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Research Article

Fuzzy Comprehensive Evaluation of Decoupling Economic Growth from Environment Costs in China's Resource-Based Cities

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Most of China's resource-based cities are recently threatened by the problems of environmental pollution, resource depletion, and even economic recession. There is an urgent need for these cities to decouple economic growth from environmental degradation through improving resource utilization efficiency and eco-efficiency. This paper quantitatively evaluates the decoupling trends between GDP and environmental damage in major Chinese resource-based cities using big data. To explore the decoupling trends in the development of 115 resource-based cities in China, we develops a model to evaluate the eco-efficiency between economic growth and environmental pollution. Industrial pollutants are used as indicators of environmental degradation and GDP as an index for economic growth. This study finds diverse decoupling levels among the cities and that nearly one-third are developing unsustainably. The cities have encountered serious environmental problems due to past economic policies which have encouraged extensive GDP growth for the past 4 decades. This study demonstrates that the urban development and environmental protection of Chinese resource-based cities are not on a good path. It will be more difficult for the cities with quicker GDP growth to achieve a satisfactory decoupling trend. Therefore, there is an urgent need for industries to undertake resource-conserving and environmental protection measures, and, particularly, endorse technology innovation and the green economy. In order to achieve an overall balanced decoupling in China's resource-based cities, it is essential for local governments to encourage environmentally friendly behaviors and enhance eco-efficiency when developing the country's economy. Finally, the findings illustrate significant unbalanced decoupling levels across Chinese resource-based cities.

1. Introduction

With the development of big data, the study of resource-based cities is more effective, and the research conclusions are more accurate using big data [1]. Resource-based cities have played an important role during China's ascendance to the position of the world's second largest economy by providing resources, energy, and their own continuous economic growth. However, Chinese resource-based cities face challenges due to the nonrenewable nature of natural resources, such as the minerals, energy, and forests, on which they depend [2]. They are far from achieving the sustainability goals of balanced development towards a green economy, ensuring ecological protection and social advancement. More broadly, the world, including China, will not be able to meet future demands for minerals, ores, fossil fuels, and biomass if economic growth does not decouple from the rate of natural resource consumption. The Chinese government and the leaders of resource-based cities recognize that the natural environment and resources should not be sacrificed for achieving fast economic growth and are looking for possible solutions. This paper investigates the issues that are related to the sustainable development of these resource-based cities, which, as a special economic group, are playing a key role in China's economic development.

Previous studies indicate that China's resource-based cities, mainly established in the 1950s and 1960s, have contributed significantly to the fast economic growth and industrial expansion of the country [3, 4]. Before the 1960s, the resource industries played a constructive and significant role in achieving economic growth, with natural resources, such as energy and mining, being the main engine of industrialization [4–6]. However, after six decades of resource-based industrial development and boom, these cities are now confronted with issues, such as shrinking mining sites, structurally imbalanced economies, slowing economic growth, high unemployment, and the unsustainable use and overexploitation of natural resources [5, 7]. Recently, other scholars have also drawn attention to the imbalanced development of resource-based cities and ecological problems in China and have examined the cities' shrinking resources, slowing economic growth, serious industrial pollution issues, and declining ecological environment [6, 8]. However, most studies are mainly focused on development in individual resource-based cities. For example, Liu and Li [9] studied the relationship between industrial waste gas emissions and economic and population growth as well as industrial structure in Xuzhou, China, suggesting the waste gas discharged from resource industries of the city accounted for more than 90% of total emissions.

In fact, Chinese resource-based cities are responsible for many environmental damage problems. They have an unevenly distributed ecological footprint. Furthermore, during the expansion of the resource industries, they have contributed significantly to environmental pollution [10, 11] and resource depletion [12]. Recently, Xu and Tian [13] used DEA model to analyze the eco-efficiencies of 27 coal-sourced cities, selecting waste gas and wastewater pollution as indicators, and they suggest that overall eco-efficiency has increased. However, the study also illustrated imbalanced eco-efficiencies with the eastern region being higher than the western and the central regions. In addition, the life cycle of resource-based cities has also been explored by Wang and Liu [14], who examined the coupling between economic and population growth and the ecological environment in resource-based cities in central China. It was found that, since 2005, the relationship between urbanization and the ecological environment of most resource-based cities in central China has remained unchanged. The resource-based cities with deteriorating relationships are mainly located in the provinces of Anhui, Jiangxi, and Hunan, and the better performing resource-based cities are generally located in Shanxi. Huang et al. [15] have studied the spatial convergence of eco-efficiency in selected Chinese resource-based cities, using the Meta-US-SBM model to analyze the relationship between the cities' spatial distance and eco-efficiency [16]. Their research suggests that the closer the distance is between the resource-based cities, the smaller the difference is in eco-efficiency. This paper uniquely analyzes the eco-efficiency of China's resource-based cities as a whole, selecting key indicators, which have caused China's environmental problems, including SO_2, industrial soot, and wastewater to systematically analyze the eco-efficiency of the resource-based cities from the perspectives of both resource types and life cycle. Since the previous study did not cover many resource-based cities and lacked a comparative analysis of the resource-based cities, this study analyzes the eco-efficiency of 115 resource-based cities from two angles, GDP growth and environment deterioration, and proposes development suggestions for resource-based cities in China.

China's substantial demand for resources due to continuous economic expansion intensifies environmental degradation. Resource exploitation is a process which seriously damages the natural environment, including its geological balance, surface ecology, and air. The atmospheric ecological damages include air pollution and climate change, as well as droughts and floods, due to surface and geological changes. China's National Resource-based Sustainable Urban Development Plan 2013–2020 put a strong emphasis on transforming Chinese resource-based cities to green economies. To avoid economic development and environmental health being perceived as contradictory demands, decoupling between economic growth and environmental degradation is a necessary requirement to achieve sustainability. While there are quite a few studies on resource-based cities in China, such a decoupling relation is yet to be explored and quantified.

This study evaluates the decoupling trends between economic growth and environmental degradation in Chinese resource-based cities. Based on data availability, 115 prefectural level cities were selected and their eco-efficiencies were analyzed. This study examines why and how these cities rely on their industrial resources base and the potential for developing new industries. Firstly, a review of the existing literature is presented followed by an examination of environmental issues and a sustainable development path for resource-based cities in China. The life cycle theory of resource-based cities is explained afterwards, allowing the classification of China's prefecture-level resource-based cities. An evaluation of the cities' decoupling trends is then conducted leading to policy implications and recommendations. A major innovation of this study is that it establishes a new evaluation model for calculating eco-efficiency by combining both the OECD decoupling index and Tapio's decoupling elasticity index. Another innovation is the measurement of eco-efficiency for China's resource-based cities.

2. Resource-Based Cities in China

2.1. A Historical Perspective. Most resource-based cities in China were established in the 1950s as a result of planned development which allowed for heavy reliance on a limited number of industries and imbalanced development within and between these settlements [17, 18]. Achieving economic growth was the main objective at the time, and this was further reinforced with the economic reform of the 1970s. As it was difficult to establish modern industries without access to technology, resource development was seen as the only effective choice to improve living standards in China. The emergence of a large number of resource-based cities followed extensive utilization of a development model around low-level technology. This created overdependence on resource industries, which leads to overexploitation of natural reserves. As a result, the resources in many such cities became exhausted too early and too quickly without proper replacement industries. For example, small industrial and mining cities in coal and mineral resource-rich Shanxi Province attracted attention with their unsustainable development model, which produced alarming waste creation, resource damage, serious ecological destruction, and environmental problems [19].

While resource-based cities in Eastern and Southern China have since undergone transformation [20], those in the central and western regions have been trapped in an unsustainable development mode. Since China's open-door policies of the 1970s, special economic zones were established in Eastern and Southern China with better access to modern technology, better management, and greater foreign direct investment. Many new industries developed quickly and the once resource-based cities in those regions changed dramatically. The resource-based cities in China's central and western regions lacked such supporting policies. Instead, they provided substantial raw materials and primary resource products for the eastern and southern cities. These different roles created a large development gap between China's resource-based cities [21]. After more than 60 years of development, many resource-based cities, mainly in Central and Western China, face resource exhaustion, including Yichun, Liaoyuan, Jiaozuo, Pingxiang, and Daye. Over 20 resource-based cities are in decline with poor economic prospects and serious pollution issues.

Since 2007, the Chinese government began to focus its attention on the resource-based cities. Its official policy, "Suggestions about Promoting Sustainable Development in Resource-based Cities" encouraged local governments to establish long-term mechanisms for ensuring the sustainable development of resources industries and improved nature conservation and environmental protection. In 2013, the State Council articulated "Sustainable Development Strategies for Resource-based Cities, 2013–2020" in a revised document, which set clear sustainability goals for further economic development, improvement in people's quality of life, resource conservation, and ecological protection [22]. These strategies incorporated for the first time the goals of establishing a diversified industrial system while effectively utilizing natural resources and enhancing people's well-being, which corresponds to the three sustainability pillars of enhancing economic prosperity, strengthening environmental protection, and ensuring social advancement. Furthermore, in 2014, the Chinese government fully implemented an action plan for air and water pollution prevention and drafted strategies for eliminating soil contamination. The current 13th Five-Year Plan also covers actions and plans for resource preservation. At the 19th Communist Party Congress, China declared its commitment to pursue a model of sustainable development and to maintaining green GDP growth, through upgrading industrial structures, improving production, and ensuring better living standards and a healthy ecological environment. Sustainability in resource-based cities should be achieved through an integrated progress involving all three aspects of socioeconomic and environmental development and green GDP growth. This will allow for improved, protected, and optimized use of the natural environment as well as the improvement of people's lives in an ecologically civilized society.

A necessary condition to achieve sustainable development is the decoupling between GDP growth and natural resource consumption [23]. The intensity of natural resource exploitation combined with poor technology and management has caused severe environmental degradation and ecological damage in China, particularly in its resource-based cities. These problems are magnified by the fast urban development and industrialization in all resource-based cities. Previous research on the sustainability of resource-based cities in Northeastern China indicates a declining overall trend: while the sustainability of the economic subsystem increased, that of the environmental subsystem decreased and the social system remained stable [24]. There appear to remain significant decoupling challenges.

2.2. Life Cycle Theory. Unlike other human settlements, resource-based cities go through a distinctive life cycle [6, 8, 25]. Lucas [26] described their development as a four-stage life cycle covering construction, development, transformation, and maturity. Given the end-of-life possibility, two additional stages were added later by Bradbury and St-Martin [27], namely, decline and closure (see Figure 1). At the construction stage, the exploitation of resources is at a small scale and the level of economic growth is slow due to limited resources being available during industrial development, and therefore, the ecological footprint is relatively good. During the growth stage, labor and capital are heavily invested, and the economy grows quickly due to the fast development of resources industries; however, there is progressive ecological deterioration. After a longer period of growth, the development of resource-based cities would face issues characteristic of the whole resource market with less exploitative reserves available and fluctuating demand. Because of unstable profits, enterprises would feel more competition pressure, and consequently, some would start to consider transforming their operations, and therefore, the city would enter the transformation stage.

There are two different paths after the transformation stage. On the one hand, the successfully transformed cities enter into a mature stage, changing their single-industry structure into a comprehensive industrial system. As a result, they are on a new track towards a cleaner ecological environment with less environmental pollution due to better prevention and control measures and less reliance on natural resources. On the other hand, the cities which are not able to transform successfully enter a decline stage where their economy quickly deteriorates, their population decreases because labour and capital move to new locations, and environmental pollution decreases, allowing the natural environment to gradually recover. Eventually, resource-based cities will enter into a closing stage because of declining industries and society should return to its state before resource exploitation and development [6].

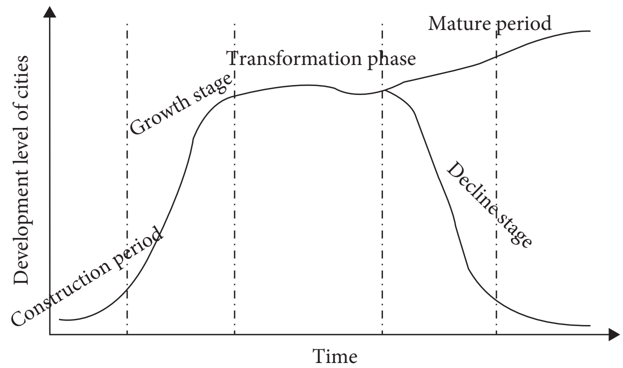

Figure 1: Life cycle of resource-based cities (source: based on Lucas [26] and Ding and Zhang [5]).

2.3. Classification and Sample Selection. In this study, "resources" refer to nonrenewable resources which are extracted and processed. When the natural reserves are exhausted, they become difficult to access or economically unviable, and the related resource industries would also decline. The definition of a resource-based city is one based on natural resources and resource industries. These cities have resource exploitation and related industries as economic pillars, which directly support a large labor force employed directly and indirectly for the resource industries.

From a development perspective, a city's prospects depend on the richness of natural resources and their exploitation. Resources may be found first and then a city developed, or the other way around—a city is developed and resources are discovered later [28]. In both cases, the discovery and utilization of resources play an important role in local development. Resources include not only oil, coal, ferrous and nonferrous metals, and mining reserves, but also forests, water, or other biological and environmental assets [23]. A city's resource utilization is important, including its eco-efficiency, as that is the link between environmental costs and environmental impacts for economic activities [29] and eco-industrial chains allowing a better resource utilization [30]. On the other hand, from a functional perspective, with resource commodities being the major local output, a city's function becomes the provision of these products to other places in the country.

According to the 2013–2020 National Resource-based Sustainable Urban Development Plan [18], there are 262 resource-based cities in China, 126 of which are at a prefecture level and the other 100 at a county level. The prefecture-level resource-based cities can be classified according to the dominant major industry as oil- and gas-based, metal-based, coal-based, and forest- and other resource-based (see Table 1). Furthermore, these cities can be categorized according to their life cycle stage, namely, developing, transforming, mature, and declining (see Table 1 and also Figure 1). This classification however does not provide any insights about the environmental performance of the resource-based cities and in particular, about their eco-efficiency. The analysis to follow is based on 115 of the 126 prefecture-level resource-based cities with 11 large prefectures (in italics in Table 1) excluded because of data unavailability.

Because the data cannot be obtained, we put 11 resource-based cities aside, which include Haixi Mongol and Tibetan Autonomous Prefecture, Altay Prefecture, Qiannan Buyei and Miao Autonomous Prefecture, Chuxiong Yi Autonomous Prefecture, Qianxinan Buyei and Miao Autonomous Prefecture, Ngawa Tibetan and Qiang Autonomous Prefecture, Bayingolin Mongol Autonomous Prefecture, Yanbian Korean Autonomous Prefecture, Puer, Liangshan Yi Autonomous Prefecture, and Da Hinggan Ling Prefecture; all of them are minority autonomous regions. Then, we have studied 115 resource-based cities in China.

3. Methodology

This study evaluates the eco-efficiency of the selected 115 resource-based cities by calculating the decoupling elasticity between GDP and pollutant discharge based on a fuzzy comprehensive analysis model of the eco-efficiency evaluation theory and Tapio's decoupling index. Eco-efficiency evaluation is one of the most important methods for assessing decoupling trends for sustainable development. All definitions include balancing the use of resources and environmental impact with human demands, expressed as the ratio between economic value added and added environmental impact. The Organization for Economic Co-operation and Development (OECD) defined eco-efficiency as "the efficiency with which ecological resources are used to meet human demands" [26]. According to the World Business Council for Sustainable Development, this is a management philosophy for environmental improvements leading to economic benefits. In other words, more human demands are met with less stress on the environment with environmental impacts and resource use kept within Earth's bearable level.

Decoupling describes the relationship between two upward curves—of economic growth and of the utilization of resources or environmental impacts. In environmental studies, decoupling assessment is used to measure the link between environmental pressure and GDP growth [33, 34]. A decoupling index represents the changing rate of an environmental indicator over the changing rate of an economic indicator. If the former is not growing with economic growth, the trend is considered decoupling [35, 36].

3.1. Two Decoupling Indexes. In order to assess the decoupling trends of China's resource-based cities, the indicator chosen is the separation degree between the environmental indicator curve and the economic indicator curve [32]. Two decoupling indexes are used, namely, the OECD decoupling index [37] and the decoupling elasticity index [38].

According to the OECD [39], the decoupling index is the separation degree between the environmental pressure (EP) and the development momentum (DM):

$$\text{decoupling index} = \frac{(\mathrm{EP}/\mathrm{DM})_{\text{beginning}}}{(\mathrm{EP}/\mathrm{DM})_{\text{end}}}. \tag{1}$$

Table 1: Classification of selected 126 resource-based cities at prefecture level in China.

	Oil and gas [13]	Metal [26]	Coal [47]	Forest and others [27]
Developing [22]	Yan'an Qingyang Longnan *Haixi Mongol and Tibetan Autonomous Prefecture* [4]	Songyuan Hezhou Liupanshui Wuwei *Altay Prefecture* *Qiannan Buyei and Miao Autonomous Prefecture* [6]	Shuozhou Hulun Buir Erdos Zhaotong Xianyang Yulin *Chuxiong Yi Autonomous Prefecture* *Qianxinan Buyei and Miao Autonomous Prefecture* [9]	Nanchong Bijie [2]
Transforming [17]	Panjin Nanyang [2]	Huludao Tangshan Baotou Anshan Tonghua Ma'anshan Zibo Luoyang Zhangye *Ngawa Tibetan and Qiang Autonomous Prefecture* [11]	Xuzhou [1]	Suqian Linyi Lijiang [3]
Mature [66]	Daqing Dongying Baoshan Karamay *Bayingolin Mongol Autonomous Prefecture* [5]	Benxi Longyan Ganzhou Laiwu Ezhou Hengyang Handan Chenzhou Shaoyang Loudi Hechi Panzhihua Dazhou Ya'an Baoji Jinchang [17]	Zhangjiakou Xingtai Datong Yangquan Changzhi Jincheng Linfen Xinzhou Yuncheng Lvliang Chifeng Heihe Jixi Huainan Hebie Pingdingshan Guangyuan Guang'an Anshun Qujing Weinan Pingliang *Yanbian Korean Autonomous Prefecture* [24]	Chengde Jinzhong Jilin Suzhou Mudanjiang Huzhou Bozhou Chuzhou Chizhou Xuancheng Nanping Sanming Yichun (Jiangxi Province) Jining Taian Sanmenxia Yunfu Baise Zigong Lincang *Puer* *Liangshan Yi Autonomous Prefecture* [18]
Declining [25]	Puyang [1]	Tongling Xinyu Huangshi Shaoguan Baiyin [5]	Wuhai Fuxin Fushun Liaoyuan Yichun (Heilongjiang Province) Hegang Shuangyashan Qitaihe Huaibei Zaozhuang Pingxiang Jiaozuo Luzhou Tongchuan Shizuishan [16]	Baishan Jingdezhen *Da Hinggan Ling Prefecture* [3]

Note: the number in parentheses is the quantity of the city, and the cities written in italics cannot be studied because of data lacking.

Environmental pressure can be represented by energy consumption, greenhouse gas emissions, and pollution indicators while development momentum is represented with GDP. The decoupling is breaking the link between "environmental bads" and "economic goods" [39], hence between growth in environmental pressure and the generation of economic benefits and services [37, 40]. Decoupling is considered to occur when the GDP growth rate is higher than environmental damage over a certain period [2].

Alternatively, according to Tapio [34], the decoupling elasticity index is the changing rate of an environmental indicator over the changing rate of economic development calculated according to the following equation:

$$\text{decoupling elasticity index (DEI)} = \frac{\Delta \text{EI}/\text{EI}}{\Delta \text{GDP}/\text{GDP}}, \quad (2)$$

where ΔEI/EI is an environmental indicator's change rate and ΔGDP/GDP is the change rate of GDP. Using the decoupling elasticity index, Tapio divides the relationship between environmental pollution and GDP growth into 8 types: strong positive decoupling, expansive weak decoupling, declining strong coupling, expansive coupling, declining coupling, expansive strong coupling, declining weak decoupling, and strong negative decoupling [40, 41] (see Table 2).

In Tapio's decoupling elasticity model, data for the start and end year of the time period are used to calculate the index, which does not show annual trends. Due to the wide yearly fluctuation of pollution in the Chinese cities, Tapio's model does not properly represent the real decoupling relationship between economic growth and environmental degradation [39]. According to the observation of the GDP, INS, INW, and SO_2 data of resource-based cities, it is found that the annual data fluctuate greatly. For example, consider two randomly selected cities—Karamay and Tangshan. Karamay is located in the Xinjiang Uygur Autonomous Region of China in the northwest areas and is a mature oil and gas resource-based city. Tangshan is located in Hebei Province, which is a metal resource-based city in the stage of transformation. They are both typical resource-based cities in China.

Karamay would show strong positive decoupling between GDP and industrial soot emissions only if the start and end of the 2004–2017 period are used (see Figure 2). However, due to considerable volatility in the data for industrial soot emissions, the real decoupling trend with GDP over the entire sample period is difficult to estimate. Similarly, for Tangshan, if only the start and end year of the 2004–2017 period are used, the city would also show a strong positive decoupling between GDP and industrial soot emissions (see Figure 3). In fact, a strong positive decoupling was observed only from 2003 to 2010. Furthermore, Tapio's eight decoupling trends (shown in Table 2) are not suitable for Chinese resource-based cities which experience fast economic growth.

3.2. Eco-Efficiency of China's Resource-Based Cities. This study adopts both the OECD decoupling index and Tapio's decoupling elasticity index, but also includes the middle year variations to establish a new evaluation model for calculating the eco-efficiency of the resource-based cities (see equation (3)):

$$\text{DEI}_{\text{EP,ED}} = \frac{\Delta \text{EP}/\text{EP}}{\Delta \text{ED}/\text{ED}} = \frac{(\text{EP}_t - \text{EP}_{t-1})/\text{EP}_{t-1}}{(\text{ED}_t - \text{ED}_{t-1})/\text{ED}_{t-1}}, \quad (t = 1, 2, \ldots, n). \quad (3)$$

$\text{DEI}_{\text{EP,ED}}$ is the decoupling elasticity between environmental pressure and economic growth; EP_t is the environmental pressure in year t of the study period; EP_{t-1} is the environmental pressure in year $t-1$ of the study period; ED_t is the economic growth in year t of the study period; ED_{t-1} is the economic growth in year $t-1$ of the study period.

Environmental pressure (EP) is represented by industrial wastewater (INW) discharge, industrial SO_2, and industrial soot emissions (INS) while economic development is represented by GDP growth.

In recent years, China is suffering from serious pollution, including air pollution, water pollution, and soil pollution. The pollution sources mainly come from domestic waste and industrial pollutants. While the high pollution industries of resource exploitation and resource and primary processing are the main industries of China's resource-based cities, industrial pollution is the main source of pollution in resource-based cities. In these pollutions, industrial soot, industrial wastewater, and SO_2 are the main pollutants that cause air pollution, water pollution, and soil pollution, so the 3 indicators of INS, INW, and SO_2 have been selected to represent environmental pressure.

Table 2 shows Tapio's decoupling-elastic model, which is suitable for evaluating the decoupling of economy and environment in mature economies. Because the value range of each stage is narrow in 8 decoupling trends of Tapio's model, meanwhile the trends of economic development and environmental degradation are relatively flat in mature economies, the narrower value interval can reflect the difference among trends [6]. While resource-based cities GDP increase rapidly with environmental deteriorating severely, then the narrower numerical area is not enough to show the decoupling trends between economy and environment [7]. Tables 3 is obtained based on Table 2, Figure 2 and 3.

Taking into consideration economic growth, environmental degradation, and decoupling indexes, the decoupling trends are categorized into five levels, namely, excellent, very good, satisfactory, poor, and unsatisfactory (see Table 3 and Figure 4). The decoupling trends are then evaluated using the fuzzy comprehensive evaluation method.

4. Empirical Results

The evaluation method is presented first using the illustrative example of Karamay. This is followed by the full sample results. There are 38 resource-based cities with data available for 2003–2014, 76 with data for 2004–2017, and one (Bijie) with data only for 2011 to 2017. This should not affect the evaluation results as yearly evaluations are used.

Table 2: Tapio's evaluation of eco-efficiency.

Decoupling trend	ΔEI/EI	ΔGDP/GDP	DEI	Trends
Strong positive decoupling	<0	>0	<0	GDP grows while pollution decreases
Expansive weak decoupling	>0	>0	0–0.8	GDP grows while pollution increases slowly
Declining strong decoupling	<0	<0	>1.2	GDP declines slowly while pollution decreases quickly
Expansive coupling	>0	>0	0.8–1.2	GDP grows while pollution increases
Declining coupling	<0	<0	0.8–1.2	GDP declines while pollution decreases
Expansive negative decoupling	>0	>0	>1.2	GDP grows slowly while pollution increases dramatically
Declining negative decoupling	<0	<0	0−−0.8	GDP decreases quickly while pollution decreases slowly
Strong negative decoupling	>0	<0	<0	GDP declines while pollution increases

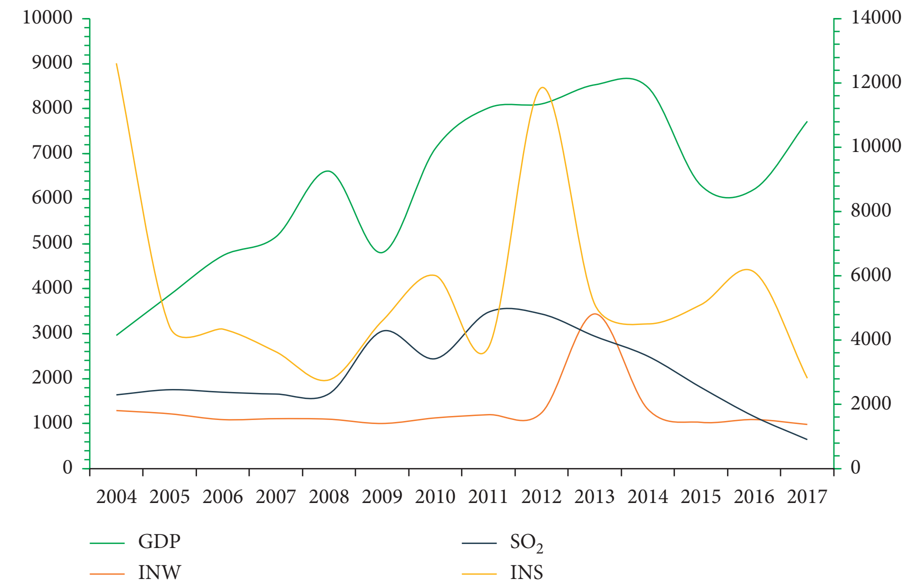

Figure 2: Pollution and GDP of Karamay.

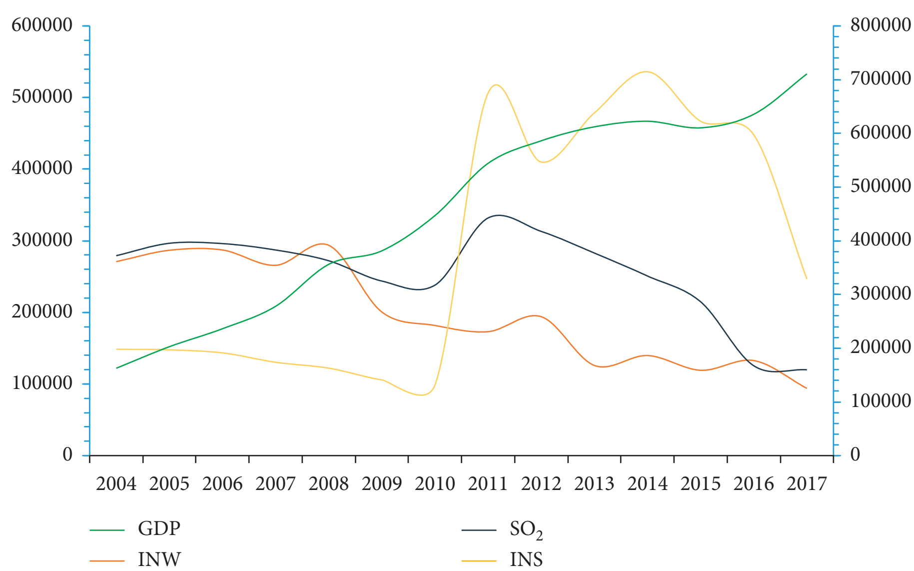

Figure 3: Pollution and GDP of Tangshan.

Table 3: Evaluation of eco-efficiency.

Decoupling trends	ΔEP	ΔED	DEI	Level	Trends
Strong positive decoupling	<0	>0	<−0.5	A: excellent	Economic growth increases while pollution decreases at a rate not less than half the rate of economic growth
Weak positive decoupling	<0	>0	>−0.5	B: very good	Economic growth increases while pollution decreases at a rate less than half the rate of economic growth
Expansive decoupling	>0	>0	<1	C: satisfactory	Economic growth increases while pollution increases at a rate not higher than the rate of economic growth
Declining decoupling	<0	<0	>1.2		Economic growth decreases while pollution decreases at a rate more than 1.2 times the rate of economic growth
Expansive negative decoupling	>0	>0	>1	D: poor	Economic growth increases while pollution increases at a rate higher than the rate of economic growth
Declining negative decoupling	<0	<0	<1.2		Economic growth decreases while pollution decreases at a rate less than 1.2 times the rate of economic growth
Strong negative decoupling	>0	<0	<0	E: unsatisfactory	Economic growth decreases while pollution increases

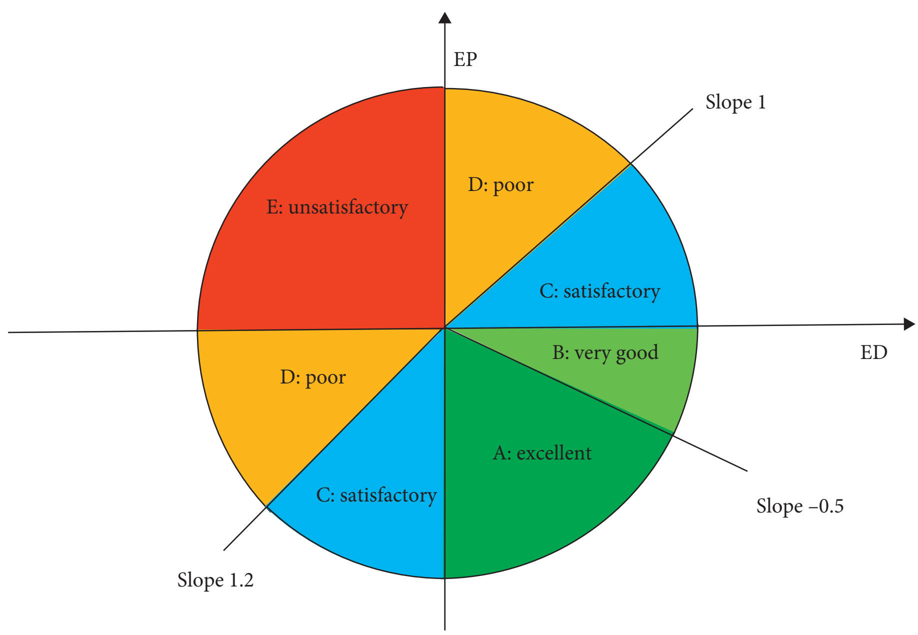

Figure 4: Evaluation areas of resource-based cities' eco-efficiencies.

4.1. Illustrative Calculation for Karamay. The following four steps are used for the evaluation model:

Step1: data processing–data for GDP, INW, SO_2, and INS from 2004 to 2017 (14 years) are used for Karamay.

Step 2: evaluating yearly indexes according to equation (3), divided into three pollutants:

$$\frac{(\mathrm{INW}_t - \mathrm{INW}_{t-1})/\mathrm{INW}_{t-1}}{(\mathrm{GDP}_t - \mathrm{GDP}_{t-1})/\mathrm{GDP}_{t-1}},$$
$$\frac{(\mathrm{SO}_{2t} - \mathrm{SO}_{2t-1})/\mathrm{SO}_{2t-1}}{(\mathrm{GDP}_t - \mathrm{GDP}_{t-1})/\mathrm{GDP}_{t-1}}, \tag{4}$$
$$\frac{(\mathrm{INS}_t - \mathrm{INS}_{t-1})/\mathrm{INS}_{t-1}}{(\mathrm{GDP}_t - \mathrm{GDP}_{t-1})/\mathrm{GDP}_{t-1}}.$$

Table 4 presents the calculation results for Karamay.

Step 3: evaluating according to the maximum subordinate degree principle, ΔEP, ΔED, and DEI are calculated and the eco-efficiency level is assigned by a computer program. The evaluation level is assigned based on the highest frequency level; if there are several similar frequency levels, the lowest eco-efficiency is assigned. Table 5 shows the eco-efficiency levels by pollutants for Karamay. As there are 9 records of "A," 8 of "B," 10 of "C," 7 of "D," and 5 of "E," according to the maximum subordinate degree principle, the comprehensive evaluation level for Karamay is "C."

4.2. Full Sample Results. Figure 5 shows the combined evaluation outcomes for all 115 cities by pollutants. The DEIs for industrial wastewater and industrial SO_2 are moderate, while that for industrial soot is even better. Table 6 presents

Table 4: Data of Karamay.

Year	ΔGDP	ΔINW	ΔSO_2	ΔINS	ΔINW/ΔGDP	$\Delta SO_2/\Delta GDP$	ΔINS/ΔGDP
2005	0.3022	−0.0558	0.0696	−0.6489	−0.1847	0.2302	−2.1470
2006	0.2269	−0.1060	−0.0315	−0.0192	−0.4670	−0.1390	−0.0846
2007	0.0885	0.0194	−0.0240	−0.1621	0.2187	−0.2714	−1.8322
2008	0.2836	−0.0106	0.0034	−0.2412	−0.0375	0.0119	−0.8504
2009	−0.2736	−0.0870	0.8359	0.6629	0.3180	−3.0551	−2.4228
2010	0.4811	0.1238	−0.1999	0.3085	0.2572	−0.4156	0.6413
2011	0.1270	0.0633	0.4227	−0.3730	0.4984	3.3286	−2.9377
2012	0.0113	0.0351	−0.0116	2.1462	3.1214	−1.0295	190.7563
2013	0.0523	1.7694	−0.1436	−0.5685	33.8288	−2.7459	−10.8681
2014	−0.0064	−0.6161	−0.1510	−0.1194	96.6737	23.7013	18.7408
2015	−0.2575	−0.2201	−0.2778	0.13296	0.85496	1.07889	−0.5164
2016	−0.0134	0.06033	−0.3581	0.19886	−4.5043	26.7310	−14.847
2017	0.2432	−0.1001	−0.4418	−0.5340	−0.4115	−1.8170	−2.2206

Data source: calculated from the originally collected data from the Development Research Centre Net (DRCNET, 2017), http://www.drcnet.com.cn/www/integrated/#.

Table 5: Evaluation of Karamay.

Year	INW	SO_2	INS
2005	B	C	A
2006	B	B	B
2007	C	B	A
2008	B	C	A
2009	D	E	E
2010	C	B	C
2011	C	D	A
2012	D	A	D
2013	D	A	A
2014	C	C	C
2015	D	D	E
2016	E	C	E
2017	B	A	A

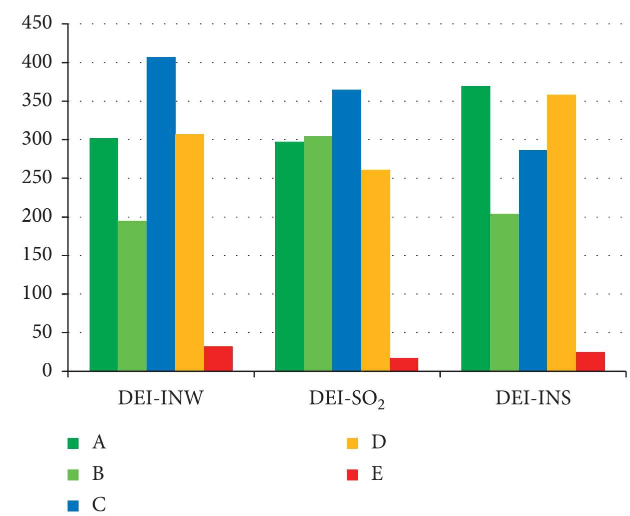

Figure 5: Evaluation of DEI of INW, SO_2, and INS.

the eco-efficiency evaluation results for each of the 115 resource-based cites while the map on Figure 6 shows their geographical location.

The eco-efficiency assessment shows that overall, there are 30 level A, 10 level B, 39 level C, 34 level D, and 2 level E cities (see Figure 7). There were several provinces with relatively low eco-efficiencies. Heilongjiang and Jilin provinces in Northeast China had no level A or B cities but two level E cities and the others at C or below. Hebei, Henan, Sichuan, Hunan, Hubei, and the Inner Mongolia Autonomous Region also had low eco-efficiencies with six cities at level D and one at level C. Jiangxi, Guizhou, and Guangxi were also not performing well.

4.3. Results by Commodity Type. Figure 8 and Table 7 show the distribution of the evaluation results according to resource types. Level A cities account for the highest percentage in the coal-based cities which is equal to that of level C cities. The coal cities also have overall the highest share of excellent and good eco-efficiencies. Level C cities also represent the highest percentage in oil and gas and forest and other categories while level D cities are the highest in metal-based resource-based cities. The two level E cities belong, respectively, to the coal and forest and other group. Overall, there is no significant difference among different commodity types. This suggests that the challenges for resource-based cities are not affected by the different price performance of different commodities.

Among the 115 resource-based cities, environmental pollution is most serious among oil and gas resource-based cities, with 90% of the cities being at levels C, D, and E. The forest and other resource-based cities are performing better in pollution control with nearly 60% of them being at levels C, D, and E. The coal and metal-based cities account for less cities at levels C, D, and E, 57% and 56%, respectively.

4.4. Results by Life Cycle Type. The results presented in Figure 9 and Table 8 show the distribution of the eco-efficiencies according to life cycle stages of the resource-based cities. Level A cities represent the highest percentage in the transforming cities which indicates that there are efforts to decrease the environmental impacts of economic activities. There are no level E cities in the two categories of developing and transforming cities, but this unsatisfactory eco-

Table 6: Evaluated eco-efficiencies of the 115 resource-based Chinese cities.

No.	City	Level	No.	City	Level	No.	City	Level
1	Anshan	D	40	Hulun Buir	C	79	Sanming	C
2	Anshun	D	41	Huzhou	C	80	Shaoguan	A
3	Baise	D	42	Jiaozuo	A	81	Shaoyang	A
4	Baishan	A	43	Jilin	E	82	Shizuishan	B
5	Baiyin	A	44	Jinchang	D	83	Shuangyashan	C
6	Baoji	B	45	Jincheng	B	84	Shuozhou	C
7	Baoshan	C	46	Jingdezhen	C	85	Songyuan	C
8	Baotou	A	47	Jining	D	86	Suqian	C
9	Benxi	A	48	Jinzhong	D	87	Suzhou	B
10	Bijie	D	49	Jixi	C	88	Taian	C
11	Bozhou	D	50	Karamay	C	89	Tangshan	A
12	Changzhi	C	51	Laiwu	D	90	Tongchuan	B
13	Chengde	D	52	Liaoyuan	C	91	Tonghua	D
14	Chenzhou	C	53	Lijiang	C	92	Tongling	B
15	Chifeng	B	54	Lincang	C	93	Weinan	A
16	Chizhou	D	55	Linfen	A	94	Wuhai	C
17	Chuzhou	C	56	Linyi	D	95	Wuwei	D
18	Daqing	C	57	Liupanshui	B	96	Xianyang	A
19	Datong	A	58	Longnan	D	97	Xingtai	A
20	Dazhou	A	59	Longyan	D	98	Xinyu	D
21	Dongying	D	60	Loudi	C	99	Xinzhou	D
22	Erdos	A	61	Luoyang	A	100	Xuancheng	A
23	Ezhou	B	62	Luzhou	A	101	Xuzhou	A
24	Fushun	A	63	Lvliang	C	102	Ya'an	D
25	Fuxin	D	64	Ma'anshan	C	103	Yan'an	C
26	Ganzhou	D	65	Mudanjiang	D	104	Yangquan	A
27	Guang'an	D	66	Nanchong	A	105	Yichun (Heilongjiang Province)	C
28	Guangyuan	A	67	Nanping	C	106	Yichun (Jiangxi Province)	C
29	Handan	C	68	Nanyang	A	107	Yulin	C
30	Hebei	C	69	Panjin	C	108	Yuncheng	A
31	Hechi	D	70	Panzhihua	C	109	Yunfu	C
32	Hegang	C	71	Pingdingshan	C	110	Zaozhuang	D
33	Heihe	D	72	Pingliang	D	111	Zhangjiakou	A
34	Hengyang	B	73	Pingxiang	D	112	Zhangye	D
35	Hezhou	C	74	Puyang	D	113	Zhaotong	D
36	Huaibei	C	75	Qingyang	D	114	Zibo	D
37	Huainan	C	76	Qitaihe	E	115	Zigong	A
38	Huangshi	A	77	Qujing	A			
39	Huludao	A	78	Sanmenxia	C			

Data source: calculated from the originally collected data from the Development Research Centre Net (DRCNET, 2017), http://www.drcnet.com.cn/www/integrated/#.

efficiency is demonstrated in the group of mature and even stronger among declining cities. Level C cities dominate developing and mature cities. The declining group is quite interesting as overall it has the highest share of excellent (A) and very good (B) eco-efficiency but also the highest number of cities with only satisfactory eco-efficiency. This could be interpreted as indicating that unless concerted efforts are made early in the life cycle of resource-based cities to conserve the natural resources on which they depend, eco-efficiency comes a stage when the environmental damage, including resource depletion, becomes irreversible. The improved eco-efficiency is not capable of stopping the overall decline.

Table 8 shows that, among the resource-based cities classified by life cycle, the cities in the developing stage have encountered the most serious ecological problems with 73% of such cities falling in categories C, D, and E. However, the transforming, mature, and declining cities are performing better with 60%, 68%, and 25% of cities falling in C, D, and E, respectively. Although the declining cities show the positive decoupling trend, there is a need for local governments to formulate proper strategies of transformation to revitalize their cities' economy.

5. Discussion

There are many factors influencing the evaluation results. The data analysis showed that from the perspective of city types, in coal-based cities, the decoupling between INW discharge and GDP was large while the decoupling between GDP and SO_2 or INS was smaller. The decoupling of environmental discharge and economic growth may be caused by the fast growth of coal production in the 2000s and increases in coal prices. The relatively better performance of

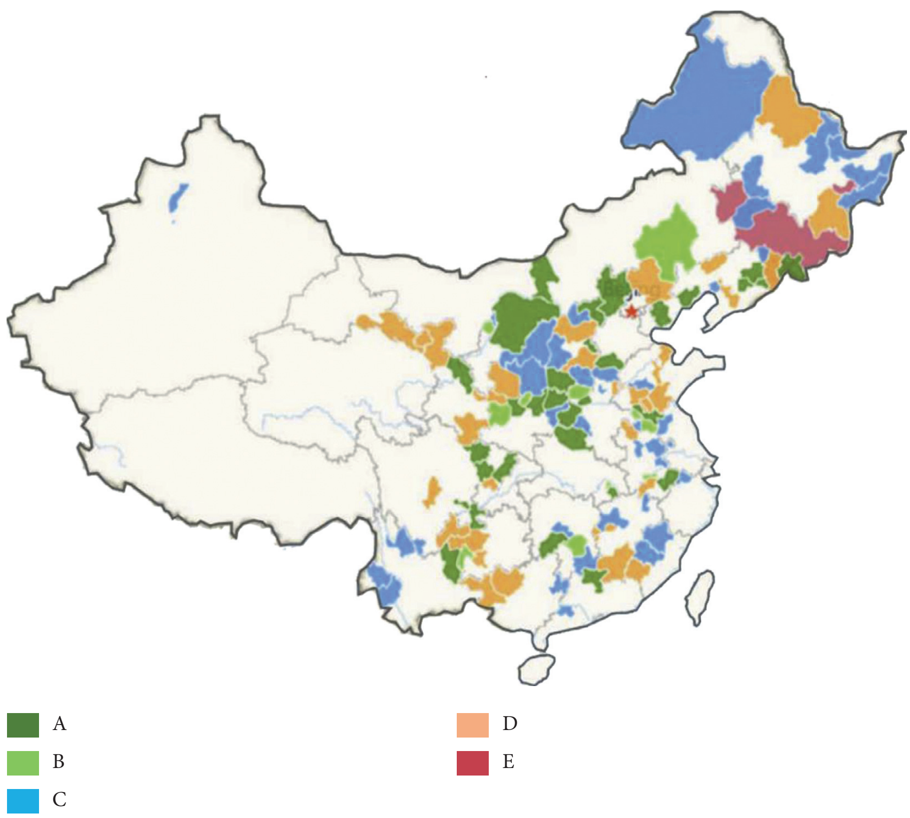

Figure 6: Location of the evaluated Chinese resource-based cities.

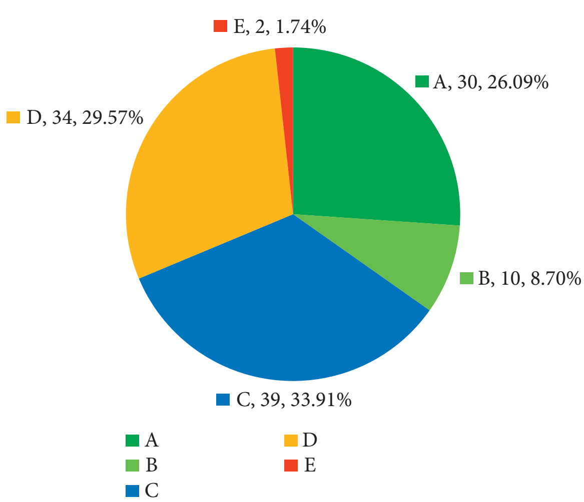

Figure 7: Eco-efficiency distribution of the 115 evaluated Chinese resource-based cities.

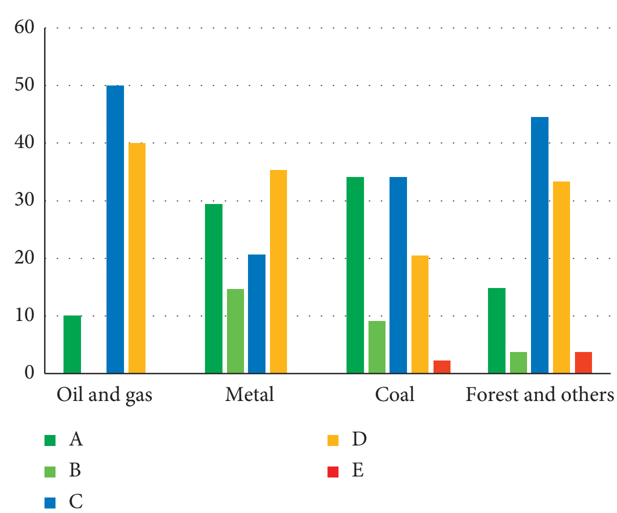

Figure 8: Eco-efficiency evaluation results by resource type (%).

wastewater compared to SO_2 and INS is likely due to improved regulations about INW discharge during the sample period. On the other hand, SO_2- and INS-related regulations were enforced before the sample period and there were no significant changes in both technology and policy environment. Therefore, the trend is stable.

In oil resource-based cities, GDP was increasing relatively slowly and the increase in pollution discharge was also small. A possible explanation is that oil-based cities faced the threat of resource depletion accompanied by decreasing resource exploitation. Most oil-producing cities, except those in Xinjiang, are no longer able to sustain their production.

Prior to 2010, GDP was growing quickly in metal-based cites while the pollution growth rate was lower than that of GDP. After 2010, the pollution growth rate decreased and was accompanied by decreased GDP growth rate. In addition, before 2010, the industries of the steel-based cites were booming, but after 2010 with the slowing of national

Table 7: Eco-efficiency evaluation results by resource type.

Number	A	B	C	D	E	Total
Oil- and gas-based cities	1	0	5	4	0	10
Metal-based cities	10	5	7	12	0	34
Coal-based cities	15	4	15	9	1	44
Forest and other resource-based cities	4	1	12	9	1	27
Total	30	10	39	34	2	115

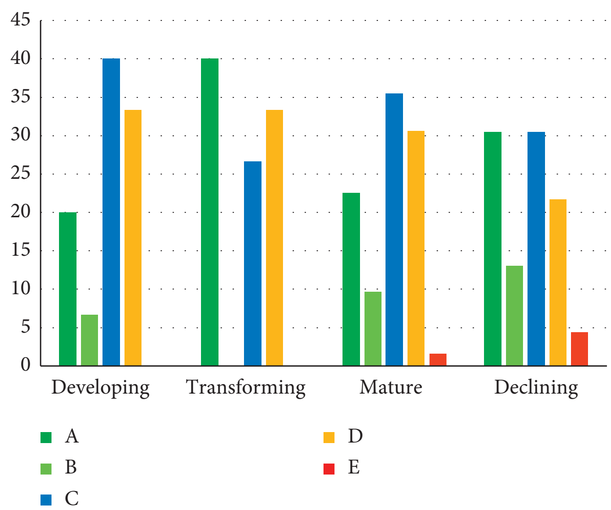

Figure 9: Eco-efficiency evaluation results by life cycle stage type (%).

Table 8: Eco-efficiency evaluation results by life cycle stage type.

Number	A	B	C	D	E	Total
Developing cities	3	1	6	5	0	15
Transforming cities	6	0	4	5	0	15
Mature cities	14	6	22	19	1	62
Declining cities	7	3	7	5	1	23
Total	30	10	39	34	2	115

economic growth, the industries which required large amounts of steel such as construction have been developing slowly. As a consequence, the GDP and pollution growth rates started to slow down.

In the forest and other resource-based cites, the GDP growth rate was relatively slow and the decoupling rate between GDP and pollution emission rates was also small. This was due to a lack of significant changes in either technology or regulation.

From a regional perspective, in the resource-based cities of Northeast China (Heilongjiang, Liaoning, and Jilin) and in Southwest China (Yunnan, Guizhou, Sichuan, and Guangxi) as well as in Shanxi Province, the GDP growth rate was relatively slower and their pollution emissions were decreased quickly. Moreover, in North China (Hebei and Mongolia) and Central China (Henan, Wuhan, Hunan, and Anhui), the GDP of the resource-based cities was increasing relatively fast; however, the pollution emission rate was lower than the GDP growth rate. In East China (Jiangsu, Zhejiang, and Jiangxi) and South China (Fujian and Guangdong), the resource-based cities experienced the fastest GDP growth rates and their pollution emissions were generally decreasing. Overall, East China presents the most desirable case of decoupling, which is likely due to technology progress allowing the economy to grow with less environmental damage. The decoupling in Northeast and Southwest China is also acceptable, even at the cost of lower economic growth. The North China pattern however needs to be monitored as environmental deterioration may continue with economic growth.

6. Conclusion and Policy Implications

This paper quantitatively assesses the decoupling between economic growth and environmental degradation in 115 Chinese resource-based prefectural level cities using an innovative method to calculate eco-efficiencies. The results suggest that, among the 115 resourced-based cities, 30 level A cities are performing well in decoupling between economic growth and environmental degradation, and the performance of 10 cities of level B has been slightly improved. However, 39 cities of level C have just maintained the decoupling and 36 cities of level D have been performing in deteriorating rate, particularly with last 2 cities of levelE being deteriorating seriously. The results indicate that about one-third of these cities fall in level D or E, which indicates unsustainable development. Moreover, there are very different decoupling levels among the cities located in different regions of the country. The extensive environmental degradation in China's resource-based cities has been accompanied by fast economic expansion. Yet, it is encouraging to see that the Chinese government is currently taking strict measures to protect resources and the natural environment. The imbalance in resource-based cities' decoupling trends should be able to allow the poorly performing cities to search for more development opportunities.

In order to protect the natural environment, there is an urgent need for the resource-based cities to decouple GDP growth from environmental degradation. Achieving sustainability in the resource-based cities should be taken from a concept to proper engagement with weakening the link between GDP growth and environmental degradation. This is essential for their future [38]. There is a need to summarise the key experiences from those cities, who have achieved levels A and B, and lessons from those who failed into levels D and E. Such a share of knowledge might help resource-based in China and the rest of the world to achieve sustainable development.

In addition, the urban transition and environmental performance of Chinese resource-based cities are not equally smooth [1, 37]. For the cities with fast GDP growth, it is harder to achieve a high decoupling level. As suggested by Mao [41] and Ru et al. [12], the urban transformation should be achieved through enhancing technology innovation, improving resource utilization, and upgrading the industrial structure, particularly in the cities in North and West China and this will help them increase their competitiveness. Local leaders should support green investment and encourage industries to increase their eco-efficiency and avoid resource waste and utilization [42]. Most importantly, local governments need to take effective actions to achieve a balanced future development for resource-based cities, including improving local resource utilization and promoting the circular and green economies as the key solutions [12].

The extend of the decoupling between economic growth and environmental degradation changes considerably with different macroeconomic circumstances and policy adjustments as well as depending on local government efforts, the types of resources exploited, resource management abilities, and anticorruption and environmental regulation policies. This study believes that improving eco-efficiency and choosing the economically desired level of environmental and resource management as suggested by Schaltegger and Synnestvedt [31] can effectively enhance sustainability. This is particularly important for achieving a more effective decoupling and a more balanced development of the resource-based cities in China.

Data Availability

The evaluation data used to support the findings of this study can be accessed publicly at the website https://github.com/zhidongli98762020123/China-s-resource-based-cities/.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

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