—e.g., requiring developers to allocate a percentage of affordable housing and optimizing community service accessibility (Talen, 2006). Second, deploy neighborhood-level carbon monitoring systems to visualize and publicize real-time community footprints.

(4) Corrective Policies for Low-Level Transition Paths: First, implement infrastructure deficit compensation (30% of land transfer fees allocated to aging pipe network upgrades). Mandate $\geq 85\%$ runoff control for newly developed land. Second, share innovation benefits by directing 20% of tech park tax revenues to subsidize low-income households. Third, provide low-carbon special loans to finance urban green transition.

5.2.2 Universal Urban Green Transformation Policy Framework

(1) Strengthen Government Support & Coordination:

Resource-exhausted cities cannot rely solely on market forces; government coordination is essential (Ye Xuejie et al., 2018). First, prioritize subsidies for transitioning enterprises/industries to incentivize participation via economic and policy tools. Second, formulate mid-to-long-term green transition plans with enforceable implementation mechanisms—existing Chinese urban plans lack enforcement, diminishing their value.

(2) Boost Urban S&T Innovation Investment: Innovation capacity correlates with funding. Redirect fiscal resources (historically reliant on resource-based industries) toward improving innovation ecosystems—e.g., attracting talent, subsidizing eco-facilities, increasing education budgets, and building incubators. Cultivate local firms' innovation capabilities through government-facilitated partnerships with external R&D institutions and technology adoption support. Nationally, prioritize recognition and support for innovation enterprises in resource-exhausted cities to enhance their

locally and improve external perception, thereby attracting talent and investment.

Formatting of funding sources

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Appendix A

1. Measurement method of green transformation efficiency of resource-exhausted cities

In this paper, the super efficiency SBM model with unexpected output is used to measure the efficiency of urban green transformation in 39 research samples. Among them, input variables include: capital input, labor input, energy input, land input and system management. Expected output variables include: economic growth, industrial transformation, quality improvement of human settlements, and resource protection. Undesirable output variables include sulfur dioxide emissions, wastewater emissions, and PM2.5.

2. Measurement results of green transformation efficiency of

Table A1 Measurement results of green transformation efficiency of resource-exhausted cities

id	Shijiaz huang	Zhangjiakou	Chengde	Baotou	Wuhai	Fushun	Fuxin	Liaoya ng	Panjin	Huluda o
2020 UGTE	1.037	1.042	1.068	1.059	1.066	1.082	1.016	1.041	1.036	1.057
id	Liaoyu an	Tonghua	Baishan	Hegan g	Shuangya shan	Yichun	Qitaih e	Xuzho u	Huaibei	Tonglin g
2020 UGTE	1.046	1.013	1.053	1.023	1.021	1.015	1.046	1.061	1.016	1.034
id	Jingde zhen	Pingxiang	Xinyu	Ganzh ou	Zibo	Zaozhua ng	Jiaozu o	Puyang	Huangsh i	Shaogu an
2020 UGTE	1.049	1.061	1.055	1.066	1.025	1.023	1.018	1.010	1.005	1.034
id	Hezho u	Luzhou	Kunming	Yuxi	Tongchua n	Weinan	Lanzh ou	Baiyin	Shizuish an	
2020 UGTE	1.043	1.027	1.042	1.034	1.044	1.028	1.015	1.024	1.005	

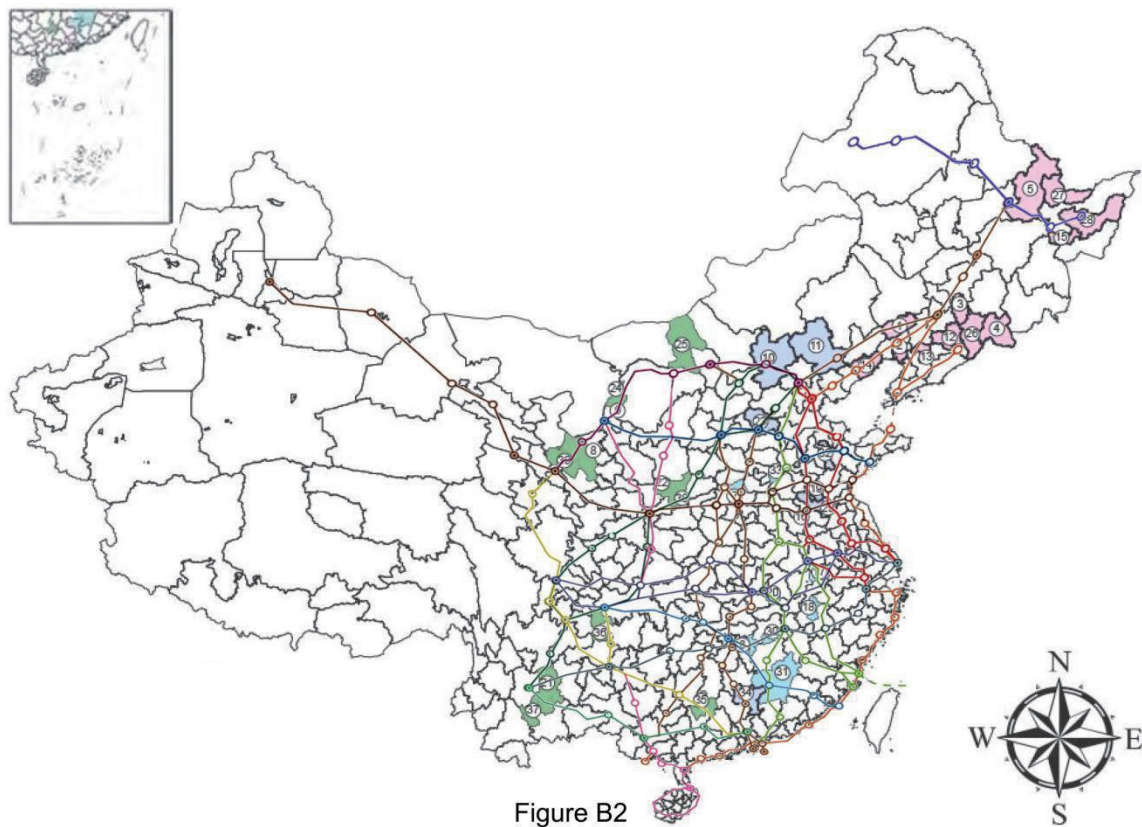
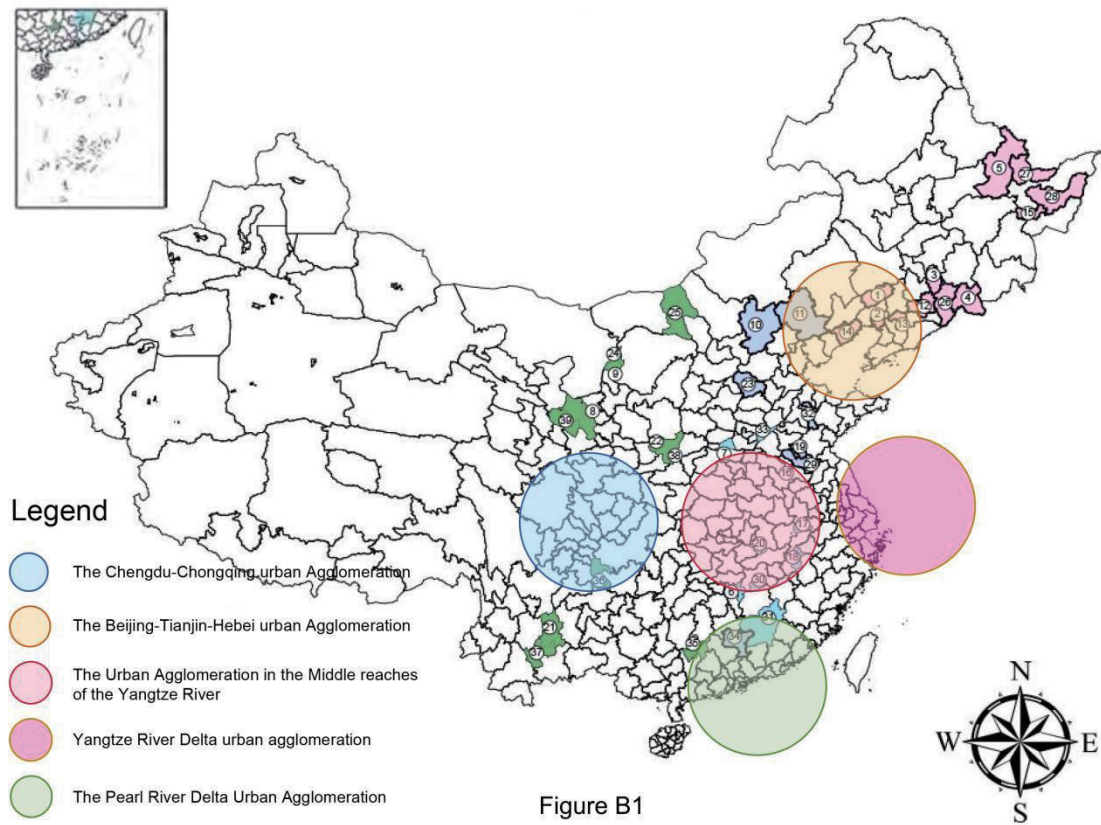
competitiveness.

(3) Embed Green Development Concepts: Society-wide participation is critical. First, promote green awareness in public spaces (e.g., waste sorting, water recycling education). Second, leverage media to advocate green consumption—residents' rational, resource-saving consumption choices can steer enterprises toward sustainable production. Third, launch citywide green branding campaigns (e.g., in parks/scenic areas) to shape environmental values

resource-exhausted cities (Table A1)

Appendix B

① Research samples and major urban agglomerations in China (Figure B1)



② Research samples and the scale of the city to which it belongs (Table B1)

Table B1 Research samples and their scale

Research samples	Urban scale & level
Jingjin mining district (Shijiazhuang)	Megacity
Dayu county (Ganzhou); Zibo district (Zibo); Lu zhou; Honggu district (Lanzhou); Shiguai district (Baotou); Zao zhuang; Jiao zuo; Huai bei; Xiahuayuan district (Zhangjiakou); Pan jin; Fu shun	Type II large city
Jiawang district (Xuzhou); Dongchuan district (Kunming); Shi zuishan; Bai shan; Yi chun; Qi taihe	Type I large city
Yimen county (Yuxi); Pu yang; Xin yu; Ping xiang; Jing dezhen; Huang shi; Shao guan; Pinggui Management District (Hezhou); Tong ling; Erdaojiang district (Tonghua); Yingtanyingzi mining district (Chengde); ;Tongguan county (Weinan) Bai yin; Fu xin; Liao yang; Yangjiazhangzi (Huludao); Liao yuan; He gang; Shuang yashan; Wu hai; Tong chuan	Medium-sized city

③ Research samples and the main transportation networks in China (Figure B2)

④ Classified by region and recognition batch (Table B2)

Table B2 Research samples and their regions

	Western	Middle	Eastern	Northeastern
Samples of research in the first group of resource-exhausted cities	Baiyin, Shizuishan	Pingxiang, Jiaozuo		Fuxin, Panjin, Liaoyuan, Baishan, Yichun
Samples of research in the second group of resource-exhausted cities	Dongchuan district (Kunming), Tongchuan, Wuhai, Shiguai district (Baotou), Pinggui Management District (Hezhou),	Huaibei, Tongling, Jingdezhen, Huangshi, XInyu, Dayu county (Ganzhou), Puyang,	Xiahuayuan district (Zhangjiakou), Yingtanyingzi mining district (Chengde), Zaozhuang, Jingjin mining district (Shijiazhuang), Jiawang district (Xuzhou), Zibo district (Zibo), Shaoguan,	Fushun, Gongchangling district (Liaoyang), Yangjiazhangzi (Huludao), Qitaihe
Samples of research in the third group of resource-exhausted cities	Luzhou, Yimen county (Yuxi), Tongguan county (Weinan), Honggu district (Lanzhou)			Erdaojiang district (Tonghua), Hegang, Shuangyashan,

Reference

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